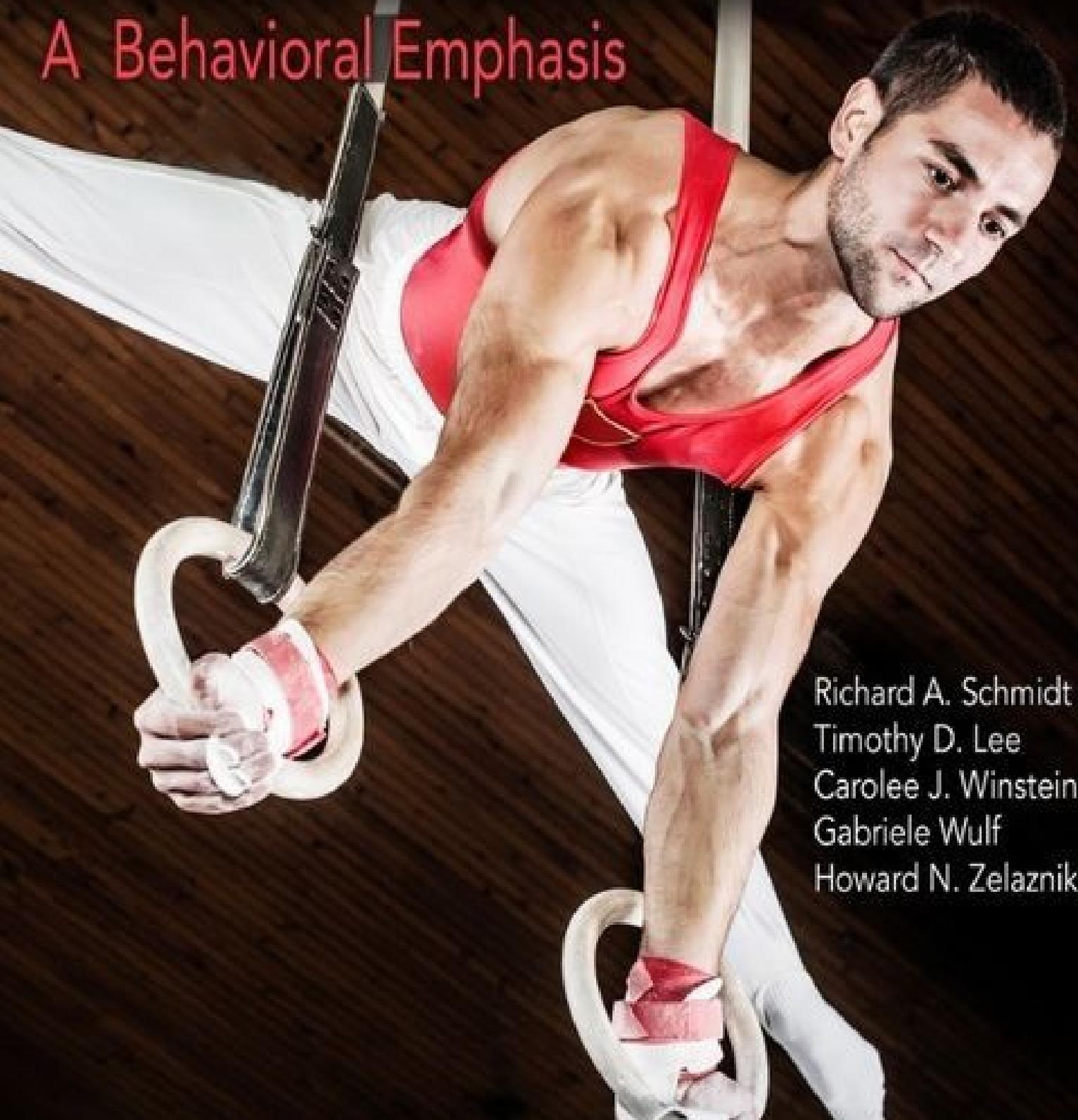


Sixth Edition

# MOTOR CONTROL AND LEARNING

A Behavioral Emphasis

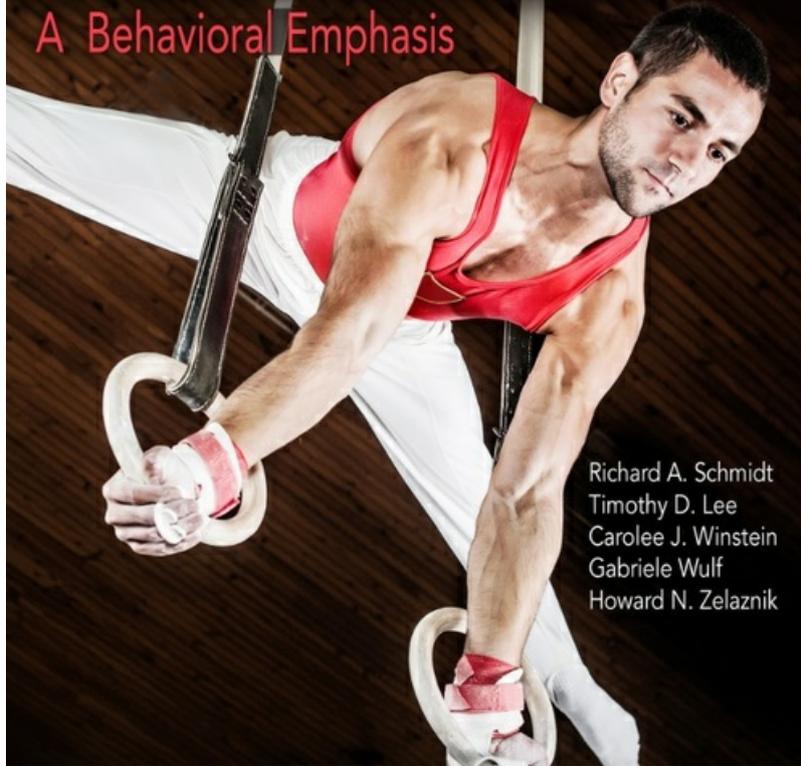


Richard A. Schmidt  
Timothy D. Lee  
Carolee J. Winstein  
Gabriele Wulf  
Howard N. Zelaznik

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# Motor Control and Learning

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## *A Behavioral Emphasis*

Sixth Edition

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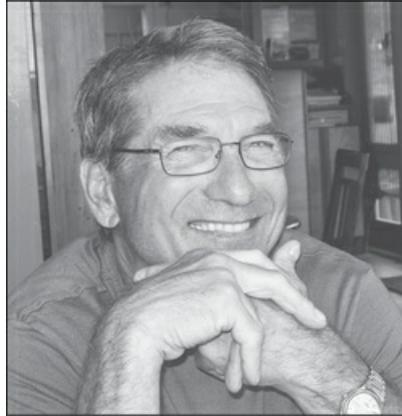
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# Dedication to Richard Allen Schmidt (1941-2015)



Courtesy of Ann Chamberlin

Richard Allen Schmidt, or "Dick," as he preferred, died on October 1, 2015. The day before his death Dick had completed signing the last copies of his memoir (Schmidt, 2015a), which he was sending out to the friends, colleagues, and acquaintances he had mentioned in his book. The book is a testament to a life lived to the fullest, including triumphs and shortcomings, wins and losses. Originally he had intended the book to serve as a blueprint for how to become a success in academia. What he didn't seem to realize, however, was that not everyone possesses the necessary skills and abilities to do what he did. In fact, very few do.

The four coauthors of this book collaborated to write a comprehensive memorial about Dick in the *Journal of Motor Behavior*, the journal that Dick founded in 1969 and for which he served as sole editor until 1980 (Lee, Wulf, Winstein, & Zelaznik, 2016). This memorial is available as an open access article, so we will not repeat those comments here. Instead, we simply point the reader to search for the Schmidt references cited in the pages of the book you are now reading to get a clear understanding of the important contributions that Dick made to the study of motor control and learning. He was a giant in our field, and his influence remains throughout these pages.

## Comments from Tim Lee

The year 1982 was an important one for me. I completed my PhD at LSU, moved back to Canada to begin a job as an assistant professor at McMaster University, and, at some point during the year, received my copy of the first edition of *Motor Control and Learning: A Behavioral Emphasis*. As a newly minted PhD, seeing the "bigger picture" role of motor learning and motor control and trying to relate that to 300 undergraduates in a second-year kinesiology course was a daunting task. This book guided me through those early teaching years in immeasurable ways. It provided a conceptual framework for teaching, led me to a wealth of information that I did not know existed, and underscored the importance of this field of study for issues of practical and theoretical importance. Quite simply, the first edition of this book was a landmark in not only the field of motor control and learning but in the discipline of kinesiology in general. Dick had produced his *magnum opus*.

The second edition of the book was published in 1988 and, to my astonishment, it was even better than the first. Some sections had been eliminated (e.g., theory building and hypothesis testing), but significant additions had been made, especially to the chapters that interested me the most—the ones on motor learning. Around that time I got to know Dick a little better. He invited me to Los Angeles for a few weeks to hang out in his lab with his students, and I stayed with Dick and his wife, Gwen, at their home in Westwood. We remained in frequent contact after that and, some years later, after Dick had left UCLA to work in the field of ergonomics, he called and asked me something that changed my life forever: Would I join him as a coauthor of the third edition? The decision to say yes was an easy one; the task of doing so was not. Living up to the standards of excellence that Dick had established in terms of advancing the analysis of a field of study, and writing about it in a way that was both

academically rigorous and pleasing to read, quite frankly, scared me. My overriding mantra was *Don't screw this up*. Fortunately for me, Dick was pleased with the results and we coauthored the third (1999), fourth (2005), and fifth (2011) editions over the next dozen years.

Dick's passing in 2015 represented a devastating loss, both personally and professionally. Although his health had declined slowly over a few years, Dick remained on top of his research game and continued to contribute to his profession in many ways. In particular, his analysis of why human error causes automobiles to suddenly accelerate out of control attracted dismay from those who wished to see the machine accept the blame but praise from others who understood the fallibility of actions. He was invited to contribute an op-ed piece to the *New York Times* (Schmidt, March 10, 2010) and was interviewed by renowned author Malcolm Gladwell for an episode of his Revisionist History podcast (the "Blame Game," August 3, 2016). His views on driver error were cogently summarized in a review article on two-foot driving (Schmidt, 2015b) that should influence how driving skills are taught in years to come. Personally, I especially miss his sense of humor and incredible wit, something I wish everyone who reads these words could have been fortunate enough to experience as often as I did.

The decision to contribute to a sixth edition of *Motor Control and Learning* was not an easy one. I had recently retired when first contacted by the publishers and knew that I did not have the capacity to revise it again, alone. Fortunately, I knew that Dick would have been overjoyed to have three of his former students join on as coauthors, and I was happy beyond words when each agreed to my proposition. The result that you have before you represents a collective thank-you to a mentor, teacher, and friend. But—as all four of us know so well—this was, is, and always will be Dick's book.

Comments from Howard Zelaznik

I first met Dick Schmidt in the spring of 1974 when I visited Ann Arbor as a college senior. After that visit I was convinced that I wanted to study with him. In the fall of 1975 I became his PhD student at the University of Southern California. I was familiar with many of the ideas and studies described in this text. When I became a professor and the first edition of *Motor Control and Learning: A Behavioral Emphasis* was published, the book became a staple of my first-year graduate course. At the time I dreamed that one day I might coauthor the subsequent editions of the text to help keep the book current.

My dream did not materialize; Dick found and cultivated Tim Lee as his wonderful coauthor. Tim kept true to the behavioral emphasis aspect of the text, modernized the material, and maintained the "Schmidt" voice of subsequent editions.

Upon Dick's death I confessed to Tim about one of my career dreams and thus was offered an opportunity to join him, Carolee Winstein, and Gaby Wulf to revise the text for the sixth edition. I have tried to keep the behavioral emphasis at the forefront of the book. Many levels of analyses can contribute to understanding motor control and learning. Dick Schmidt took an experimental psychological approach (the behavioral emphasis). I have tried not to deviate from that path too much.

Chapter 8 on coordination has been revised to give much more credence to the dynamical-systems perspective. Although the tenor of the debate between information processing scientists and those of the dynamical-systems perspective has subsided, the issues are still important and real. Dick was a vigorous opponent of the dynamical-systems perspective. Nevertheless, we do provide the reader with a more balanced discussion of these issues. I know that Dick would not endorse this approach, but I believe we owe it to our readers. Were Dick still around to write this edition, he would be compelled to describe and explain this perspective objectively. I tried to do so without any of the historical rancor.

Finally, this edition clearly has the Schmidt voice. It is our best way to honor one of the most influential scientists of motor behavior in the past 50 years.

Comments from Gaby Wulf

*Motor Control and Learning: A Behavioral Emphasis* has accompanied me throughout my career. When the first

edition was published in 1982, I had just started my doctoral studies in Germany (which I completed a few years later with a dissertation on Schmidt's schema theory). The textbook provided me with a solid foundation of motor behavior research during this period of time.

It also served as the basis for the first motor learning class I taught in the United States in the late 1980s. Being a nonnative English speaker teaching my first class in English, I memorized many passages from the book and essentially recited them in my early lectures—much to the students' dismay.

Since then, I have used all subsequent editions of the book for my graduate classes. Needless to say, I was thrilled when Tim asked me to coauthor the current edition with him, Carolee, and Howie. Given Dick's influence on the field of motor control and learning, and on my own research, I felt incredibly honored to be able to contribute to this excellent book.

I have attempted to update various chapters by integrating findings related to the influence of attentional focus and motivational variables, such as learner autonomy and enhanced performance expectancies. These factors are also key to a motor learning theory, the OPTIMAL theory, which Rebecca Lewthwaite and I published in 2016. This textbook is the first to include this new perspective on motor learning.

Just a few days before his death, Rebecca and I visited Dick and his wife, Gwen. Much to our surprise, Dick discussed recent studies with us. He also noted that there was no theory to account for motivational influences on motor learning. We did not mention the theory that we had been working on for the past few years and that was about to be published, but now it's in Dick's book.

Comments from Carolee Winstein

The year the first edition of *Motor Control and Learning: A Behavioral Emphasis* was published, I accidentally discovered it while roaming around in the UCLA Bookstore. Coincidentally, I had just met with Dick at his office to plan my first semester as an incoming graduate student. I began work on my PhD in January of the following year. I left behind a 10-year career as a successful physical therapist with an exclusive caseload in the area of neurorehabilitation and at one of the top-ranked rehabilitation hospitals in Southern California.

In 1983, education programs for physical therapists were at the master's level and were based on the traditional medical model. I decided to go back to graduate school and pursue a PhD in kinesiology so that I could better understand the science of motor control and learning that was missing from my basic physical therapy education. I remember discussing this with Dick in the second year of my PhD studies when he asked me, "Why would a physical therapist want to know anything about motor control and learning?" He said, "For me, the problem for physical therapy was an organic one. . . . To use computer terminology, physical therapy seemed to be involved with 'hardware' problems." He went on to say, "Motor learning, on the other hand, has always been concerned mainly with the acquisition of new skills with practice. . . . To me, these issues are essentially 'software' problems, analogous to understanding the programs that control the hardware's activities, and they had little in common with the hardware problems of physical therapy" (Schmidt, 1991).

After I earned my degree with Dick and completed a 2-year postdoctoral fellowship at the University of Wisconsin at Madison, I took a faculty position at the University of Southern California (USC) in the Department of Physical Therapy. (In the mid-1990s we changed the department name to Biokinesiology and Physical Therapy to reflect both our academic (biokinesiology) and professional (physical therapy) education programs). In the same year that I started at USC, I found myself on the program committee for the II STEP (Special Therapeutic Exercise Program) conference, titled Contemporary Management of Motor Control Problems. It was sponsored by the Foundation for Physical Therapy and the Sections on Neurology and Pediatrics of the American Physical Therapy Association. I convinced the program committee to invite Dick; he was the only nonphysical therapist on the program. He was given 2-1/2 hours to present his talk, titled Theoretical Issues in Motor Learning. His talk and the papers that came out of II STEP had a tremendous, lasting impact on physical therapy education programs. Dick and a handful of his contemporaries, including Anne Gentile and Ron Martenuik, were instrumental in establishing a foundational link between the behavioral science of motor control and learning and the practice of physical therapy.

I teach a graduate-level course in biokinesiology at USC titled The Neurobehavioral Basis of Movement. I adopted *Motor Control and Learning* as one of the required textbooks for that class, and I have done so since 1990. In that class, I focus on the link between the science of motor control and learning and the translation of that science to a number of fields concerned with motor skill learning, including athletics, rehabilitation, and the performing arts. When Tim invited me to update four of the chapters for the sixth edition of the text, I wanted first and foremost to preserve Dick's voice; at the same time I wanted to show how recent advances in neuroscience—the discovery that the brain is plastic and ever changing—are intimately coupled with all learning, especially motor learning. I think Dick would have approved of the updates that I contributed to this edition.

Dick was a consummate scientist and educator. Like Alfred Hitchcock in his own films, Dick posed in brief cameos in the fifth edition of *Motor Control and Learning*. In the style of Alf Brodal, the famous neuroanatomist who suffered a stroke, Dick wrote the words that appear in the fifth edition sidebar: Neurological Disorders and Problems in Movement Control. During the last few years of his life, Dick was dealing with a rare set of neurological problems, yet he did not shy away from the challenge. A curious scientist, he was forever testing new theories of motor control. I remember watching him during one of his therapy sessions with my colleague, Julie Hershberg. He was testing the notion that if he attempted to pick up the cup with his more impaired arm *after* practicing with his less impaired arm, it would be easier than if he simply practiced with his more impaired arm. When his real-time empirical experiment did not support his theory, an elfish grin came over his face that developed with each ensuing trial, until he finished his attempts and declared, "So much for that theory."

Dick will forever be my mentor and a true inspiration for how to embrace life to its fullest.

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# Preface

Do you ever wonder how highly skilled performers in industry, sport, music, or dance make their actions appear so simple and easy? Do you marvel at the way they can perform with such efficiency, smoothness, style, and grace? Like the previous five editions of this text (Schmidt, 1982, 1988; Schmidt & Lee, 1999, 2005, 2011), the sixth edition of *Motor Control and Learning: A Behavioral Emphasis* was written for people who want to understand how some experienced performers can achieve such artistry while others who are beginners in a similar task seem clumsy, inept, and unskilled. This book was written initially as a textbook for university or college undergraduate and graduate students taking courses in human performance or motor learning, primarily in fields such as kinesiology or psychology. Over the years it has become a resource for students in other fields that relate to movement behavior, such as the neurosciences, physical therapy, occupational therapy, speech therapy, biomedical or industrial engineering, human factors or ergonomics, and sport. For practitioners or emerging practitioners in these fields, the principles of motor behavior outlined in this book can provide a solid basis for tasks such as designing human-machine systems, developing training programs in sport or industry, or teaching progressions in dance or music.

The emphasis of the text is behavioral. It focuses primarily on movement behavior that one can observe directly, on the many factors that affect the quality of these performances, and the ease with which they can be learned. In this sense, the book has strong ties to the methods and traditions of experimental psychology, now called cognitive psychology. At the same time, the book focuses on the cognitive, motivational, neurological, and biomechanical processes out of which these complex movement behaviors are crafted. Brain mechanisms that allow the detection of errors, spinal cord processes that are capable of generating patterns of skilled activities in locomotion, biomechanical factors, and various social, cognitive, and affective influences that act to determine the nature of human movement behaviors are all critical to understanding highly skilled performance. This blending of behavioral, neurophysiological, and biomechanical analyses reflects the fact that the fields of motor behavior and motor learning, movement neurophysiology (motor control), psychology, and biomechanics have moved together rapidly in recent years toward the shared understanding of complex movement behaviors.

This edition of the text retains the same goal of presenting an up-to-date review of the state of knowledge in movement control and learning, and it does so with a format similar to that of the previous editions. It includes the most recent knowledge from a number of rapidly developing subfields, and each chapter has been revised extensively in light of these newer concepts. At the same time, the book also pays homage to some key early research developments in the various areas. The previous two editions introduced sidebars, which highlighted specific research issues throughout the book. This edition includes sidebars with the idea that certain material requires a more detailed treatment to ensure understanding. Some of these sidebars highlight quotations from selected historical papers, others highlight careers of key researchers in motor control and learning, and still others deal with various applications of specific concepts in motor control and learning.

Some chapters from the previous edition have been reduced in order to lessen complexities in the text without sacrificing the in-depth coverage or richness of the concepts. Other chapters and sections have been expanded to present new, exciting areas of research that have emerged since the previous edition. Unfortunately, this expansion to cover new and emerging research comes with a cost. The reader who is familiar with previous editions will notice that the chapter titled “Individual Differences and Capabilities” no longer appears in this edition. Although parts of that chapter have been redistributed throughout the present edition, its loss as a separate chapter represents an acknowledgment of the changing trends in motor control and learning research.

This book includes many figures to help illustrate and emphasize concepts and data that are difficult to communicate effectively in words. Practical examples from areas such as human factors, sport, physical rehabilitation, and music illustrate motor control and learning concepts and provide suggestions for application. As before, the sixth edition reflects a logical progression so that later chapters build on concepts presented in earlier chapters; the final result is a consistent, defensible framework of ideas about motor skills. Such a framework

(point of view) is helpful to those who will use the information to contribute to new applications and those who will use it to facilitate the design of new research.

The book is divided into three parts. Part I introduces research and fundamental concepts in motor behavior. Chapter 1 provides a brief history of the field, and chapter 2 presents methods in movement research, focusing on various paradigms and statistical techniques used in the study of movement behavior. Chapter 3 looks at the human as a processor of information, and it focuses on the many ways of dealing with information in motor behavior. The concept of attention is the focus of chapter 4, with particular emphasis on the role of attention in motor behavior.

Part II deals with motor control. Chapter 5 explains motor control from a closed-loop perspective, in which it examines the sensory contributions to movement control, with particular emphasis on new research regarding the role of vision. In chapter 6, the focus shifts to contributions of the central nervous system to movement control, with emphasis on preorganized actions that involve motor programs and generalized motor programs. Chapter 7 presents some principles related to speed and accuracy, and it discusses theoretical concepts that integrate the central and sensory contributions to movement control. Chapter 8 presents a discussion of the factors involved in movement control that make coordination both easy and difficult to achieve.

Part III deals with the acquisition of skill, or motor learning. Chapter 9 concentrates on some special methodological problems for studying learning. Chapter 10 discusses the effects of attentional focus, motivational influences, the structure of the practice session, and the many variables under the control of a teacher, coach, or therapist. Chapter 11 presents the roles of feedback in learning. In both of these chapters, much information is covered that demands changes in people's understanding of the processes involved in practice and the ways in which these processes influence learning. Chapter 12 presents motor learning theories and other theoretical views of motor learning. Finally, chapter 13 deals with the factors associated with the retention and transfer of skills.

This edition is accompanied by an instructor guide and web resource. The web resource contains 47 narratives from *Motor Control in Everyday Actions* by Timothy Lee. These narratives provide examples of performance errors; motor skill learning; and perception, attention, and action. Self-directed learning activities at the end of each narrative encourage students to think critically about the scenarios. The instructor guide provides valuable suggested answers to the learning activities. These ancillaries are available at [www.HumanKinetics.com/MotorControlAndLearning](http://www.HumanKinetics.com/MotorControlAndLearning).

As with any text that undergoes a revision by multiple new authors, you will find that some sections of the book take on a slightly different voice in this edition of *Motor Control and Learning*. What may not be obvious, however, is that all of the coauthors of the sixth edition share a deep respect and admiration for the contributions that Dick Schmidt made to the first five editions; the additions, deletions, and changes made in this edition were done with the simple wish that they would have met with Dick's approval.

Finally, the last word in this preface is reserved for Dick. For the (now-removed) chapter on individual differences in the fifth edition, Dick wrote a special essay on neurological disorders and problems in movement control, and he referenced a patient ("RS") who showed some severe motor control deficits; that patient was himself. This essay captures the essence of Dick—his curiosity, his scientific approach, and the objectivity he displayed for science and education, even with something as personal as the disease that affected his own motor control and learning. We have included a portion of this essay here:

Recently we have become aware of a neurology patient (RS) who demonstrates some curious movement coordination disorders. These disorders seem especially interesting when considered in relation to some of the issues discussed in this chapter and chapter 8. RS, who is right-handed and in his late 60s, originally sought medical treatment because of clumsiness in his left hand and arm as well as balance problems. His right hand and arm seem to be nearly unaffected; conscious detection of tactile stimuli in the left hand seems not to be disrupted.

Testing (e.g., X-rays, MRIs, behavioral testing) revealed a rather diffuse pattern of neurological degeneration

that apparently affects several brain structures, including the frontal cortex, basal ganglia, and cerebellum (see Ivry & Hazeltine, 1999; Mauk et al., 2000; Mauk & Buonomano, 2004). A conclusive diagnosis for RS is unclear, but a degenerative process called multiple systems atrophy has been suspected.

Following are some of the movement difficulties that RS experiences. Note the relationships of these deficiencies to some of the issues about motor control and coordination discussed throughout this book and particularly in the work of Franz and colleagues.

- RS has a marked decrement in left-hand fine motor control that is manifested in tasks such as typing, fastening buttons, picking up small objects with the fingers, using eating utensils, and tying shoelaces. Because consciously perceived tactile stimulation is essentially unaffected, these difficulties may then be due to some lack of nonconscious feedback control (full vision of the objects does not compensate for these difficulties). See the discussion of tactile feedback in chapter 5.
- Using a medical version of the Fitts' tapping task (see Desrosiers et al., 1995), where the neurologist has the patient tap alternately between the examiner's finger and the patient's nose as quickly as possible, the number of taps RS could produce in 15 seconds with his left hand was only half the number that he produced with the nearly unaffected right hand.
- The tendency for the two hands to be coupled strongly to each other appears to be absent. (See the section on bimanual control in chapter 8.) In fact, even when RS tries to move his hands in the same pattern together, the left hand appears disconnected from the right, and the patterns do not resemble each other. The coordination of the hands together as one, which is one of the most striking phenomena of "normal" motor behavior, seems almost totally absent in RS.
- Making a large (2 ft diameter, or 60 cm) horizontal circle with the right hand and arm displays the requisite coordination between the muscles controlling the elbow and shoulder. In attempting this task with the left hand and arm, RS seems to lack this intralimb coordination. This is also seen in an underhand ball toss with the left hand, where the timing of the ball's release is in gross error.
- We appear to control limbs with one hand in the "foreground" while the other hand automatically does some nearly trivial task in the "background." An example might be brushing teeth with the right hand and simultaneously dropping the toothpaste tube in a drawer with the left hand. When RS tries such a task combination, his left hand acts as if it is frozen over the open drawer and will not release the toothpaste tube until nearly full attention is directed to it.

These are just a few of the many ways in which motor control and coordination are disrupted by neurological damage. We find it interesting that some of the strongest and most obvious features of "normal" motor behavior and coordination (e.g., interjoint coordination in one arm, the almost trivially easy coupling of one hand to the other in rhythmic tasks) can be so easily lost (Schmidt & Lee, 2011, pp. 320-321).

# Accessing the Web Resource

The web resource is a useful new addition to this text. It contains 47 narratives that translate research on motor control and learning into understanding actions of everyday life. Real-life anecdotes prompt readers to consider how research in motor control and learning helps us to better understand the cognitive, perceptual, and motor processes that underlie human behavior. The narratives appear courtesy of *Motor Control in Everyday Actions* by Timothy Lee.

To access the narratives, visit [www.HumanKinetics.com/MotorControlAndLearning](http://www.HumanKinetics.com/MotorControlAndLearning). If you purchased a new print book, follow the directions included on the orange-framed page at the front of your book. That page includes access steps and the unique key code that you'll need the first time you visit the *Motor Control and Learning, Sixth Edition* website. If you purchased an e-book from [www.HumanKinetics.com](http://www.HumanKinetics.com), follow the access instructions that were e-mailed to you following your purchase.

Once at the *Motor Control and Learning, Sixth Edition* website, select Web Resource in the ancillary items box in the upper left corner of the screen. You'll land on a page with links to each chapter that has narratives in the web resource. The narratives correspond with most chapters from *Motor Control and Learning, Sixth Edition*.

## Chapter 2

- Public Opinion Polls
- Cutting Wood and Missing Putts
- The Hot Hand
- The Babe

## Chapter 3

- The Grocery Store
- Push or Pull?
- Friendly Fire
- Method to His Bratness
- Red Light, Green Light
- Jumping the Gun
- Antilock Brakes

## Chapter 4

- Choking Under Pressure
- Turn Right at the Next Gorilla
- The Toad and the Centipede
- The Preshot Routine
- Gumbo
- Fakes

## Chapter 5

- The Magnetic Hill
- Preventing Penalties and Batting Baseballs
- Craps and Weighted Bats
- The Curling Draw
- Cool Papa Bell
- Wayne Gretzky

## Chapter 6

The Farmers' Market  
Is the Bean Dizzy?  
Moving Sidewalks and Beer Glasses  
The Tickle  
The Point of No Return  
Forensic Motor Control

#### Chapter 7

The Calculator  
The Gimme Putt  
Pouring Coffee

#### Chapter 8

Websites and Silly Walks  
Party Tricks  
Disappearing Act

#### Chapter 9

How You Get to Carnegie Hall  
Learning to Win From Losing  
Zero-Sum Training

#### Chapter 10

But I Was Great on the Practice Range!  
Bend It Like Becker

#### Chapter 11

The Coach as a Dictionary  
The Golfer's Little Helper

#### Chapter 13

Sport Snake Oils  
The Keypad  
Shooting Two From the Line  
Like Riding a Bicycle  
H.M.

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# Part I

## Introduction to Motor Behavior

- Chapter 1 Evolution of a Field of Study
- Chapter 2 Methodology for Studying Motor Performance
- Chapter 3 Human Information Processing
- Chapter 4 Attention and Performance

The four chapters in part I introduce you to the field of motor control and learning. Chapter 1 describes the field, distinguishes between motor control and learning, and clarifies the relationship between this and other fields of study. It provides a brief history of the field, showing how it has combined knowledge about movement from psychology, kinesiology, physical rehabilitation, ergonomics, and the neurosciences. Chapter 2 deals with the various scientific methods used for studying motor skills. It explains the tools of motor behavior research, focusing on the various ways to measure motor behavior and skill. Chapter 3 presents the information-processing model, which is fundamental to understanding how humans think and act, and describes research that provides an understanding about how humans process information. Finally, chapter 4 describes the broad study of attention and its role in motor behavior.

# Chapter 1

## Evolution of a Field of Study

Movement is a critical aspect of life. We would not survive without movement. Our capacity to move is more than just a convenience that enables us to walk, play, or manipulate objects; it is a critical aspect of our evolutionary development, no less important than the evolution of our intellectual and emotional capacities. Some assert that our highly developed cognitive capacities evolved so that we could make the movements essential to survival—those involved in the construction of shelter, the making of tools, and communication. Surely the study of movement needs no further justification than its significance in terms of the evolution of humankind.

Movement takes many forms. Some forms can be regarded as genetically defined, such as the way in which people control their limbs or the ability of centipedes to coordinate their legs. Other examples include the “scratch reflex” of dogs or the rapid blink of the eye in response to an unexpected puff of air. Here, the patterns of action appear to be determined by genetic makeup, through growth and development, or in both ways; and these actions appear to be quite stereotypical for members of the same species. A second class of movements can be thought of as “learned”—for example, those involved in controlling an automobile, typing on a keyboard, or performing a triple twisting somersault dive. These learned movements are often termed *skills*. They are not inherited, and mastering them requires long periods of practice and experience. Guthrie (1952) perhaps provided the best definition: “Skill consists in the ability to bring about some end result with maximum certainty and minimum outlay of energy, or of time and energy” (p. 136). Skills are especially critical to the study of human behavior, as they are involved in operating machines in industry, controlling vehicles, preparing meals, playing games, and so on. Skills and genetically defined movements can range from very simple (e.g., snapping fingers or blinking eyes) to very complex (e.g., pole-vaulting).

This book is about all these kinds of movements, whether primarily genetically defined or learned through practice. In particular, we will be concerned with how these various movements are *controlled*—how the central nervous system is organized so that the many individual muscles and joints become coordinated. We will also be concerned with how sensory information from the environment, the body, or both is used in the control of movement. The scientific field of study that addresses these issues is known as *motor control*—the study of the control of movements in humans and animals.

In this book, we also address the study of how movements are *learned*, that is, how movements are produced differently as a result of practice or experience. Indeed, much evidence suggests that many of the movements already mentioned consist of a complex combination of genetic determinants coupled with modifications made through practice or experience. Understanding how movements are learned is the major concern of a field of study called *motor learning*. We see no good justification, however, for separating the study of motor learning from the study of movement or of motor control in general, as this artificial separation inhibits the understanding of both issues. For these reasons, as the title reveals, the subject matter of the book is motor control *and* learning.

# Understanding Movement

How can knowledge and information about movement be acquired? A logical way to proceed would be to study some relevant aspect of the movement-control process using scientific methods. But which processes should be examined? One possibility would be to focus on the nature of biochemical interactions that occur within cells as individuals move. Or we could focus on the cell itself, asking how cells interact with each other in the control of movement. In a similar way, we could consider groups of cells, such as a whole muscle, the spinal cord, or the nerves, and ask how these relatively more complex structures are involved in movement control. Another possibility would be to focus on the movements of the freely moving animal or human, concentrating on the factors that determine movement accuracy, speed, the choice of movement, or the patterns of action. Along the same lines, we could study movement in an even more global context, asking questions about the role of movement in society, the choice of certain skilled occupations or sports, movement in groups or teams, and so on.

Clearly, there are various ways to consider the same phenomenon. They involve the study of a phenomenon on different *levels of analysis*, and analogous levels are present in any area of scientific concern. Illnesses, for example, can be considered at levels that range from the biochemical and neurological determinants of disease through the historical and sociological effects of illnesses on entire societies. Because these various ways of considering a single problem are so diverse, an individual scientist usually focuses on one, or at most two, of these levels of analysis.

## A Behavioral Level of Analysis

The focus of this text is primarily at the *behavioral* level of analysis, centering on *cognitive*, information-processing concepts. The major goals will be to understand the variables that determine motor performance proficiency and to understand the variables that are most important for the learning of movement behaviors. We also want to understand how such information can be used in the solution of certain practical problems such as those involved in the design of equipment that humans must operate, in the selection of individuals for occupations, in the teaching of skills in sport and industry, and in the rehabilitation of skills after injury or stroke.

This behavioral level of analysis, however, is more interesting and complete when combined with two other fields of study, each representing a deeper level of analysis. The field of *biomechanics* concerns the mechanical and physical bases of biological systems. Certainly in order to understand movement we must understand something of the body itself, with all its joints, levers, and associated mechanical characteristics. The field of *neurophysiology* concerns the functioning of the brain and central nervous system and the ways in which they control the contractions of muscles that move the limbs. The study of movement will be addressed at various levels of analysis—but as the subtitle of the book suggests, the emphasis is at the behavioral level.

## Emphasizing Movements

In considering movements, especially skills, it is often difficult to isolate a movement from its environment. In driving a standard-transmission car, for example, there are the coordinated actions involved in changing gears (clutch, accelerator, shift lever, etc.) as well as the movements involved in steering. These parts of the skill are the means through which the driver *affects* his environment. But skills are also *affected by* the environment. For example, whether or not there are turns in the road or whether snow is present influences the driver's interactions with the vehicle controls. Such reciprocal relations between the environment and the individual make it very difficult to pinpoint the various determinants of motor behavior, because the interaction of the many motor control and environmental factors is extremely complex and difficult to study with experimental procedures.

The approach taken in this text is to focus on the mutual interactions between the environment and the motor system. A large portion of this approach deals with the behavior and capabilities of the motor system to produce movements, studied more or less independently of the role of sensory or environmental information. But at the same time, the role of environmental information such as vision, and the ways in which it is processed and used to

guide movements, is important. In any case, we are deliberately not concerned with skills in which the quality of the *movement* components per se is almost irrelevant to the outcome (as in playing chess).

In deciding which skills to include in our field of study, it is helpful to consider the probable limiting factors in the performance. In the chess example, intellectual decision making seems to be the important factor and should not be included in this treatment. In a marathon, or in weightlifting, the factors seem to be more closely related to cardiovascular fitness and strength, respectively—also not within the confines of the present field of study. We will emphasize skills in which the focus is on the capabilities to use environmental information in the complex control of the limbs.

## Potential Applications

Given an understanding of some of the processes underlying the control of movements, where can these principles be applied? High-level sports, games, and athletic events come to mind as areas for application, as these activities often involve the same kinds of processes that are studied in the area of motor control and learning. But potential generalizations should not be limited to these kinds of activities. Many actions that appear to be genetically defined, such as walking and maintaining posture, are under consideration here. How these movement capabilities, when disrupted by injuries or disease, can be improved by treatments emphasizing the learning of *new* movement patterns—the subject matter of *physical therapy*—is also an application area. Many industrial skills, such as using a lathe, typing, woodcarving, and handwriting, are of critical importance to this field of study. Artistic performances, such as the playing of musical instruments, the creation of a painting, or the production of a dance, are certainly under the heading of motor behavior as treated here. The use of voice, whether by the vocalist in an opera or by the student learning a new language,<sup>1</sup> is also a motor task, as the sounds are controlled by muscular activity of the vocal apparatus in ways analogous to the control of the hands and fingers of the skilled typist. The potential applications for the principles discovered in the field of motor control are present in nearly every aspect of our lives.

# Origins of the Field

In an examination of the early research on movement and learning, it will be evident that the field, as we know it today, emerged from two isolated bodies of knowledge. These two areas are

1. the branch of neurophysiology primarily concerned with the neural processes that are associated with (or are causes of) movements, with only slight reference to the movements themselves; and
2. the branch of psychology (and related fields) primarily concerned with high-level skills with very little reference to the neurological mechanisms involved.

For nearly a century, these two fields developed knowledge at different levels of analysis but with little mutual influence. Only toward the end of the 1970s did the two fields begin to come together. For the reader interested in more detail on these historical developments, see Irion (1966), Adams (1987), and Summers (1992, 2004).

## Early Research

A fascinating account of some of the early insights regarding actions and movement appears in a review by Meijer (2001). In this historical paper, Meijer traces the origins of a number of ideas within current thinking to philosophers such as Plato, Aristotle, and Galen. Some of the earliest empirical investigations of motor skills were performed around 1820 by the astronomer Bessel (cited by Welford, 1968), who tried to understand the differences among his colleagues in recording the transit times of the movements of stars. This skill involved estimating the time required for the image of a star to move through the crosshairs of a telescope. Bessel was interested in the processes underlying this complex skill, as well as in the reasons some of his colleagues estimated accurately and others could not. Considerably later, studies addressed the visual contributions to hand movements in localizing targets (Bowditch & Southard, 1882). Leuba and Chamberlain (1909) studied the accuracy of limb-positioning movements; Fullerton and Cattell (1892) examined force reproducibility; Stevens (1886) studied timing; and Judd (1908) studied transfer of learning with dart-throwing tasks. Some researchers used experimental methods to study expertise in sport performance (Scripture, 1894; see also Fuchs, 1998). An important trend was established by Bryan and Harter's (1897, 1899) work on receiving and sending Morse code; periods of no improvement (plateaus) between segments of improvement were identified, and considerable debate about the existence and interpretation of these plateaus continued for some decades (e.g., Book, 1908/1925; Keller, 1958). Galton (see Boring, 1950) studied the relationships among strength, steadiness, and body configuration in over 9,000 British males and females; Book (1908/1925) examined typing skills for very large samples of participants ranging widely in ability and age. Retention of skills over long intervals of no practice was an important theme, and typing was a convenient way to study it (e.g., Bean, 1912; Swift & Schuyler, 1907). A remarkable series of studies on the retention of typing skill, initiated by Hill, Rejall, and Thorndike (1913), showed "savings," in terms of practice time or the amount of practice, involved in the relearning of typing skill after two consecutive 25-year periods of no practice (Hill, 1934, 1957).

One of the earliest systematic approaches to the understanding of motor skills was used by Woodworth (1899), who sought to identify some of the fundamental principles of rapid arm and hand movements. This work, together with that of Hollingworth (1909), uncovered principles about visual-motor performance that remain a topic of current debate (e.g., Elliott, Helsen, & Chua, 2001; Newell & Vaillancourt, 2001b). Some other research, published in German and French, went uncited in the English literature for many years. Work on such topics as memory for movements, speed-accuracy trade-offs, and phase transitions in bimanual movements appeared in German and French publications during the middle and late 1800s. Some of this research was later summarized by Worringham (1992).

A major influence of the time was Thorndike (1914), who was concerned with processes underlying the learning of skills and other behaviors. His "Law of Effect," which continues to have its influences in psychology, states that responses that are rewarded tend to be repeated. Responses that are not followed by a reward tend not to be

repeated. This idea formed the cornerstone for much of the theorizing about learning that was to follow in the 20th century (Adams, 1978). Thorndike was also a pioneer in the area of individual differences, in which the focus is on the differences among individuals surrounding practice.

Most of the work mentioned here originated from the field of psychology, and much of the field of motor behavior today is the legacy of this early thinking and research. But the early research, which is similar in method to at least some of today's work, marked a severe break in tradition from the pre-1900 views of behavior. The pre-1900 research often involved *introspection*, including subjective self-reports of feelings that were unobservable. Skills were studied only because they were thought to provide "access to the mind." As the 19th century ended, there was a shift to more systematic and objective approaches to the study of skills. And, of equal importance, skills were beginning to be studied because investigators wanted to know about the skills themselves.

Toward the end of this period, the number of studies involving skills increased slightly. Some of these concerned handwriting proficiency, ways in which practice sessions could be structured to maximize motor learning, and whether or not skills should be "broken down" into their components for practice. Skills research placed greater emphasis on industrial applications (Gilbreth, 1909; Stimpel, 1933). So-called "time-and-motion" studies analyzed production-line assembly movements; such research became the target of criticism by workers because of the strict standards of performance it imposed on them. There was rising interest in the most efficient ways to perform tasks such as carrying mortar and shoveling coal and in methods of improving the conduct of work in extremely hot environments; these studies became the early contributions to the emerging fields of human factors and ergonomics. Some early theories of learning were published (e.g., Snoddy, 1935), and work by physical educators interested in sports and athletic performances emerged (e.g., McCloy, 1934, 1937). An interest in factors associated with growth, maturation, and motor performance began to surface; and studies by Bayley (1935), Espenschade (1940), McGraw (1935, 1939), and Shirley (1931) led the way to the formation of the subarea called *motor development* (see Thomas, 1997). Esther Thelen, profiled later in this chapter, was an important motor-development researcher.

The evolution of the study of the physiological or neural bases of movement paralleled work in the motor behavior area during this period but without much formal contact between the fields. The characteristics and contraction properties of muscle tissue were a topic of early study by Blix (1892-1895) and Weber (1846; see Partridge, 1983), who identified "spring-like" properties of muscle. Jackson conducted early investigations of the neural control of movement in the 1870s, well before the advent of electrophysiological techniques that were to revolutionize the field. But what led to the development of various electrophysiological methods was the discovery by Fritsch and Hitzig (1870) that the brain is electrically excitable. These methods gave rise to studies by Ferrier (1888) on the responses in the brain's cortex to movements, as well as to the work by Beevor and Horsely (1887, 1890) on sensory and motor areas of the brain.

One of the more important influences in the neural control area was the work on reflexes at about the end of the 19th century by Sherrington and his coworkers. Sherrington studied and classified the major responses to stimuli presented to the extremities, and he believed that most of our voluntary movements resulted from these fundamental reflexes. Sherrington is credited with the creation of a number of classical concepts of motor control, most of which influence thinking today. For example, he first talked of *reciprocal innervation*, the idea that when the flexors of a joint are activated, the extensors tend to be automatically deactivated, and vice versa. Also, Sherrington coined the term *final common path*, which referred to the notion that influences from reflexes and sensory sources, as well as from "command" sources in the brain, eventually converge at spinal levels to produce the final set of commands delivered to the muscles. Indeed, Sherrington's early writings (e.g., Sherrington, 1906) remain relevant today (see tributes to his work in Gallistel, 1980; Stuart, Pierce, Callister, Brichta, & McDonagh, 2001).

Sherrington was one of those involved in research on the perception of movement. Various sensory receptors were identified, such as the Golgi tendon organ, thought to signal changes in muscle *tension*, and the muscle spindle, thought to be involved in the perception of muscle *length* and hence joint position. Sherrington coined the now-common term *proprioception*, which refers to the sense of body position and orientation thought to be signaled by the various muscle and joint receptors together with receptors located in the inner ear.

Somewhat later, scientists conducted research on various brain structures. Herrick (1924) proposed numerous hypotheses about the functions of the cerebellum. Also, patients with accidental cerebellar damage were studied (e.g., Holmes, 1939) in an attempt to pinpoint some of the movement-control deficits associated with this structure. Other brain structures, studied in patients with various kinds of brain damage, became subjects of interest (Adrian & Buytendijk, 1931).

Early neural control research mainly involved very simple movements. Indeed, experimenters sometimes isolated nerve–muscle preparations or used animals with various degrees of experimentally induced spinal cord damage; here the concern about movement was usually secondary to interest in the neurological processes. When movements were studied, the movement itself was often not considered in much detail; and measures of the speed, accuracy, or patterns of movement were usually missing from these reports. The motor behavior work, on the other hand, typically involved very complex actions (e.g., typing, telegraphy) but with very little emphasis on the underlying neural or biomechanical mechanisms that controlled these actions.

We can see an exception to this general separation of the neural control and motor behavior areas in the research of two important physiologists in the 1930s and 1940s. During this period, Nikolai A. Bernstein and Erich von Holst published a number of seminal papers that have had a significant impact on motor control theorizing today (for more on Bernstein see “Nikolai A. Bernstein”). Unfortunately, many scientists involved in the study of movement, from both behavioral and neural control areas, were unaware of the contributions made by Bernstein and von Holst until translations of their work appeared in English—Bernstein’s work had been published in Russian, von Holst’s in German. Their early papers reappeared in English in the late 1960s and early 1970s (see Bernstein, 1967, 1996; Whiting, 1984; von Holst, 1937/1973; Gallistel, 1980). Thus, while the two areas were being blended in Russia and Germany, these trends were not seen in the United States or England, where most of the work on movement was being conducted. Ironically, it was the translation of this work many years later, and the attention that it received (e.g., Turvey, 1977), that served as a significant catalyst to the merging of the neural control and motor behavior areas.

## Nikolai Bernstein

At the same time that Ivan Pavlov dominated the field of Russian physiology during the 1920s and 1930s, Nikolai A. Bernstein, in relative obscurity, was publishing his remarkable discoveries on movement coordination. The differences between Pavlov and Bernstein could not have been more dramatic. For Pavlov, the movements of an animal were seen as a passive bundle of conditioned reflexes; for Bernstein, movements were active and goal-directed. Pavlov was proudly supported by the Russian government; Bernstein lost his job because of his criticisms of Pavlov’s research.

Figure 1.1 Nikolai A. Bernstein (1897-1966).



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There has been a remarkable rise in interest in Bernstein's ideas since the English translation of some of his papers in 1967. One of his ideas that received considerable attention has been called the *degrees of freedom problem*. The issue concerns the fact that the motor system has many different independent parts that move—too many for an individual to control separately at a conscious level. One problem for the motor control scientist is to explain how so many degrees of freedom are coordinated in such an elegant manner if only a few of them are regulated at a conscious level. Parts of chapters later in this book are devoted to this problem.

Another important contribution, to be discussed in detail later, concerns the problem of learning a new movement pattern. Again, Bernstein used the *degrees of freedom* concept to great advantage. His idea was that, in the early stages of skill acquisition, learners tend to “freeze” the nonessential body parts by reducing the number of degrees of freedom so that they can concentrate on the essence of the action. The elegance of movement is seen when skill develops and coincides with the “release” and “exploitation” of the degrees of freedom.

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## Postwar Research

World War II had profound effects on the world, and it is not surprising that it also had major effects on motor-skills research. One of the earliest and most direct effects can be traced to the need to select the most suitable people for pilot training, which resulted in the creation of the U.S. Army Air Force's Psycho-Motor Testing Program, initiated by Arthur Melton in the early stages of the war (see Melton, 1947, for a description of some of this work). Important studies were conducted on underlying motor, perceptual, and intellectual abilities as they related to the selection of pilots and other military personnel. Similar studies were conducted in many other countries. In addition, scientists studied gunnery, physical training in the heat and cold, vehicle control, and many other issues related to combat performance.

When the war ended in 1945, the prevailing attitude in the United States was that the efforts related to selection and training of military personnel should not be abandoned. Consequently, this research continued for many years (see Druckman & Bjork, 1991, 1994). The military research effort was sustained when Arthur Melton created the U.S. Air Force Human Resources Research Center in 1949, which not only carried on many of the wartime programs but also expanded to include studies of more general interest. A major contribution of this program was Fleishman's work on individual differences and abilities (e.g., Fleishman, 1965, 2004; see "Edwin A. Fleishman"). The wartime programs, devoted to personnel selection and motor abilities, had not resulted in the success in pilot selection that had been anticipated. Researchers began to realize that training—not selection—was perhaps more important to the development of proficient pilots. Hence, much attention was directed toward procedures for teaching motor skills, the transfer of motor skills from one activity to another, and the retention of skills (chapter 13).

### Edwin A. Fleishman

In the years after World War II, when pilot performance and pilot selection procedures were being examined, Edwin A. Fleishman developed a program that linked correlational and experimental methods in the study of perceptual-motor abilities. Fleishman and his colleagues published numerous studies in which factor-analytic methods were used to examine the fundamental structure of human motor abilities. These studies identified and defined the abilities required by individuals to perform a variety of perceptual-motor tasks, ranging from those involving fine manipulations of objects to those involving gross and coordinated movements or complex timing operations (see Fleishman, 1954, 1972). Fleishman later broadened this focus to measures of physical fitness; he found that the abilities required for physical fitness are largely separate from those involving perceptual-motor skill. In this area he identified and defined the abilities involved in performing physically demanding tasks and specified the tests most diagnostic and reliable in measuring each ability (Fleishman, 1964).

Figure 1.2 Edwin A. Fleishman (b. 1927).



Courtesy of Edwin Fleishman.

With an understanding of the fundamental perceptual-motor abilities developed in his factor-analytic studies, Fleishman then sought to determine how these abilities could be used in the prediction of success in piloting and in many other occupations. Fleishman was also interested in how individual differences could be used in the study of learning (Fleishman & Rich, 1963) and retention (Fleishman & Parker, 1962) of complex perceptual-motor skills. He was one of the first to show that the particular combination of abilities involved in learning such skills changes at different stages of skill acquisition. In later years, Fleishman and Quaintance (1984) and Fleishman and Reilly (1992) developed methods for analyzing the ability requirements of jobs; these methods were based on his earlier taxonomic work and were extended to cognitive abilities. Fleishman showed that tests predicting job performance could be administered with the use of these methods.

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In addition to the formal laboratories that were supported by defense funds, research relevant to the military was given increased federal funding. This funding, in the form of contracts, grants, and training programs, was responsible for a shift of attention among psychologists toward motor behavior research. The directions imposed by federal funding agencies had, and continue to have, a profound influence on the behaviors studied and the research questions asked. The area of motor behavior was important at the time, and a great deal of funding was directed toward it, convincing a large number of psychologists to become interested in research in this area.

A second major influence in the creation of the boom in motor behavior research in the postwar period was the emergence of various theories of learning, most notably that of Hull (1943). In scientific inquiry, theories generally provide an organization of the conceptual issues and findings as well as strong suggestions for future research. Theories stimulate and provide focus for the research of others, and Hull's theory was no exception. His was a general learning theory, applying to animals and humans and to verbal and motor behavior, and it was often tested with motor tasks. A major emphasis of the theory was the fatigue-like process associated with long practice periods. The theory attempted to explain how fatigue and recovery processes combined to determine the learning of motor skills, and many scientists worked with motor tasks to test Hull's predictions. Most of this work has relevance to the distribution of practice (see chapter 10) or to the effects of fatigue on performance and learning. Hull's theory later proved to be an inadequate account of the processes and variables that determine motor learning and performance. However, theories like Hull's provide strong directions for research and contribute experimental data for use by future generations, even though the original theory may be shown to be inadequate.

As the complexity of machines increased in this period and industrial methods became more complicated, it became obvious that the capabilities of humans to operate machinery effectively were being exceeded. For example, a number of serious airplane accidents that were initially attributed to "pilot error" were eventually traced to the way in which the instruments and controls in the cockpit were arranged (Chapanis, 1965; Fitts & Jones, 1947; Schlagler, 1994). Thus, shortly after the war emerged a study of man-machine interactions, variously termed *human factors*, *ergonomics*, or *engineering psychology* (a subarea of industrial psychology). The guiding concepts were that humans were an important component in most of the machinery involved in industry, and that such machinery must be designed with humans in mind. Although this thinking began in the military, it is now seen in automobile design (Lee, 2008), the organization of assembly lines and work spaces, the design of home appliances and computer workstations, and many other areas (Chapanis, 1999; Jagacinski & Flach, 2003; Karwowski, 2001; Wickens & Hollands, 2000). Professional societies and journals were founded in the mid-20th century and continue to flourish today (Cooke, 2008; Waterson & Sell, 2006).

This period also saw a great deal of experimental effort in England. One of the most important contributions was by Craik (1948), who proposed that we consider the brain as a kind of computer in which information is received, processed, and then output to the environment in the form of overt actions of the limbs. An important part of this general idea is the notion of *central intermittency*, by which the human movement is seen as a series of discrete bursts rather than as continuous (as it might appear). Craik's idea paved the way for other English psychologists such as Welford, who in 1952 proposed the still-relevant *single-channel hypothesis* of attention (see chapter 4). Also, a great deal of work was done in ergonomics, on training and conditions of practice, and on hand movement control, particularly with respect to anticipation and timing (Poulton, 1950).

The ideas about central intermittency and the analogies of the brain to the computer were accompanied by similar new directions in psychology and related fields. One of the new ideas was represented by Wiener's (1948) book *Cybernetics*, which outlined an information-processing basis for human behavior. Also, Shannon and Weaver's (1949) *The Mathematical Theory of Communication* established important principles of information processing that later led to systematic attempts to study the motor system in terms of its capabilities and limitations in processing information (see Hick's law in chapter 3). In keeping with the information-processing basis for behavior suggested by Craik and others, Fitts (1954) established some now-famous fundamental relations among characteristics of aiming movements—movement time, movement extent, and accuracy (see "Paul M. Fitts" and chapter 7). The discovery of these two laws of behavior was an important advance in research, tied together by information theory (Seow, 2005).

## Paul M. Fitts

Probably no empirical discovery in the area of motor control is better known than Fitts' law, which states that the time observed to complete an aimed movement depends on a simple mathematical relationship

between the distance to move and the size of the intended target (see chapter 7). Called “Fitts’ law” out of respect for its originator, this formulation was an early attempt to apply mathematical and information-processing principles to the understanding of human movements, and it suggested that more complex limb control could be understood by future application of such methods and thinking. The mathematical equation described in Fitts’ law characterizes the trade-off between speed and error during simple aiming movements in a way that has remarkable generalizability.

Figure 1.3 Paul M. Fitts (1912-1965).



But Fitts' law was just one of many legacies of a psychologist whose research had many implications for activities of daily living, especially for equipment design. Fitts' early research on the effects of the spatial compatibility between work-space displays and the controls used in responding to these displays had a profound influence on the then-emerging field of ergonomics and human factors (see chapter 3). In later years, Fitts also wrote about perceptual-motor learning, suggesting that learning involves a progression through various stages, each with distinctive characteristics regarding the capabilities of the human to process information (see chapter 12). Paul M. Fitts was widely regarded as a leader in his area of research when he died unexpectedly in the mid-1960s at the age of 53, well before his full potential could be realized.

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In the middle of this postwar period, a great deal of motor behavior research was being conducted—enough that Robert and Carol Ammons, themselves researchers in this area, created a journal in 1949 titled *Perceptual and Motor Skills Research Exchange*.<sup>2</sup> The journal now publishes both motor and nonmotor research, but during its early years it served as a major outlet for motor behavior work. In addition, *Research Quarterly*,<sup>3</sup> a physical education research journal, and the *Journal of Experimental Psychology*<sup>4</sup> published a great deal of motor behavior research during this period.

Toward the end of the postwar period, the number of psychologists interested in motor behavior research gradually declined, while the number of physical educators interested in the study of motor skills greatly increased. The psychologists' lack of interest may be attributed to decreased federal support for motor behavior research, disillusionment with Hull's theory, and increasing interest in other types of human behavior such as verbal

learning and memory. This trend away from motor behavior research reached its peak in the mid-1960s when an “academic funeral” sponsored by Ina and Edward Bilodeau was held at Tulane University. Renowned motor behavior psychologists gathered to hear the “last rites” and to bid each other farewell as each moved on to different research topics in psychology. The eulogies were recorded in a volume titled *Acquisition of Skill* (Bilodeau, 1966), which well describes the attitude of the times.

Motor behavior research was dead, or so the psychologists thought; but they did not consider a man named Franklin Henry, trained in psychology and working in the Physical Education Department at Berkeley, who had a continuing interest in motor behavior research (see “Franklin Henry”). Together with A.T. Slater-Hammel and other leaders in physical education, these new motor behavior scientists organized the North American Society for the Psychology of Sport and Physical Activity (NASPSPA) and the Canadian Society for Psychomotor Learning and Sport Psychology (SCAPPS). These groups flourished in the 1970s. During this period, two books devoted strictly to motor behavior and motor learning were published, one in England (Knapp, 1963) and one in the United States (Cratty, 1964). Many more followed (including the first edition of this book in 1982).

## Franklin M. Henry

Fittingly acknowledged as the father of motor behavior research in physical education, Franklin M. Henry advocated an approach using psychological techniques, laboratory tasks, and careful measurement. Unlike most psychologists, he used whole-body activities (as well as the psychologists’ traditional fine-motor tasks) in his research, and many of these tasks included very rapid motor actions representative of activities in sports and games. One of Henry’s most important contributions to motor control research was the “memory drum theory,” and his experiments in 1960 provided rather convincing evidence that measures of reaction time (RT) were sensitive to the “complexity” of the action that was to be produced (see chapter 3). Among Henry’s many other contributions was the controversial idea that individuals possess many independent abilities. He argued that the so-called all-around athlete is not someone who has a very “strong” general motor ability, but rather someone who has many specific, highly effective capabilities. His innovative research methods showed that there was very little correlation between an individual’s performances on two or more tasks, even if these tasks seem to be very similar in an assumed underlying ability. Henry educated many doctoral students who subscribed to his general method and point of view as they assumed positions in physical education departments during the college growth boom of the 1960s. Many of these scholars created PhD programs and trained more students in this basic tradition, with the result that Henry’s influence became pervasive by the 1970s and continues today.

Figure 1.4 Franklin M. Henry (1904-1993).



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Not all psychologists of the period were bored with motor behavior research. Fitts and Peterson (1964) presented influential experiments on limb movement accuracy; Bilodeau and Bilodeau (1961), Adams (1964), and Noble (1968) wrote needed reviews of motor behavior research; Adams (1968) wrote a theoretical treatment of the role of sensory feedback in movement learning; and Keele (1968) wrote an often quoted review of motor control (see "Jack A. Adams" and "Steve Keele"). But these were the exceptions. As the 1970s approached, the cluster of scientists in physical education and, to a limited extent, psychology began to evolve in new directions. Posner and Konick (1966) and Adams and Dijkstra (1966) presented seminal articles dealing with short-term memory for movements; Henry and his students (e.g., Henry & Rogers, 1960) were interested in motor programs; Posner (1969) studied attention and movement control; Pew (1966) examined practice and automaticity; and Adams (1971) initiated a return to theorizing about motor learning. These emphases provided strong leadership for the motor behavior area in the 1970s.

## Jack A. Adams

One of the landmark advances in the developing field of motor learning was the publication of "A Closed-Loop Theory of Motor Learning" in the *Journal of Motor Behavior* in 1971. This paper described one of the very first theories directed specifically at *motor* learning and presented numerous testable hypotheses that became the focus of a considerable number of research studies in the 1970s. Although many of the

tenets of closed-loop theory were later found to need revision (see chapter 12), which is the case for most theories that are scrutinized carefully, Adams' theory was clearly a catalyst that moved the research "bar" in motor learning much higher. But the 1971 theory was only one of many contributions to motor learning research that Adams made in a long and fruitful career. His early work on psychological warm-up effects as a source of memory decrement in practice (e.g., Adams, 1961) led to one of the very first of many investigations on short-term memory for movement information (Adams & Dijkstra, 1966). Throughout his research career, Adams maintained an interest in the application of motor learning research in the area of human factors and ergonomics, beginning with his work at Lackland Air Force Base in Texas. Later he turned his attention to the effects of *modeling* and observational learning (e.g., Adams, 1986), again spearheading a rise in research activity in that area. Perhaps his most lasting legacy, however, will be as a research historian—Jack A. Adams' ability to accurately and concisely synthesize volumes of research history into manageable chunks of understandable knowledge will serve students of motor control and learning for many years to come. His 1964 paper in the *Annual Review of Psychology* and 1987 paper in the *Psychological Bulletin* remain as landmark reference works in motor behavior.

Figure 1.5 Jack A. Adams (1922-2010).

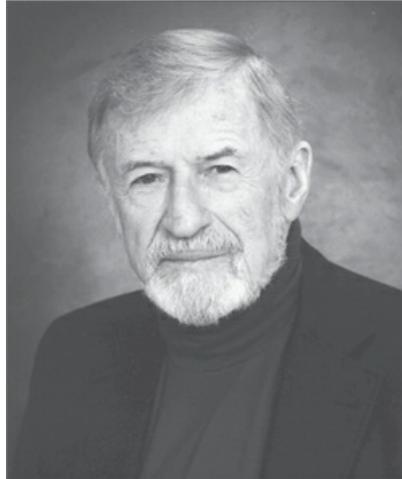


Photo courtesy of Jack Adams.

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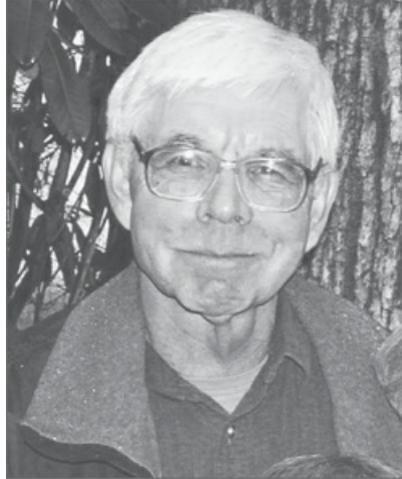
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As in the early period, the neural control and motor behavior scientists were nearly oblivious to each other, but important contributions were being made in neural control that would later be influential in joining the two areas. One of the more important contributions was the work on muscle spindle mechanisms by Merton (1953; Marsden, Merton, & Morton, 1972), to be discussed in chapter 5. While the specific mechanisms proposed by Merton now appear to be incorrect (Houk, 1979; Smith, 1977), Merton's original ideas about automatic regulation of movement are reasonable in very general terms. Merton was one of the first to measure movements *and* neurophysiological processes in the same investigation, creating a beginning for a blend of behavior and neurological emphases that was to follow. At about the same time, a great deal of research was devoted to the sensory receptors associated with movement perception and kinesthesia. Skoglund (1956) published a classic paper showing that the various receptors in a joint capsule appear to be activated at certain specific joint angles, suggesting that these receptors have a large role in the perception of joint position.

Steve Keele

The 1960s marked a critical time in the history of motor behavior research, as many psychologists shifted their focus to issues of cognition, such as memory and attention. Psychology appeared to have abandoned the study of motor behavior, with a few notable exceptions. The appearance of Keele's motor control literature review in 1968 created renewed interest in important issues such as the motor program and the role of vision in movement regulation. His paper (with Michael Posner) on the period during a movement that is required to process and act on visual information remains one of our favorites for its simple, elegant methods of answering a difficult question. Keele's book, *Attention and Human Performance*, published several years later, situated movement prominently within a late-filter theory of attention, reminding psychologists that movement is not just a simple "output" in the human-computer metaphor (Rosenbaum, 2005). Updated and expanded reviews of motor control in later years were considered mandatory reading for students in this area. Keele's later research interests included important contributions to our understanding of individual differences, timing, and sequence learning.

Figure 1.6 Steve Keele (1940-2005).



Courtesy of Betty Jean Keele.

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Numerous studies on the nature of muscle and its contractile and mechanical (e.g., spring-like) properties were also completed during these postwar years, and these studies attracted the attention of contemporary researchers in motor behavior and motor control (Rack & Westbury, 1969). These mechanical characteristics of muscle and of the motor apparatus were utilized by scientists in the Moscow laboratories who were following the earlier tradition of Bernstein. The extensive work on movement control by this group, originally published in Russian and thus generally unknown to American and British researchers, attracted a great deal of attention through various translations (e.g., Gelfand, Gurfinkel, Tomin, & Tsetlin, 1971; Kots, 1977). This research has special relevance for the control of locomotion and provides important links between the neural control mechanisms and behavioral principles. But despite these efforts, by 1970 almost no association existed between the behavioral scientists interested in more global and complex skills and the neurophysiological scientists interested in simple movements and neural control.

## End of the Century

The 1970s brought massive changes in the field of movement control and learning. The strict stimulus–response (S-R) orientation that had had such a strong foothold during most of the century was overshadowed by the cognitive, information-processing approach. The publication of two books during the 1960s—Miller, Galanter, and Pribram’s (1960) *Plans and the Structure of Behavior* and Neisser’s (1967) *Cognitive Psychology*—had a large impact on the field of experimental psychology in general and, later, on motor behavior too. The move toward cognitive psychology was a reaction to S-R theories of behavior. Ideas about mental and motor processes, together with many methods and paradigms for understanding them, took the place of S-R theories. Perhaps more than anything else, the books by Miller and colleagues and Neisser popularized the study of mental processes such as response selection and movement programming, whose existence must be *inferred* from the behaving individual rather than directly observed (see also Baars, 1986; Miller, 2003).

Influenced by cognitive psychology, the motor behavior field seemed to undergo a transition from a *task orientation*, which focuses primarily on the effects of variables on the performance or learning of certain motor tasks (or both), to a *process orientation*, which focuses on the underlying mental or neural events that support or produce movements (Pew, 1970, 1974b; Schmidt, 1975b, 1989a). Humans were considered processors of information, and this approach was an attempt to understand how movement information is coded and stored, how actions are represented in memory, and how information about errors is processed so that learning can occur.

Led by such researchers as Adams and Dijkstra (1966) and Posner and Konick (1966), the process orientation helped to create the area of *short-term motor memory*—the study of the processes underlying memory loss in simple movements over short periods of time. Many studies were conducted in this area during the late 1960s and early 1970s (see chapter 13). Studies were also completed on information-processing activities during the learning of simple motor tasks (see chapter 11).

More importantly, theorizing returned to motor behavior and learning, a style of inquiry that had been relatively dormant since the failure of Hull’s (1943) theory. Adams sparked the interest in theory when he presented a feedback-based theory of verbal learning (Adams & Bray, 1970), followed the next year by a similar theory devoted to motor learning (Adams, 1971). Pew (1974a) returned to the old idea of a movement *schema* (Bartlett, 1932)—the abstract hypothetical structures responsible for movement control and evaluation, to be discussed in chapter 12. And, one year later, the schema theory for the learning of simple motor skills was presented (Schmidt, 1975b). Together, these theoretical ideas generated a great deal of interest in motor skills, as this text makes evident later.

The motor behavior field not only changed its direction, but also grew rapidly. Formal courses of study in universities flourished, and new journals appeared. In 1969, Richard A. Schmidt founded the *Journal of Motor Behavior*, which was closely followed in 1975 by the *Journal of Human Movement Studies*, created by the English motor behavior scientist John Whiting (see “H.T.A. (John) Whiting”). A review journal titled *Exercise and Sport Sciences Reviews* was created in this period, and it devoted a major portion of its space to motor behavior research. Two more journals devoted to the study of motor control also appeared before the turn of the century; *Human Movement Science* in 1982 and *Motor Control* in 1997. And throughout this time, the psychological journals (e.g., *Journal of Experimental Psychology: Human Perception and Performance*, *Psychological Research*, *Psychological Bulletin*, *British Journal of Psychology*, *Psychological Review*, *Human Factors*, and *Ergonomics*) continued to publish motor behavior research. As the field grew, motor behavior textbooks proliferated. More than 30 textbooks written subsequent to Knapp’s (1963) and Cratty’s (1964) work were published, as were a large number of edited volumes on more specific topics.

## H.T.A. (John) Whiting

Another pioneer who had tremendous influence on motor behavior research was H.T.A. (John) Whiting. Like Franklin M. Henry in the United States, discussed earlier in the chapter, Whiting introduced traditional psychological techniques to the study of human motor control in the performance of sport

tasks. His research on catching performance was the first to demonstrate that continuous vision of a ball in flight is not necessary in order to support accurate performance (see chapter 5). Whiting's book, *Acquiring Ball Skill* (1969), was one of the first psychologically oriented texts to be devoted to the study of motor skills. Later Whiting turned his attention to the study of learning in the Bernstein tradition (see chapter 12). During this time Whiting also founded and served as the editor of the *Journal of Human Movement Studies* and, later, *Human Movement Science*. Another important legacy was the many graduate students Whiting supervised at Leeds during the 1960s and 1970s and then at the Free University of Amsterdam in the Netherlands during the 1980s and 1990s. Many of these scientists continue to carry on Whiting's legacy today.

Figure 1.7 H.T.A. (John) Whiting (1929-2001).



Courtesy of Vrije Universiteit.

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The 1970s were the beginning of a long-needed merger between the neural control and the motor behavior scientists. Many people were trained formally in both motor behavior and neural control, and these people completed the bridge between the two levels of analysis. More and more behavior-oriented scientists began to ask questions about movement control and made increased use of various electrophysiological and biomechanical techniques to understand the functions of the central nervous system in movement. The neural control scientists were shifting from studies that examined only the neural mechanisms to studies investigating these mechanisms during complex movements. Much of this latter work was done with animals, principally monkeys and cats. Records from electrodes implanted in the brain, spinal cord, or muscle were taken while the animal was engaged in motor activity. Representing this approach are Grillner and colleagues (1972, 1975) and Smith and colleagues (1986), who studied locomotion in cats; Evarts (1972, 1973), who studied a number of separate brain structures in monkeys; and Houk (1979) and Granit (1970), who studied the gamma motor system in monkeys and humans.

The essential feature of all this work is the strong attempt to find an association between movement behaviors and neurological processes in order to provide a more complete understanding of how movements are controlled. This emphasis marked a refreshing change from the earlier research in which the movements per se were hardly considered. The association between motor behavior and motor control resulted in several reviews written toward

the end of the 1970s, such as those by Brooks (1975, 1979, 1986), Grillner (1975), Wetzel and Stuart (1976), and Gallistel (1980). Behaviorists and neurophysiologists participated in a number of scientific meetings, and the results appeared in edited volumes (e.g., Gandevia, Proske, & Stuart, 2002; Stelmach & Requin, 1980, 1992; Swinnen, Heuer, Massion, & Casaer, 1994).

An additional change occurred toward the end of the century—one far more subtle than those just mentioned. Rather than remaining a mere blending of two different fields, the field of motor control acquired an independent identity. It became a field of study in its own right, complete with its own journals and methods for asking research questions and collecting data. Such methods involve the use of sophisticated techniques for recording and analyzing movements (such as electrophysiological recordings), cinematographic and three-dimensional analyses, measurement of the kinematics of movement, and advanced methods for examining the involvement of brain structures, integrated with the more traditional techniques for studying learning (e.g., Corcos, Jaric, & Gottlieb, 1996; see also chapter 2).

The influence of Bernstein (and others) resurfaced in the writings of a number of scientists who conducted motor control research (e.g., Greene, 1972; Kelso, 1995; Kugler & Turvey, 1987; Reed, 1988; Turvey, 1977). According to Turvey (1990), Bernstein's legacy resulted in two rounds of theorizing and experimentation. The first round dealt with the degrees of freedom problem—research addressing how a system with many independent parts could be controlled without the need for an executive “decision maker.” The second round extended Bernstein's thinking on coordination and the degrees of freedom problem to a search for laws and principles of self-organization. Much of this work uses physical biology as its basis. The dynamical-systems perspective (e.g., Kelso, 1995) suggests that coordinated movement evolves over time as a function of the interaction among the body parts, and between the body parts and the physical world, especially in the context of motor development (see “Esther Thelen”). Also associated with this view are the ideas that perception and action are functionally inseparable—that understanding the motor system depends on understanding the physical principles of our actions and how they interact with biological functions. Advocates of these traditions showed a reluctance to use cognitive–psychological styles of inquiry with hypothetically defined brain mechanisms such as memory, motor programs, schemas, and the like. This approach contributed a different emphasis to the attempt to understand motor behavior (e.g., Anson, Elliott, & Davids, 2005).

## Esther Thelen

The study of infant development, and particularly so the research on complex movement and behavior development, was influenced greatly by the remarkable work of Esther Thelen. With graduate training in both animal and human development, Thelen was unmoved by the dominant views of the day suggesting that the emergence of stereotypical movements in infants unfolded according to a predetermined, neural maturation process. For example, the newborn stepping reflex is characterized by “walking-like” rhythmic movements that are seen when the bottom of an infant's feet are stimulated, but these usually disappear from the infant's behavioral repertoire after 6 to 8 weeks of age. A dominant view was that the disappearance of the stepping reflex reflected the natural neural maturation of the infant's motor development. However, Thelen's research showed that the reflex “reappeared” when an infant was suspended in water. Conversely, the reflex “disappeared” when an infant who normally showed the reflex was fitted with small weights on their feet. The disappearance and reemergence of these reflexes, therefore, were not a matter simply of neural maturation. Rather, they reflected a much more complex interaction of the infant's sensory motor system with the gravitational influences of the environment, suggesting that movements are largely determined as emergent behaviors.



Figure 1.8 Esther Thelen (1941-2004).



Photo courtesy of Indiana University.

Thelen's research and thinking extended beyond the boundaries of motor development to include perception and cognition. She viewed action as a process by which infants learn to solve problems. Her views therefore embodied cognition as part of a much more complex system of interactions of infants with their environment. She passed away in 2004, but her legacy lives on as a true paradigm shift in the study of infant development.

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See also the papers in the special issue of *Infancy*, 2008, 13(3), 197-283.

The late 1970s and early 1980s were also characterized by a general decline in interest in *motor learning*, with a corresponding increase in issues of movement control or human performance. This was unfortunate, because the issues involved in learning have perhaps the most practical application to training, rehabilitation, and teaching in general. But there was a renewed interest in learning toward the end of the century, sparked in part by counterintuitive findings regarding how practice scheduling (Shea & Morgan, 1979; Lee & Magill, 1983b; Magill & Hall, 1990) and augmented feedback (Salmoni, Schmidt, & Walter, 1984; Schmidt, 1991a) could be organized to optimize the learning environment. Much of this work is described in chapters 10 and 11.

## Motor Control and Learning Research Today

The integration of motor control research that developed toward the end of the 20th century continues today. For example, behavioral studies of motor control and learning now appear in journals that in the past were strictly oriented toward neuroscience (e.g., *Experimental Brain Research*, *Neuroscience Letters*, *Journal of Neuroscience*), and neuroscience-oriented studies appear in journals that were formerly primarily behavioral (e.g., *Journal of Motor Behavior*, *Human Movement Science*). Studies of the specific brain mechanisms involved in the performance of movement tasks have appeared in specialist journals (e.g., *NeuroImage*) and represent a rapidly growing approach to the study of motor control. Studies of motor control and learning also continue to be published in journals devoted to specific professional topics (e.g., *Physical Therapy*, *Human Factors*, *Journal of Sports Sciences*), and this list continues to expand to include journals that did not previously publish motor behavior articles (e.g., *American Journal of Surgery*, *Journal of Voice*). New societies (e.g., International Society of Motor Control) and journals (e.g., *Motor Control*, *Frontiers in Psychology*, *PLoS One*, *Journal of Motor Learning and Development*) have emerged. In short, more research in the area of motor control and learning is being published now than ever before. And that research is being conducted by researchers who have a greater diversity and breadth of knowledge than ever before.

The computer was employed in relatively few laboratories for research investigations prior to the 1980s. Today, data is almost entirely stored electronically, and analyses that used to take many hours can now be performed in a matter of minutes. In short, the *capacity* to conduct research of very high quality has grown at a dizzying rate.

This is an exciting time for research in motor control and learning, an area of literature now so broad in scope that it would seem to be more and more difficult for the student to remain aware of the most recent publications. Ironically, however, it has never been easier to retrieve research information in this area. The Internet, which did not even exist at the time the second edition of this book was published, revolutionized the way in which motor behavior research is made public today, access to information is faster, easier, and more convenient than ever. Alerting services deliver the tables of contents of new journal issues as soon as they are published and individual papers are often available online well ahead of publication. Electronic journals are now more prevalent than print, and the articles are available to consumers instantly, and often-times at no expense to the reader ("open-access" articles). Moreover, many journals are not only publishing current issues in electronic formats but also archiving all of their pre-electronic issues. General search engines (such as Google) and specialized search engines (such as Google Scholar, PubMed, Web of Science) make the literature retrieval for a particular topic, author, or paper very fast and effective. The Internet has also made databases easy to access. And some research articles have the capacity to "go viral" thanks to social media.

However, the student of motor behavior must also be aware, now more than ever, that what is available online can be of variable quality. Respected journals maintain the peer review process, whereby a paper submitted for publication undergoes careful scrutiny by a small committee of established peers ("referees") before it can appear in press under the journal's title. This scrutiny is maintained regardless of whether the published work appears in paper or electronic format. However, not all articles that one can retrieve on the Internet have undergone this peer review process. As in the previous centuries, the best and most influential research articles are almost always those that have undergone careful and rigorous scientific scrutiny.

It is impossible to know what changes will emerge in the next decade, however, the lessons of history tell us that the scientific disciplines combining to define *motor control and learning* will continue to undergo refinement with further accumulation of knowledge and application.

## Summary

This text is fundamentally concerned with movements of human beings. Some of these movements are probably genetically defined while others are *skills*, requiring practice or experience. Even though most of the field of human behavior deals in one way or another with movement, in this text we focus primarily (but not exclusively) on those movements in which cognitive involvement is relatively slight, and for which the nature of the movement itself—rather than the choice of the movement from already learned alternatives—is the primary determinant of success. We focus on movements that do not have a heavy concentration on cardiovascular endurance or strength, as these activities seem to be more closely aligned with other fields of study. Finally, the focus is on many different movements that fall within the categories mentioned, such as those in musical performance, work, industry, and sport and other activities of daily living.

The field of movement control and learning, viewed from a historical perspective, emerged from the separate but parallel fields of motor behavior and neurophysiology. Both fields showed steady growth through the beginning of World War II, then increased in growth and sophistication after the war and through the 1960s and 1970s. The two fields, however, were largely separated until the early 1970s, when they began to share common problems and methods. Motor learning research, largely forgotten during the '70s, reemerged as a strong research area toward the end of the century. Today the electronic delivery of information has revolutionized the way in which research is conducted and disseminated.

### Student Assignments

1. Answer the following questions and bring the information to class for discussion:
  - a. How does a behavioral level of analysis of motor control and learning differ from biomechanical and neurophysiological levels of analysis?
  - b. If you could interview one of the people featured in the highlight boxes (Bernstein, Fleishman, Fitts, Henry, Adams, Keele, Whiting, Thelen), what would you ask them about motor control and learning?
  - c. What has the proliferation in publication outlets contributed to our current understanding of research in motor control and learning?
2. Find a research article authored by any of the eight people listed in question 1b. Are the findings of that research article still relevant today?

### Notes

<sup>1</sup> Learning the rules (grammar) of a language would probably not be of much relevance for the area of motor control, but learning to make the guttural sounds involved in German or the nasal sounds inherent in French could logically be included in the area of motor control (MacNeilage, 1970).

<sup>2</sup> Now called *Perceptual and Motor Skills*.

<sup>3</sup> Now called *Research Quarterly for Exercise and Sport*.

<sup>4</sup> Now subdivided into five different journals (one that is entitled *Journal of Experimental Psychology: Human Perception and Performance*).

## Chapter 2

# Methodology for Studying Motor Performance

A major goal of this book is to present not only relevant principles and theories about the nature of motor performance, motor control, and motor learning but also the research evidence that supports (or, in some cases, refutes) these principles and theories. In evaluating this evidence, it is necessary to understand some of the methods involved in the research and the ways in which motor behaviors are measured, so that we can more effectively establish the relevance of the evidence to the particular principle or theory in question. Later in the book (chapter 9), we focus on the methods and paradigms used specifically in the study of motor *learning*.

# Classification of Motor Skills

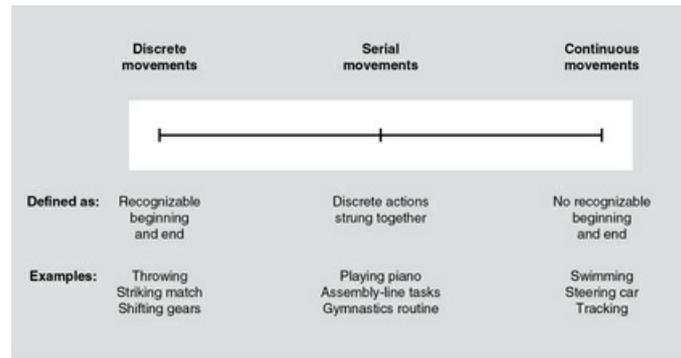
In any field of study, the objects under investigation are usually classified according to some scheme or framework in order to simplify discussion and foster the generation of research questions and testable hypotheses that will ultimately advance the field. The field of motor behavior is no exception. Classification of movements and motor tasks is important for two fundamental reasons. First, in the research literature on motor behavior and control, various terms are used to describe the tasks and movements. These terms must be understood if we are to communicate about the field. The second reason is that the laws of motor behavior seem to depend on the kinds of performances (i.e., the class of task) under consideration. That is, the relation between certain independent and dependent variables is often different for one class of task or behavior when compared to another. Without classification, the laws of motor control would be far more difficult to understand.

Movement behaviors have been classified in various ways. Two important classification schemes are the discrete/continuous/serial dimension, which is based on the particular *movements* made, and the open/closed dimension, which is determined by the *perceptual* attributes of the task.

## Discrete, Continuous, and Serial Skills

*Discrete movements* are those with a recognizable beginning and end. Kicking a ball, throwing, striking a match, and shifting gears in a car are examples ([figure 2.1](#)). The end of the movement is defined by the skill in question, not arbitrarily by the time at which an observer ceased examining it, as would be the case for swimming or jogging, for example. Discrete skills can be very rapid, requiring only a fraction of a second to complete (e.g., kicking, blinking an eye); but they can also require much more time for completion, as in writing your signature. Discrete skills can also be quite cognitive. For example, one laboratory task is to press one of four buttons when one of four lights comes on; the problem for the participant is to decide which button to press in response to which light. Thus, the decision about which button to push is paramount, and the “how” of pushing the button is clearly secondary in importance. While many discrete skills have large verbal–cognitive components, there are certainly examples of discrete skills that are primarily “motor” as well.

Figure 2.1 The discrete/serial/continuous continuum for motor behavior.



*Continuous movements*—defined as those that have no recognizable beginning and end, with behavior continuing until the movement is arbitrarily stopped—are at the opposite end of the continuum in [figure 2.1](#). Swimming, running, and steering a car are examples of tasks that have arbitrary ends. Continuous tasks tend to have longer movement times than do discrete tasks and can be repetitive in nature (they might even continue all day). This, however, should not be taken as basic to their definition.

A common class of continuous skills, both in everyday experience and in the laboratory, involves tracking tasks. The tracking task is characterized by a pathway (track) that the individual intends to follow and a device that the person attempts to keep on the track via certain limb movements. In steering a car, for example, the track is the road, and the device is the car, steering wheel, and so on. A common laboratory example used in the past involves two objects on a monitor. One object is moved by the experimenter (or by a computer), and it can move in either a predictable or an uncertain way on the screen. A second object is moved by the participant via a hand control, and the participant’s task is to minimize the distance (or error) between the two cursors.

Two kinds of tracking tasks are used commonly in motor behavior research: *pursuit* tracking and *compensatory* tracking. In pursuit tracking, experimenter-produced actions of the target and the participant’s own movements are both displayed. The previously mentioned task of steering a car is a good example of pursuit tracking. In compensatory tracking, the experimenter-produced variations in the track are combined with the participant’s movements to produce a single displayed value, and the participant’s goal is to maintain this value at some constant location. Practical examples of compensatory tracking are often seen in aircraft instruments, such as the glide slope indicator. Here only the difference between the proper altitude and the actual altitude is displayed; and when the pointer is in the middle of the screen, the pilot’s altitude is correct. Compensatory tracking tasks are almost always more “difficult” than pursuit tracking tasks, particularly if the behavior of the track is irregular and unpredictable.

Tracking tasks also vary in terms of the aspect of the display that the participant controls. The most simple is the zero-order, or positional, display. If the participant moves the handle from one position to another and then stops, the indicator on the display moves a proportional amount and also stops; that is, the handle movements control the *position* of the pointer. In *first-order*, or velocity control, movement of the handle causes changes in the *velocity* of the pointer. Moving the handle further in one direction causes the velocity of the pointer to increase in the same direction, and stopping the handle movement off center results in a constant velocity of pointer movement. In a *second-order* task, the movements of the control produce changes in the pointer’s *acceleration*. Keeping the handle centered produces zero acceleration, but moving the handle to a new position off center accelerates the pointer in the same direction. Each of these kinds of tracking tasks is used in research, and there are real-world examples of each in various control systems (see Poulton, 1974, for more details).

One final type of tracking task is step tracking. In this task, the track “jumps” from one fixed location to another, often unpredictably, and the participant’s task is to move the control as quickly as possible to correct this sudden change in the track’s location. Step tracking tasks can be either pursuit or compensatory.

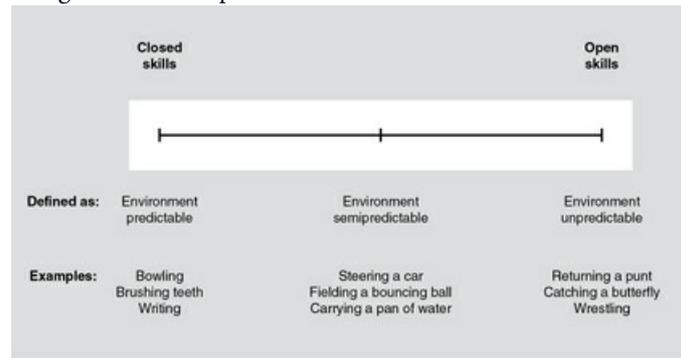
*Serial movements* are neither discrete nor continuous but usually are comprised of a series of individual movements

tied together in time to make some “whole.” These types of movements appear in the center of the continuum in [figure 2.1](#) because they can be rather long in duration but are not stopped arbitrarily. Examples are starting a car, preparing and lighting a wood fireplace, and many tasks involved in production lines in industry or 3D printing that employs additive manufacturing. Serial tasks can be thought of as a number of discrete tasks strung together, and the order (and sometimes timing) of the actions is important.

## Open Versus Closed Skills

Environmental predictability during performance provides another basis for classifying movement skills (Poulton, 1957; Gentile, 2000). *Open skills* are those for which the environment is constantly (perhaps unpredictably) changing, so that the performer cannot effectively plan the entire movement in advance ([figure 2.2](#)). A good example is the penalty shot in ice hockey. While skating toward the goalie, the player may make a general decision about whether to go left or right, but the final decision may depend on what the goalie does. Another example is driving on a busy freeway. Although you may make a general plan about what you want to do, such as pass another car, your precise plans must be left flexible enough to deal with unexpected actions of other drivers. Success in open skills is largely determined by the extent to which the individual is successful in adapting the planned motor behavior to the changing environment. Often this adaptation must be extremely rapid, and the effective responder must have many different actions ready to implement. As skill develops for a particular open skill, such as piloting an aircraft, the repertoire of actions accumulates with experience, thereby allowing for an effective response to a changing environment.

Figure 2.2 The open/closed continuum for motor behavior.



*Closed skills*, for which the environment is predictable, are at the other end of the continuum shown in [figure 2.2](#). An environment may be predictable because it is almost perfectly stable—for example, the environment in which one performs skills like archery, bowling, or sending a text message. An unstable yet predictable situation can also arise when the environment is variable but the changes are very predictable, or have been learned as a result of practice, or both; examples are juggling and industrial production-line tasks. Here, the essential feature is that the environment for the next few seconds or so is essentially predictable, so that the movement can be planned in advance. Of course, some skills have environments that are semi-predictable, and these can be classified somewhere between the ends of the open/closed continuum in [figure 2.2](#). Farrell (1975) has provided additional distinctions that help us to classify movements on this dimension. The observation that open skills seem to require rapid adaptations to a changing environment, whereas closed skills require very consistent and stable performances in a predictable environment, raises interesting questions about how the two classes of skills might best be learned and taught. Should the methods for teaching open and closed skills be different? Do different individuals perform better in one of these skill classes or the other? Are the laws of performance different for the two kinds of skills? Evidence suggests that some of the answers to these questions are yes, and we will discuss some of these issues in more detail later in this chapter.

# Basic Considerations in Measurement

A fundamental issue in science concerns how the behaviors of the objects of study are measured, and motor behavior is no exception. We often need to operationalize *skills* so that we can assign numerical values to certain performances based on the quality of the movements. Scientists must be able to measure the degree of skill exhibited by a performer in scientifically acceptable ways. Some of the criteria for good measurement systems are (a) the objectivity of the system, (b) the reliability (or stability) of the measuring system, and (c) the validity of the system.

## Objectivity

The term *objectivity* is important in measurement because of the scientific demand that observations be subject to public verification. A measurement system is objective to the extent that two observers evaluating the same performance arrive at the same (or very similar) measurements. For example, using a tape measure to determine the distance a javelin was thrown yields very similar results regardless of who reads the tape. By comparison, evaluation of performances such as diving, gymnastics, and figure skating is more subjective—although elaborate scoring rules, complete with certification tests for judges, help make it more objective. From the point of view of research in motor behavior, it is important to use performances in the laboratory for which the scoring can be as objective as possible; and this necessarily limits the usefulness of some tasks for providing an understanding of motor behavior in general.

A second aspect of objectivity relates to the *sensitivity* of the measuring device to changes in the skill of the performer. How high did the girl jump when she set the school record in the high jump? The record books report that she jumped 5 ft 6 1/2 in. (168 cm). But it is more accurate to say that she jumped *at least* 5 ft 6 1/2 in. The measurement system for the high jump (and for the pole vault) indicates only whether or not the bar was knocked off during the jump, and it is possible that the successful jumper cleared the bar by 6 in. In such situations, the scoring system is somewhat *insensitive* to the variations in the performer's actual level of skill.

In this example, the scale of measurement itself was acceptable in terms of sensitivity; in fact, we often see high jump officials measuring the height of the bar very carefully. Yet this method is not totally objective, as we have just argued. However, sometimes the scale of measurement itself is lacking in precision. Often, continuous measures are artificially categorized, as in hit/miss scoring for basketball and golf putting. For these examples the details of the movement, together with information about the performer's skill level, can be lost in the oversimplified measurement method. Such methods make it more difficult to determine whether an individual has improved on the task with practice, or to identify which of two individuals is the more skilled performer—both of which may be critical questions in the study of movement.

The method of measurement is relevant for assessing degree of recovery, such as measuring how a participant responds to rehabilitation therapy after experiencing a stroke. One frequently used method to capture performance of a specific task is *movement time (MT)*—the time it takes from start to finish to complete a given task, such as picking up a pen from the table. We might consider a faster MT as a sign of recovery and better performance than a slower MT. While a continuous measure, such as MT, is an accurate way to capture motor performance, it is insensitive to the quality of the movement (Levin, Kleim, & Wolf, 2008). It is therefore difficult to assess the performer's skill level for any given MT score, unless movement kinematics or coordination kinematics are used at the same time. Both of these methods are discussed later in this chapter.

## Reliability

A second aspect of the measurement system that is important to motor behavior is *reliability*—the extent to which the measurement is repeatable under similar conditions. A lack of reliability can result from random technological error, such as the stretch in measuring tapes, errors in clocks, and human errors in reading instruments. These

errors, while they might seem to be important, probably contribute very little to unreliability as long as a researcher uses a quality recording apparatus and careful procedures. The most important source of unreliability manifests itself when the performer does not perform the same action twice in exactly the same way. Some of these *intraindividual* variations are caused by momentary changes in the internal state of the performer (degree of attention, fatigue, or boredom, for example), while others are caused by systematic changes, such as alterations in strategy, the amount of practice, and the like. Both of these factors tend to obscure the constructs that scientists are attempting to measure.

Experimenters seek to minimize these sources of variability through experimental control in the testing situation. Researchers typically use written or prerecorded instructions in order to eliminate variability in what and how information is presented; they use testing rooms that are either silenced or sound deadened; participants are tested one at a time to eliminate variability due to another person's presence in the room; and the entire experimental session is often quite formal and impersonal. This is the primary reason some researchers tend not to measure skills in everyday settings—at a ball game or on an industrial production line, for example. In these situations, the environment is not well controlled; there are many sources of variation from other players or workers, from changes in the score of the game, from the level of proficiency of opponents, from day-to-day changes in the weather, and so on. Primarily for reasons of experimental control, motor behavior tends to be most profitably studied in the laboratory, away from these sources of variability. To be sure, there is a trade-off in this approach: Laboratory studies tend to make the situation less natural, more artificial, and the measures taken are not quite as generalizable to practical situations, but the alternative of studying skills during a game adds sources of variation that reduce the reliability of the measures.

The procedures mentioned can reduce variability in experimental settings. But even when the task is well learned and simple, when the experimental situation is well controlled, and when the performer is trying to do well, there remains a great deal of variability because biological systems are inherently somewhat unstable. Experimentally, the best method for countering this type of variability is to record many observations of the “same” behavior on the same person, taking the average of a large number of measurements under essentially identical conditions. With this procedure the variations in the person's performance tend to “average out,” raising the reliability of the measurement system, so that the mean of a large number of observations more closely represents the construct being measured.

## Validity

Another aspect of the measurement process is *validity*, the extent to which the test measures what the researcher intends it to measure. An important aspect of validity (called *construct validity*) is the extent to which the measures taken actually reflect the underlying construct of interest. We would be reasonably comfortable with a 10 min typing test to operationalize typing skill, but we would perhaps be less comfortable with a measure of finger tapping speed to assess typing skill. There are, on the other hand, situations in which validity does not seem to present much of a problem. One of these involves what are often called *face valid* tests, which are so obviously measures of the concept of interest that they usually are not questioned. For example, if we wish to determine which member of a group of individuals has the most skill in javelin throwing (a construct), we might have them all throw the javelin as a standardized test.

Another class of measurement situations in which the importance of validity is minimal is in experiments on motor learning (Schmidt, 1989a). In these situations, an arbitrary task is created that represents a motor performance novel to the participant, and the experimenter studies how the participant attempts to learn it or what variables influence that learning. The particular constructs being measured (e.g., balance, timing, movement speed) frequently are not very important to the experimenter, because the primary focus is on the variables that affect performance and learning generally.



# Measuring Motor Behavior

In the field of motor behavior and control, measurement can be approached in essentially three different ways. At the most general level, we can describe how well a movement achieved some environmental goal that was inherent in the task (e.g., whether or not a target was struck). Here the emphasis is on the *outcome* of movement. At a more specific level, we may be concerned with quantifying the actual movements the person made. In this case, the focus of analysis is describing the movement itself. The third level of analysis entails the study of the brain and central nervous system prior to and during the production of movement. At this level, researchers are interested in the neural activities involved in planning and executing movements.

## Describing the Outcome of Movements

The first aspect of measurement in motor behavior is quantification of the extent to which a given movement achieved the goal that was intended or instructed. For example, did the movement result in striking the target, or was the movement made at the right time? Such measures generally concern the movement in relation to some object or to another performer in the environment, although some movements (e.g., modern dance, diving) may not be so closely associated with other environmental elements. The achievement of such environmental goals can be assessed in essentially four fundamental ways—through measures of (a) error, (b) time and speed, (c) movement magnitude, and (d) performance on secondary tasks.

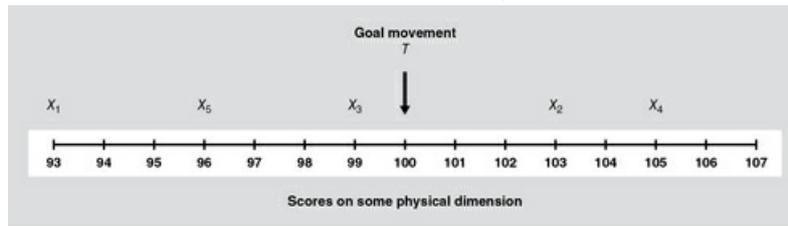
### *Measures of Error for a Single Participant*

Many performances require the participant to perform some action with maximum accuracy. Thus, the performance measures represent the degree to which the target was not achieved—a measure of error. The accuracy goal can be imposed in many ways; for example, participants can be asked to move with a certain amount of force, hit a certain spatial target, move at a certain speed, or perform some act at a particular time (e.g., hitting a baseball). A particular force, distance, speed, or time can be defined as the performer's target; then, deviations of the person's performances with respect to this target are measured. The level of analysis that is least sensitive comprises dichotic outcomes, such as when the performances are scored as hit/miss or right/wrong, as in shooting a basketball or judging which of two lifted weights is heavier. We can refine the accuracy score by dividing the possible outcomes into hit/almost hit/miss or by dividing a bull's-eye into 10 or more zones, for example. But motor performance is complex, and more sophistication in the measurement of accuracy is usually required.

In the discussion that follows, assume that a single performer is striving for accuracy in arriving at some target (e.g., a force, a speed, a location in space) and that the movement outcomes can be placed along some measurable dimension (e.g., kilograms, centimeters per second, centimeters) as in [figure 2.3](#). Let the correct value along this dimension—the target—have the value  $T$ . The values that the performer actually achieves are abbreviated by  $x_i$ , where  $i$  is a subscript notating a particular trial (i.e., the  $i$ th trial). For example,  $x_{23}$  is the score on the 23rd trial. In the simple formulas that describe these fundamental statistical accuracy scores, the symbol  $\Sigma$  means “the sum of.” For example,  $\Sigma x_i$  means to add up all of the values  $x_i$ , where  $i$  ranges progressively from 1 through  $n$ , with  $n = 5$  in the following example:

$$\Sigma x_i = x_1 + x_2 + x_3 + x_4 + x_5 \quad (2.1)$$

Figure 2.3 An arbitrary measurement scale, showing locations of a target ( $T$ ) and of five hypothetical movement attempts ( $x_1, \dots, x_5$ ).



In the following explanation, assume that the target ( $T$ ) is 100 units and that the individual does not always achieve this target score. In [figure 2.3](#) there are five scores: 93, 103, 99, 105, and 96 units for trials 1 through 5, respectively.

It is obvious that no single trial will be very effective in describing the performer's behavior, as the scores possess a great deal of variability. One solution is to combine these scores to achieve a more representative measure of the person's capability. In the study of motor behavior, researchers have typically focused on five methods for combining scores into measures of "error," and each one has a different meaning in terms of the performer's capability. These methods are described in the next sections as (a) constant error, (b) variable error, (c) total variability, (d) absolute error, and (e) absolute constant error.

### Constant Error (CE)—Computation

The first statistic to be considered as a measure of the performer's accuracy is the *constant error (CE)*, which measures the average error in responding. Its formula is

$$\text{Constant error} = \text{CE} = \sum (x_i - T) / n \quad (2.2)$$

where  $x_i$  is the score on trial  $i$ ,  $T$  is the target, and  $n$  is the number of trials the participant performed. It is very easy to compute this measure from [table 2.1](#), which can serve as a work table for computing all of the statistics presented in this section on error measures. The trial numbers are listed in column A; the scores obtained ( $x_i$ ) are given in column B. All other values in the table are computed from these initial values (remember that  $T = 100$  in this example).

A Trial	B $x_i$	C $(x_i - T)$	D $(x_i - M)$	E $(x_i - M)^2$	F $(x_i - T)^2$	G $ x_i - T $
1	93	-7	-6.2	38.44	49	7
2	103	+3	+3.8	14.44	9	3
3	99	-1	-0.2	0.04	1	1
4	105	+5	+5.8	33.64	25	5
5	96	-4	-3.2	10.24	16	4
Sum	496	-4.0	—	96.80	100	20
Mean	99.2	-0.80	—	19.36	20	4
Square root	—	—	—	4.40	4.47	—

To compute the CE, the numerator calls for finding the difference between each of the scores on the test ( $x_i$ ) and the target ( $T = 100$ ); these difference scores are shown in column C, headed  $(x_i - T)$ . It is important to notice in this column that for CE, the *sign* (+ or -) of the difference is retained. Next, the summation sign calls for adding the values (using the *signed* values) for each of the trials (in this case for each of the five trials), and this sum is presented at the bottom of column C (-4.0). Then the formula calls for dividing by  $n$ , the number of trials, in order to get the average CE over trials. The final CE score is  $-4.0/5$ , or  $-0.80$ .

### Interpretation of Constant Error

The CE score of  $-0.80$  indicates that, on average, the participant fell slightly short of the target (by 0.80 units). Notice that the CE is given in units that represent the amount *and* direction of deviation relative to the target, sometimes called *bias*. One could also ask for the performer's scores on the average by consulting the mean for column B. Thus, the average score was  $496 / 5 = 99.2$  units, meaning that the participant fell short of the target by  $99.2 - 100$  units, which is also  $-0.80$  units. The CE represents the average magnitude of the movement and measures the direction of the errors on the average.

While a measure of average error bias might, at first, seem satisfying to students as a measure of accuracy, notice that the value computed for the participant ( $-0.80$ ) was far smaller than the error for any of the single movements that contributed to the average. The movements were scattered a great deal, with the center of the movements being roughly the target that was the goal. What the CE does not consider is this amount of scatter, variability, or inconsistency in performance of the movements. Consider a second hypothetical performer with scores of 99, 99, 99, 99, and 100. These scores represent a very small scatter but would result in exactly the same CE score as for the person we have just been considering ( $-0.80$ ). For this reason, another measure of error, the variable error, is used to describe the performer's inconsistency.

### Variable Error (VE)—Computation

The *variable error* (VE) measures the *inconsistency* in movement outcome. It is the variability of the person's performances about the mean value and is calculated by the formula

$$\text{Variable error} = \text{VE} = \sqrt{\sum (x_i - M)^2 / n} \quad (2.3)$$

where  $x_i$  and  $n$  are defined as in the previous example. The  $M$  is the performer's average movement, measured in the same units as the scores for the task, so that for this example the  $M$  has the value of 99.2 units. To compute the VE for this participant, use [table 2.1](#) once again. Notice that the formula indicates first to compute the difference between the performance score and the person's own mean ( $M$ ), so the first step is to compute the person's  $M$ . As noted in the previous section, the computed  $M$  for these trials was 99.2 units. Now, the values in column D of [table 2.1](#) represent the differences between each of the scores on the trials and 99.2 (i.e., the difference between each individual score and the mean of all *that person's* scores). For example,  $93.0 - 99.2$  equals

-6.2, the first entry in column D. Since the deviations from the mean for each of the individual trials must cancel each other out, by definition the sum of the values in column D must equal zero. So, the next instruction from the formula is to square each of the values in column D, and these squared values are given in column E. Next, obey the summation sign and add the squared values, the sum of which (96.80) is shown at the bottom of column E. Then divide this sum by the number of cases ( $n = 5$ ) to get 19.36 and take the square root to arrive at the final answer of 4.40 units.

## Interpretation of Variable Error

The VE reflects the variability, or inconsistency, in movements, as can be seen from the “ingredients” in the formula. The important feature is the difference between the person’s score on each trial and his or her own average score. Thus, if one performer always moves very consistently, the VE will tend to be small. If the performer always receives the same score, even though it is not the correct one (such as a score of 99 on all five trials), then the VE will be zero. This is so because the person’s average score will be 99, and the difference between each of the scores and the average will always be zero as well.

Thus, VE does not depend on whether or not the person was close to the target, since it is the measure of spread about the performer’s *own* average. To illustrate, the VE for the set of scores 43, 53, 49, 55, and 46 achieved during aiming at a target of 100 units will be precisely the same (4.40) as that calculated in the previous example. (We obtained these five new values by subtracting 50 from each of the raw scores in [table 2.1](#).)

## Using Constant Error and Variable Error

An additional aspect of error scores is important from the point of view not only of research but also of practical application. Compare two riflemen: Rifleman A has a large VE and small CE, whereas rifleman B has a small VE and large CE. This situation was described years ago by Chapanis (1951) and is illustrated in [figure 2.4](#) (see “The Relative Importance of Constant and Variable Errors”). Which rifleman, A or B, appears to be the more skilled?<sup>1</sup>

# The Relative Importance of Constant and Variable Errors

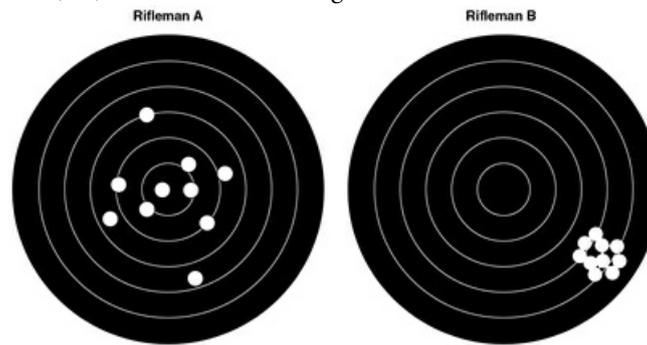
## Research Capsule

Alphonse Chapanis was one of the pioneers in the emergence of human factors research. His analysis of errors in movement is as important today as it was over a half century ago.

“Having defined constant and variable errors, we might ask: Which is the more important? Let us return for a moment to the target patterns shot by the two riflemen [[figure 2.4](#)]. At first glance, you might say that B is a very inaccurate shooter. And yet any rifleman will tell you that this is not the case at all. B is a much better shooter than A. The reason is this: The large constant error in the trial shots fired by B can be compensated for very easily by simple adjustments in his sights. With suitable corrections in elevation and windage, rifleman B will turn in a perfect score. In rifle shooting, then, constant errors are not the important ones, because they can be very easily adjusted for by changing the position of the sights on the gun. The really important errors are the variable errors. No correction of the sights on A’s gun will make all of his shots fall in the center. He is inherently much too variable.” (Chapanis, 1951, p. 1187)



Figure 2.4 Distribution of rifle shots. Rifleman A has a small constant error (CE) and large variable error (VE). Rifleman B has a large CE bias, but a small VE.



Reprinted, by permission, from A. Chapanis, 1951, "Theory and methods for analyzing errors in man-machine systems," *Annals of the New York Academy of Sciences* 51: 1181.

The study of motor learning will show that the measure of error that is most sensitive to the effects of practice is consistency (VE); bias (CE) often changes quickly in the first several trials and remains near zero thereafter, even after years of practice. There are some situations, however, in which CE is preferred to VE; but these are specialized applications. Thus, these two measures of error, CE and VE, seem to represent two distinct aspects of performance—bias and variability, respectively. But sometimes it is more desirable to have a single measure of “overall error” that combines both of these performance indicators rather than using separate measures of accuracy and inconsistency.

#### Total Variability (E)—Computation

The *total variability* ( $E$ ) around a target (or error) for a set of movements (labeled  $E$  by Henry [1975] and sometimes called *root mean square error*) can be thought of as the measure of “overall error” (see also Chapanis, 1951).  $E$  can be defined as the square root of the sum of  $VE^2$  and  $CE^2$ , or in the following formula when expressed as  $E^2$ :

$$E^2 = VE^2 + CE^2 \quad (2.4)$$

$E$  can also be computed directly from the formula:

$$\text{Total variability} = E = \sqrt{\sum (x_i - T)^2 / n} \quad (2.5)$$

where  $x_i$ ,  $T$ , and  $n$  are defined as before. To apply the formula, we can use table 2.1 again. Notice that the major “ingredient” is the difference between the score and the target ( $x_i - T$ ), and this difference (with the sign included) is given in table 2.1, column C—the same values used to compute CE. Next, square each of these values; these squared values are given in column F. The summation sign then says to add the squared values, and the sum (equal to 100) is given at the bottom of column F. Next, divide by  $n$  (5), which results in a value of 20; then find the square root. The final value for E is  $\sqrt{20}$ , or 4.47.

### Interpretation of Total Variability

The total variability, E, is the total amount of “spread” of the movements about the target, so it represents an overall measure of how successful the performer was in achieving the target. The key to understanding this formula is the expression in the numerator  $(x_i - T)^2$ . E is based on the sum of a group of squared differences, where each difference is the amount by which the person missed the target. This contrasts with VE, where the numerator  $(x_i - M)^2$  represented the deviations from the *person’s own average*, which is not necessarily equal to the target. In cases when CE is close to zero (i.e., the mean of the trials approximates the aimed-for target [ $M$  and  $T$  are nearly equal]), then E and VE come to represent very similar aspects of the person’s performance. But, in cases when the CE is very different than the target, then E will represent the combination of this error in bias plus the variability about the CE (i.e., E is a combination of CE and VE).

### Absolute Error (AE)—Computation

A statistic closely related to the total variability (E) is *absolute error (AE)*, which can also be thought of as a measure of overall accuracy in performance. It is the average *absolute deviation* (without regard to direction, or sign) between the performer’s movements and the target, and its formula is as follows:

$$\text{Absolute error} = \text{AE} = \frac{\sum |x_i - T|}{n} \quad (2.6)$$

where  $x_i$ ,  $T$ , and  $n$  are defined as before. The important difference here is the presence of the vertical bars ( $|$ ), which are the symbol for “absolute value of” and mean that we should take away the sign of the difference before summing.

To compute AE, refer again to [table 2.1](#). The first step is to compute the values for the numerator terms, and this is done in column G, headed  $|x_i - T|$ . Notice that the value in this column is the same as the corresponding value in column C, except for the sign. The summation sign  $\Sigma$  is an instruction to add up the values from each of the  $n$  trials (recall that  $n = 5$  in this example), and the sum is given at the bottom of column G as 20. The next step is to divide by the number of trials included ( $n = 5$ ), and so the final answer is 4.0.

### Interpretation of Absolute Error

In providing an interpretation of the AE, it will be helpful to consider the ways in which it is similar to E. First, notice that the numerator is essentially the same for the two statistics, each numerator having a difference between the obtained score ( $x_i$ ) and the target ( $T$ ) as the major “ingredient.” Second, the  $x_i$  values for E and AE (4.47 and 4.0, respectively) are very similar; the two values will be equal only in special circumstances but will be very close in most situations. Third, both of the formulas involve methods for eliminating the sign of the difference between the score and the target; for AE, the method is to take the absolute value, while for E, the method is to square the values in the numerator.

## Absolute Error Versus Total Variability

The AE is a very “logical” measure to use to describe the person’s overall accuracy in a task because it is sensitive to the extent to which the performer was “off target.” It was used far more commonly than E in the early research and for many different applications. A controversy, however, has arisen about the use of AE (Schutz & Roy, 1973). The mathematical properties of AE have been shown to be a complex combination of CE (accuracy or bias) and VE (variability), and it is difficult to be certain of the relative contribution of each. Because of the precise relation between E, CE, and VE (namely,  $E^2 = VE^2 + CE^2$ ), E is always an exact combination of the variability and bias, and thus is preferred to AE (Henry, 1975). The tendency today, when a researcher wishes to present a combined measure of accuracy and variability, is to prefer E, for two reasons: First, E measures essentially the same component of movement as AE, and second, E is more easily interpreted since it represents a simple combination of CE and VE. However, we will use AE a great deal in this text, because much of the earlier research reported only this measure.

## Absolute Constant Error ( $|CE|$ )

One final measure of accuracy is merely a transformation of constant error, CE:

$$\text{Absolute constant error} = |CE|$$

(2.7)

Thus, for a single person, the *absolute constant error* ( $|CE|$ ) is just the absolute value of the CE, which is simply 0.80 in the present example. Be careful to note, however, that  $|CE|$  is not calculated in the same way as AE. For AE we take the sign away immediately after calculating the difference between a single score and the target, *prior* to summation. For  $|CE|$  the sign is not taken away until *after* the average over a series of trials has been calculated.

## Interpretation of Absolute Constant Error

The situation sometimes arises (e.g., Newell, 1976a) in which approximately half the *performers in a group* have positive CE scores while the other half have negative CE scores. If one characterizes the average bias for this *group* of people by calculating a group mean score (the average score of all the performers), the positive and negative signs will tend to “cancel” each other out. This could give rise to the misleading conclusion that the average bias for the *group* was nearly zero when in fact every participant in the group might have shown a bias of considerable size. In this case, it is useful to also compute  $|CE|$ , which tells the researcher the mean amount of bias for the group of people without regard to its direction, and which will not fall prey to this “canceling” effect of the positive and negative CEs. In cases in which group data have been the focus of a researcher’s experiment, there has been a trend to report  $|CE|$  (as the measure of accuracy) along with VE (as the variability score) (see Schutz, 1977, for more statistical details).

## Relationships in the Error Scores

One way to evaluate the relative contributions of the various measures of error is to consider the following cases. At one extreme, when CE is very large (an extreme is the situation in which all the person's movements lie on one side of the target), then the AE, the E, and the CE all tend to measure the same component of performance—the bias or directional deviations of the errors. In the following case, the target is again 100, but participant 1 produces five movements, 80, 90, 85, 82, and 87—each smaller than the target. [Table 2.2](#) gives the measures of error for this person. Notice that the statistics E, CE, AE, and  $|CE|$  are all around 15, but that the VE is very much lower at 3.54. This suggests that when the CE is large in either direction, the measures of overall error (E and AE) tend to represent the magnitude of the bias, and VE alone represents the variability.

	E	CE	VE	AE	CE
Participant 1	15.61	-15.2	3.54	15.2	15.2
Participant 2	3.55	-0.2	3.54	3.0	0.2

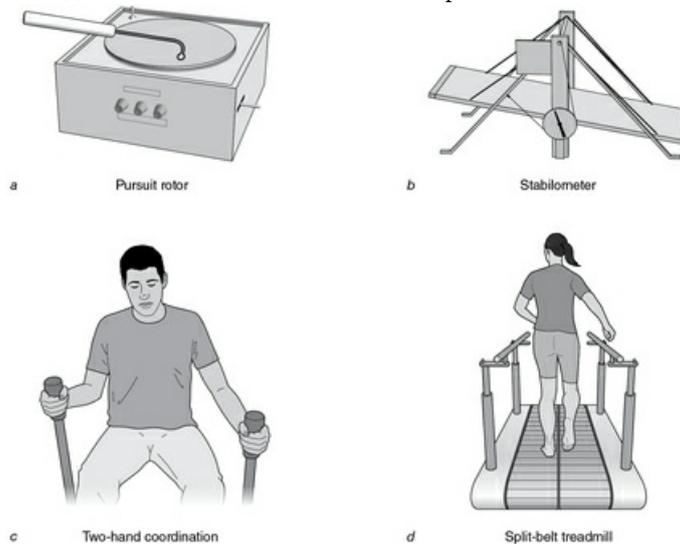
Now consider participant 2 in [table 2.2](#). This person has the same spread of outcomes as participant 1 but with much less bias. We obtained these scores by adding 15 to each of participant 1's scores to get participant 2's scores: 95, 105, 100, 97, and 102. [Table 2.2](#) gives the error measures of this set of scores. Now notice that the measures of overall error tend to be very close to the VE, all around 3. The CE (and |CE|), however, is now nearly zero. Here the measures of overall error (E and AE) represent the variability of the movements (VE), exactly the opposite of the situation with participant 1.

Therefore, when CE is large in either direction, the measures of overall error (E and AE) tend to represent the amount of bias in the scores. When CE is small, E and AE tend to represent the amount of variability (VE) in the scores. When CE is intermediate in value (with some bias but with scores falling on both sides of the target), the measures of overall error represent an unknown combination of bias and variability. This should make clear why simply examining overall error statistics does not provide a very complete picture of performance.

### Other Measures of Accuracy

There are many tasks in the motor behavior literature that could not be scored so simply. A task for which accuracy is important is the *tracking task*; in this case, performance is ongoing, thus preventing the computation of a discrete performance error. A commonly used tracking task is the *pursuit rotor*, shown in [figure 2.5a](#). There are many varieties of pursuit tracking tasks, and [figure 2.5a](#) illustrates just one type. Here, a target (e.g., a small circle) is embedded in the surface of a turntable-like structure that rotates at various speeds. The participant holds a stylus in the preferred hand and attempts to keep its tip in contact with the target as the turntable rotates. A trial might last from 10 s to 1 min, and performance is scored in terms of the amount of time in the trial that the participant maintained contact with the target. The performance measure is usually called *time on target (TOT)* and can range from zero (if the participant never touched the target) up to a value equal to the duration of a trial (if the participant was always in contact with the target). But notice that time on target can represent a complex combination of bias (if the participant is consistently behind the target, for example) and variability (if the participant is alternately ahead of and behind the target).

Figure 2.5 Four movement tasks frequently used in motor behavior research: (a) pursuit rotor, (b) stabilometer, (c) two-hand coordination, and (d) split-belt treadmill.

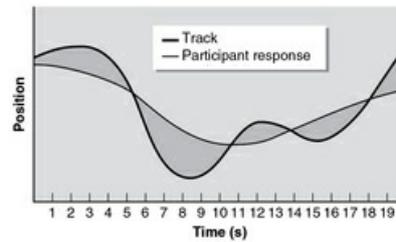


Other common variations of tracking tasks are shown in [figure 2.5](#). [Figure 2.5b](#) shows the *stabilometer*. The standing performer attempts to keep an unstable platform level; the scores denote either time in balance or the number of times the platform edge touches the floor (indicating extreme loss of balance) during a trial of perhaps 30 s. Another example of this kind of measure is the number of times a stylus touches the sides of a maze. [Figure 2.5c](#) shows the *two-hand coordination*, in which the performer attempts to produce a movement with either the same or a different displacement-time goal for each arm. The accuracy score reflects the degree to which the different goals interfere with each other. Bimanual coordination is covered in more detail in chapter 8. [Figure 2.5d](#) shows the split-belt treadmill task, in which the performer attempts to walk under one of these conditions: The two belts are tied together and move at the same rate, or the two belts are untied and move at different rates. The *split-belt treadmill* has been used to study *motor adaptation*—an iterative process of adjusting one’s movement to new environmental demands. Chapter 9 discusses adaptation and compares it to motor learning.

In each of the foregoing examples, the experimenter does not need to keep a record of the participant’s actual behavior. However, there are other tracking tasks for which a continuous record of the movements of the participant and the target is kept. From these data the experimenter can compute a measure of overall accuracy, the *root-mean-square error (RMSE)*. (Notice that RMSE is analogous to E, described earlier. Both are root-mean-square deviations of the behavior from some target, computed on successive “trials.”) Essentially, the RMSE is based on taking small “slices” of time and measuring the deviation of the person’s line from the target at each of these times, as shown in [figure 2.6](#). Depending on the capacity of the recording system, these slices can be taken every few milliseconds or so over the entire course of a 20 s trial, providing many measures of error. To compute the RMSE, square each of these deviations from the track, add up the squared deviations, divide by the number of measures, and then take the square root, giving a measure of the amount of deviation over the course of the trial. RMSE in each of these cases represents essentially (but not exactly) the area between the performer’s movements and the target, as shown by the shaded portions of [figure 2.6](#). As with TOT, the RMSE is a measure of overall error and is sensitive to both the bias and the variability in performing. Time-series analysis can be used to decompose overall RMSE. The experimenter can do this analysis by taking the performer’s position trace and sliding it systematically along the time axis in small increments. With each incremental move, a new RMSE is calculated between the performer’s position trace and the target track until RMSE is reduced as much as possible. The lowest RMSE represents the overall accuracy of tracking the target, while the amount that the performer’s trace was moved to achieve the greatest accuracy represents the time lag associated with tracking the target path. These two measures of accuracy and lag can be useful in decomposing the overall error represented by the standard RMSE into two essential elements of tracking performance. A shortening of lag time with practice can be used as a proxy for anticipation (i.e., feedforward) and thereby reflect learning of the target track over repeated trials.



Figure 2.6 Hypothetical record from a tracking task, showing the basis for computation of root-mean-square error (RMSE).



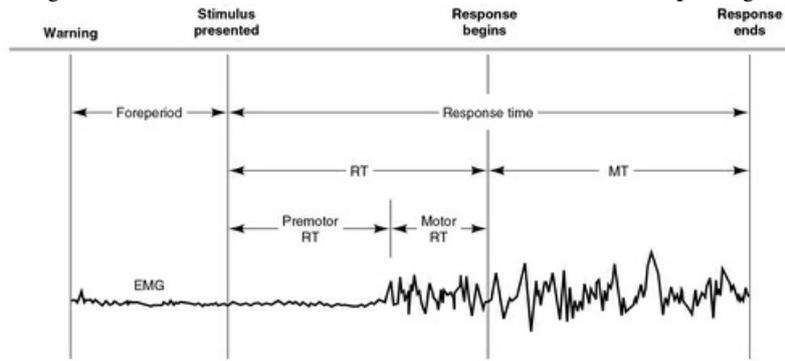
### *Measures of Time and Speed*

The second fundamental way of assessing skills is by measures of time and speed. Basic to this idea is the assumption that the performer who can accomplish more in a given amount of time, or who can produce a given amount of behavior in less time, is the more skillful. This assumption is not always true, particularly in the case where one's measure of time is reduced over practice but at the expense of movement quality. In this example, while the behavior is accomplished in less time, performance may be less skilled. Measures of time and speed are essentially the same, since a time measure (time/unit) can easily be converted to a speed measure by taking the reciprocal; that is,  $1 / (\text{time} / \text{unit}) = \text{units} / \text{time}$ , which is a measure of speed. Both speed and time measures have been used a great deal in motor behavior research. Reaction time and movement time are common examples, described next.

### Reaction Time

*Reaction time (RT)* is a measure of the time from the arrival of a suddenly presented and unanticipated signal to the *beginning* of the response to it. In the RT paradigm shown in [figure 2.7](#), the person is given a warning signal, and after a randomly determined *foreperiod* (perhaps ranging from 1-5 s), the stimulus is presented. Using the variable foreperiod represents an attempt to prevent the participant from anticipating when the stimulus will arrive (*temporal anticipation*). Sometimes “catch trials” are used, in which the stimulus is not presented at all; this allows the experimenter to “catch” a participant who is anticipating, and thus its use tends to prevent anticipation. The introduction of catch trials, given randomly perhaps on 15% of the total number of trials in an experiment, improves the experimental control. Also, participants can be prevented from anticipating which movement to make (i.e., spatial or event anticipation) through the use of two or more choices, so that the proper response is signaled by the stimulus itself (e.g., red light means move left, blue light means move right); this is termed the *choice-RT* method (when only one option or “choice” is available, this is termed a *simple-RT* method).

Figure 2.7 Critical events involved in the reaction-time (RT) paradigm.



Reaction-time measures are common in many sport settings; an example is the interval between the starter's gun and the first movement in a swimming race. This is an example of a simple-RT task in which there is only one response to make. The starter varies the time between the "ready" command and the auditory signal to start in order to reduce temporal anticipation. A car driver who suddenly observes a large object ahead in the road must decide whether to swerve left or right to avoid it. This is an example of a choice-RT situation. Reaction-time measures are also used extensively in the laboratory as measures of information-processing speed (see chapter 3).

One variation of the RT method is to partition the latency of the response initiation into "central" and "peripheral" components (Weiss, 1965). The bottom of [figure 2.7](#) shows a hypothetical electromyographic (EMG) trace taken from a muscle involved in the movement to be made. (EMG indicates the electrical activity in a muscle.) The EMG is mostly silent during a substantial part of the RT, indicating that the command to move the finger, which is initiated in the brain, has not yet reached the finger musculature. The muscle is activated late in the RT, but no movement occurs for 40 to 80 ms. The interval from the signal to the first change in EMG is termed "premotor RT" and is thought to represent central processes involved in making the response (e.g., perception, decisions). The interval from the first change in EMG to finger movement is termed "motor RT" and represents processes associated with the musculature itself. Such methods are useful in gaining further information about the effect of an independent variable on RT (e.g., Fischman, 1984).

Reaction-time measures are very common in research on skills, for two basic reasons. First, RT measures are components of real-life tasks (e.g., sprint starts), so they often have high face validity. A more important reason (which we will amplify in chapters 3 and 4) is that RT presumably measures the time taken for mental events, such as stimulus processing, decision making, and movement programming. These two motivations for using RT measures differ considerably. In the first case, RT is a measure studied for its own sake; in the second case, RT allows the researcher to understand the kinds of mental processes that lead to movement (e.g., Posner, 1978). Regardless of the motivation, the measurement of RT is the same.

## Movement Time

Movement time (commonly abbreviated as MT) is usually defined as the interval from the initiation of the response (which defines the end of the RT) to the completion of the movement ([figure 2.7](#)). Clearly, MT can be just about any value, ranging from a few milliseconds for a very quick movement to several weeks if the movement being studied is jogging from Los Angeles to Chicago. Some sport skills have minimal MT as a goal (e.g., time to run 100 m, or time for a quarterback to "set up" for a pass), and MT is used a great deal in skills research as a result of its overall external validity in these practical settings. Sometimes researchers use RT and MT tasks together in the same performance, as in requiring the performer to lift a finger from a key and move to a button as quickly as possible after a stimulus.

The sum of RT and MT is termed *response time* (see [figure 2.7](#)). Research has consistently shown that very different processes or abilities are required in reacting quickly as opposed to moving quickly once the reaction is over, and this has justified separating response time into RT and MT. What is frequently called "brake reaction

time” in the field of automobile accident analysis is really response time, because it consists of the time used to initiate the foot movement from the accelerator pedal plus the time required to move the foot to the brake pedal and press it.

Often the degree of accuracy in the task must be taken into account when measures of speed are used. A well-known phenomenon in motor behavior is the *speed–accuracy trade-off*, meaning simply that when performers attempt to do something more quickly, they typically do it less accurately. In most measures of speed, therefore, accuracy requirements are kept to a minimum so that speeding up the movement (which is the major goal for the person) does not seriously affect accuracy. In some situations, though, measures of speed are confounded with measures of accuracy, and the speed with which the person performs is dependent on the amount of error he or she is willing to make or the amount of error the experimenter will tolerate. Such trade-offs are particularly troublesome for experimenters, because it is not always clear to performers how much error will be tolerated, and experimenters are unsure about how to interpret an independent variable that produces increases in speed but decreases in accuracy or skill as mentioned earlier. One solution to this problem is to hold accuracy constant by various experimental techniques so that a single dependent variable of speed can be assessed (e.g., Fitts, 1954). Another solution is to hold speed constant, via instructions, so that accuracy can be assessed (e.g., Quinn, Schmidt, Zelaznik, Hawkins, & McFarquhar, 1980; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979).

### *Measures of Movement Magnitude*

A third way of measuring skills is by the magnitude of behavior that the performer produces, such as the distance that a discus was thrown or the amount of weight that was lifted. These measures have particularly important applications to sport settings, as many sports use such measures as the primary determinants of success in the activity. The ski simulator ([figure 2.8](#)) is a task in which large rubber bands keep a platform centered. The performer’s task is to displace the platform as far as possible from side to side using whole-body movements.

Figure 2.8 Ski simulator being used by Gabriele Wulf.



Reprinted, by permission, from G. Wulf, 2007, *Attention and motor skill learning* (Champaign, IL: Human Kinetics), 9.

While it might seem that tasks with goals of maximum movement magnitude are considerably different from those requiring speed or accuracy, their fundamental determinants may not be all that different. At first glance, producing maximum movement magnitude would seem simply to be a matter of generating more force. But these skills certainly require precise timing of the forceful contractions and accurate coordination of the core and participating limbs. Therefore these precise muscular activities might be essentially the same as those required in tasks that seem to necessitate only accuracy. Of course, inconsistency (in terms of VE) in these processes will degrade performance, and such inconsistency is probably related to the VEs that are seen in the outcomes of simpler tasks.

### *Measures of Secondary Tasks*

There are instances in both practical and research settings in which none of these basic methods of measurement will be sensitive to differences in skill among individuals or to differences in skill caused by some independent variable. Generally these situations involve tasks for which differences in performance are not evident because the tasks are well learned (driving a car down an open road), or involve tasks that do not “tax” the motor system very much because they are so simple (drinking a glass of water without spilling) at least for a nondisabled individual. How are skills assessed in such situations?

One method is to use some measure of critical incidents. In the driving example, accident rates from statistical databases for a particular kind of car, or for certain types of people (e.g., drunk drivers), might be used as measures of skill; with pilots, “near misses” (midair near-collisions) might be used. But these techniques are difficult to utilize in the laboratory because (fortunately) such critical events occur so infrequently. Thus, they are far more useful for groups of people taken over relatively long stretches of time.

Another useful technique is to employ performance on some sort of secondary task, performed simultaneously with the primary task, as a measure of the skill in the *primary* task. For example, Brown (1962) used a verbal task in which the individual was presented with eight-digit numbers at 4 s intervals. Each number contained seven of the same digits as the previous one, and the performer’s task was to detect the digit that was different and to provide a response. Errors were counted as omitted responses, incorrect responses, and late responses. In this experiment, Brown obtained measures of performance when people performed only this verbal–numerical task and also when people performed this task while driving under various conditions. The mean percentage of correct responses when the verbal task was performed alone was 90.6%. When the task was performed during driving in quiet residential areas, the mean percentage dropped to 83.8%. And when the task was performed in heavy traffic conditions, the percentage again dropped to 79.5%. Yet it was very difficult to see any differences in vehicle control in light and heavy traffic, largely because driving is so well learned by most people. This secondary task

provided evidence about the difficulty of the driving conditions when the driving task itself would not have provided such a measure.

Some experimenters have used RT tasks (so-called *probe tasks*—e.g., Kerr, 1975) inserted during a performance of the primary task. Others have used measures of finger tapping regularity (e.g., Michon, 1966) as the secondary task. In these latter cases, the implication is that these tasks require some of the performer's *limited capacity* to process information; presenting the secondary task simultaneously with the primary task necessitates the use of some of this capacity, and lowers the performance on the secondary task in relation to the amount of capacity demanded by the primary task. (See chapter 4 for more on this assumption and general method.)

Rather than a task, secondary *physiological* measures of effort can be used during the performance of a main task. One technique is to measure pupil diameter by one of various recording methods. Pupil dilation is associated with circumstances in which effort, arousal, or information processing is demanded (e.g., Beatty & Wagoner, 1978; Kahneman, 1973). Similarly, measures of heart rate, heart rate variability, oxygen consumption (as a measure of overall effort), or even EMG from the muscles of the forehead (to indicate the level of concentration) can be used, depending on the particular situation. Neurophysiological techniques, such as the recording of *event-related potentials* from the scalp, are also used. One such potential has been called *P300*, as it occurs as a positive voltage about 300 ms after the presentation of a stimulus (Duncan-Johnson & Donchin, 1982). The latency of the P300 and the magnitude of its amplitude appear to be highly correlated with RT, thus providing an unobtrusive way to measure processing activities (e.g., Radlo, Janelle, Barba, & Frehlich, 2001). In all these cases, the secondary measures become the focus of the investigator, especially when the main task does not provide sensitive measures of the participant's performance.

A variation of this technique is to use a secondary task as a distracter in order to increase the overall "load" on the performer. Normally, fatigue may not have any obvious effect on the well-learned task of driving. However, if the driver is required to perform a simultaneous mental arithmetic task at a predetermined level, then large differences between fatigued and rested driving may be seen. In this situation, unlike the others, the major interest is in the performance of the main task, and the secondary task has increased the sensitivity of the measurement system for the main task. However, care must be taken with these techniques, as Brown (1962) has shown. When truck drivers were fatigued, their performance on the secondary digit detection task actually improved, suggesting that they were devoting less capacity to the driving task and overcompensating by devoting more capacity to the secondary task. While these techniques can be somewhat tricky to use, they have served well in a number of situations.

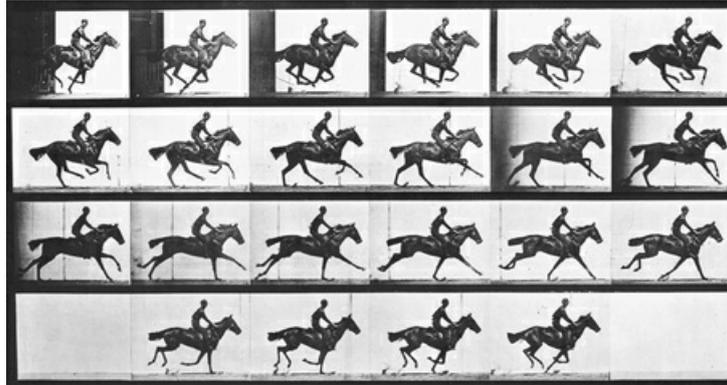
## Describing Characteristics of Movements

Countless methods could be employed to describe movements, depending on the characteristics of the movement that are of interest to the observer. At the most fundamental level, one can use verbal descriptors to characterize movement. For example, movements have been described in dance notation created by Laban (1956) and in terms of units of work behavior called "Therbligs" in early industrial time-and-motion studies (Gilbreth, 1909; note that "Therbligs" is the author's name spelled backward, almost). Another way is to illustrate movement with photographs, as was done over a century ago by Muybridge (1887, 1979) using series of still photos (see "Movement Photographs of Eadward Muybridge;" [figure 2.9](#)), or with videotape or digital images. Such methods are of some use in describing or illustrating the basic forms of movement but have limited value in detailed assessments of performance. Improvements in photographic techniques occurred early in the 20th century; some were pioneered by Bernstein (Bernstein & Popova, 1930/2003). In this section we focus on *kinematics*, a branch of mechanics in physics that involves the description of "pure" motion without regard for the forces and masses that produced the motion. The devices that can be used to collect this information also vary widely, and we will describe some of the more common ones.

## Movement Photographs of Eadweard Muybridge

In 1887 Eadweard Muybridge published what probably was the first photographic analysis of human and animal locomotion. In some series, Muybridge used 36 separate shutters, arranged so that three different angles could be photographed simultaneously, positioned at the side, front, and rear of the participant. At each angle a series of 12 shutters was electrically arranged to open in a timed sequence after a signal had been sent to the first shutter. Muybridge determined the length of the time intervals on the basis of the speed at which the participant performed the activity (e.g., picking up an object vs. running at full speed). These methods resulted in a sequence of still photographs that produced simulated motion, which one could study further by examining the changes in the action as it evolved over time. In all, Muybridge published 781 plates, each plate a series of photographs of the participant. The participants were both humans and animals. Humans of all ages, males and females, and of many different body types, performed actions such as walking, running, jumping, skipping, lifting objects, and hammering. Many of the humans were photographed in the nude, which provided rather explicit details of body actions. Animals from a wide range of species were photographed in various natural and contrived settings. It is rumored that Muybridge settled a bet concerning whether or not all of a galloping horse's feet are ever off the ground at the same time. According to his photos, they are. Muybridge's series of still-sequence photographs remains as a magnificent legacy in the history of human and animal motion analysis.

Figure 2.9 A famous series of Muybridge photos, clearly revealing a period of time when the horse has no contact with the ground.



### *Movement Kinematics*

As applied to movement behavior, kinematic measures describe the movement of the limbs or the entire body. The locations of various parts of the body during the movement, the angles of the various joints, and the time relations between the movement in one joint and the movement in another are examples of the many ways movement kinematics can be recorded.

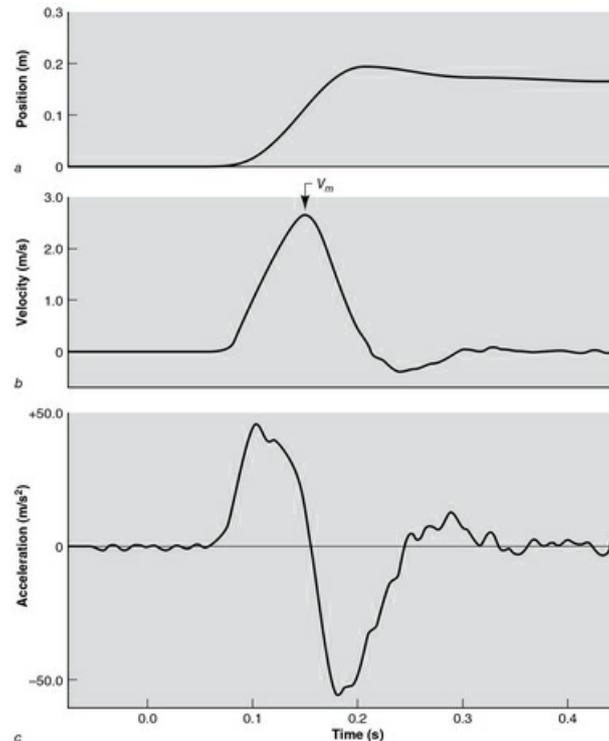
### Location

Perhaps the most common of the kinematic methods entails recording the locations of the limbs during a movement. One of the early investigations using movement kinematics as a research tool was published by Lawrence Lindahl in 1945 (Lindahl, 1945). His study concerned a practical problem; it was an industrial task in which a factory worker operated a machine that cut very thin slices off tungsten rods. The key aspect of the job involved using a foot-pedal action that moved an unseen cutting wheel through the tungsten rod. Success at the task required carefully coordinated displacement-time foot actions. Failure to coordinate these actions resulted in wasted material and damage to the equipment. Skilled machine operators made stereotypical actions of the foot, which Lindahl captured nicely using a writing apparatus that recorded the foot displacements over time. These recordings were then used for comparison with the recordings that beginner and less skilled workers produced in their disc-cutting performances. This type of recording, using kinematics as a means to provide objective feedback and goal-related movement information (so-called kinematic feedback), predated modern investigations by about 40 years (see chapter 11).

Early in the history of motor behavior and biomechanics, researchers used high-speed cinematography to record movements. Often the participant being filmed wore tape markers over certain landmarks (e.g., the wrist or ankle) so that the locations of these body parts could be studied frame by frame. These positions on successive frames were separated by nearly fixed periods of time, so a graph of the position of the landmark against time could be generated from the data. [Figure 2.10](#) shows an example of this type of graph, taken from Wadman, Denier van der Gon, Geuze, and Mol (1979). For now, consider only trace a, which represents position; it is derived from the output of a device called a potentiometer that signals angular position. This trace, read from left to right, represents an arm movement of about 17 cm. The movement began at the time when the trace left the horizontal axis. The largest amplitude (about 20 cm) was achieved about 125 ms after the movement started, and then the limb stabilized its position at the final location.



Figure 2.10 (a) Position, (b) velocity, and (c) acceleration traces representing a rapid 17 cm elbow extension movement.



Reprinted from W.J. Wadman et al., 1979, "Control of fast goal-directed arm movements," *Journal of Human Movement Studies* 5: 5. By permission of W.J. Wadman.

But examining the location of a limb in space may mask some of the more subtle factors that determine its control. For this reason motor behavior researchers often examine variables that can be derived from location information—velocity and acceleration.

### Velocity

Trace b in [figure 2.10](#) is a record of velocity of the movement at each moment in time, placed on the same time scale as the positional trace for easy comparison. The velocity trace was derived by taking the potentiometer position data and calculating the slope or inclination of the line at each moment. The slopes (called derivatives) of the positions at each moment in time represent the velocities at corresponding moments, indicating *the rate of change in position*. Then this information is output onto the same record as the position information. Such a trace is useful here in showing that the maximum velocity ( $V_m$ ) was about 2.7 m/s and that the achievement of maximum velocity occurred at about 75 ms through the movement. Also shown are a gradual increase in velocity until the peak velocity (the midpoint of the movement) is reached and then a decline toward the end. Such a trace gives a more complete description of the movement than does positional information alone.

### Acceleration

Trace c in [figure 2.10](#) is a record of the acceleration at each moment of time. This record was also derived by calculating the slope or inclination of the velocity curve at each moment. These days, most students use MATLAB tools or write code to derive these metrics of movement (Rosenbaum et al., 2015). The slopes of the velocity curve at each moment yield the accelerations and represent *the rate of change in velocity*. This output is plotted along with the other two traces on the same time scale. Initial acceleration lasts about 100 ms until the acceleration trace returns to zero. Then there is a deceleration (a negative acceleration trace) that lasts for about the same length of

time. Also, the peak velocity of the movement is achieved at the point at which the acceleration changes to deceleration (where the acceleration curve crosses the zero baseline).

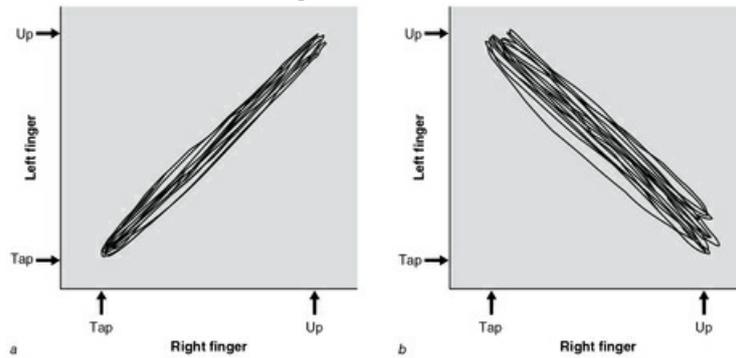
These kinematic variables, with simultaneous recording of position, velocity, and acceleration as a function of time, provide a reasonably complete picture of these movements. Scientists often search for changes in these kinematic variables when certain independent variables are changed—for instance, instructions to the performer or the size of a target to which the person is moving. Examples of this kind of research are provided later in the text.

## Coordination Kinematics

In chapter 8 we will focus on movement coordination—how the actions of one body part are controlled together with the movements of another body part. Many types of coordination exist, such as the coordination of two or more joints in one limb (as when one is reaching for a cup) or of different limbs simultaneously (as of the arms and legs during walking), or even more subtle coordinations (such as the movements of the eye and head while one is reaching for a glass in the cupboard). For movements that are oscillatory, one measure of coordination is to describe the temporal *phasing* between the two body parts.

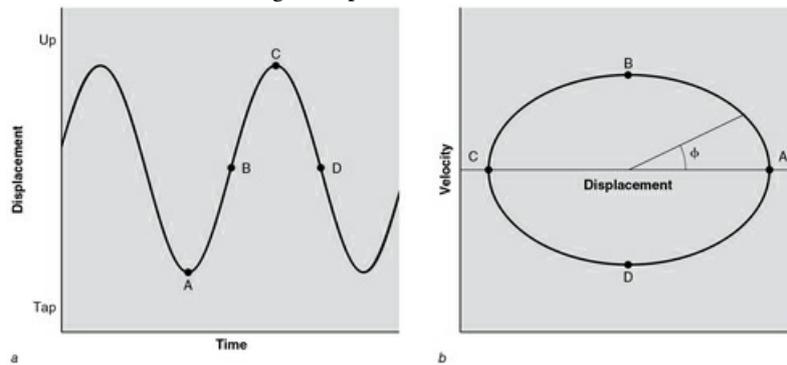
Consider the simple action of tapping two fingers on a table. Suppose we plotted the displacement records of the up-and-down tapping cycles of the right finger along the abscissa and the cycles of the left finger along the ordinate. Plotted separately, each would be represented as a back-and-forth, overlapping straight line along its respective axis. However, to assess how these two fingers are coordinated, the time records of one finger can be plotted relative to the time records of the other finger. At any point in time, the position of the left hand relative to the position of the right hand can be represented as a single data point on the graph. When the points are combined over time they produce one continuous trace, as illustrated in the two examples in [figure 2.11](#) (see also Winstein & Garfinkel, 1989). In [figure 2.11a](#), the two fingers tap the table at approximately the same time, are at maximum height above the table (in the “up” position on the graph) at about the same time, and seem to be moving within their respective cycles at about the same time—the coordinated motions are *simultaneous*. The example in [figure 2.11b](#) illustrates *alternate tapping*—one finger taps the table at about the same time that the other finger reaches maximum height, then vice versa. This figure illustrates just two of the types of temporal coordination patterns that exist between oscillating effectors (see chapter 8).

Figure 2.11 Sample displacement plots of two fingers moving simultaneously: (a) in-phase coordination and (b) anti-phase coordination.



One can also obtain a quantitative measure of temporal coordination by considering the displacements of each cycle over time. This is represented in [figure 2.12](#) in two ways. In [figure 2.12a](#), displacement of one finger is plotted over time—position A represents the finger at the time of a tap, position B is about halfway up, position C represents the “up” point, and position D is halfway back down again. [Figure 2.12b](#) represents the same data by plotting these one-finger displacements against their own velocities (called a phase-plane representation). The time axis is replaced by position. For the phase-plane plot, time is revealed through the spacing between discrete data points (not shown). Now positions A and C represent zero velocity, and positions B and D are the maximum upward and downward velocities, respectively. The value of phase-plane representations is that the position of each finger at any point within its cycle can be described as a phase angle ( $F$ ) indicating the progress through a cycle, or a circle, containing  $360^\circ$ .

Figure 2.12 Repetitive movement of a finger: displacement (a) relative to time and (b) relative to its velocity.



a) Adapted from Kelso et al. 1985. b) Adapted from Burgess-Limerick, Abernethy, and Neal 1992.

Since the phase planes of each finger can be determined independently, the measure of coordination is simply the difference between the phase angle for the left finger ( $F_L$ ) and the phase angle for right finger ( $F_R$ ). This measure is called *relative phase*, because the measure represents the position of one finger within its cycle relative to the position of the other finger within its cycle.

From figures 2.11a and 2.12, it is clear that at any one time, the two phase angles are about the same. That is, when both fingers are “down,” each phase angle is  $0^\circ$ ; when both fingers are “up,” each phase angle is  $180^\circ$ , and so on. Thus, the relative phase ( $F_L - F_R$ ) will always be close to  $0^\circ$  whenever a sample is measured. This simultaneous pattern of coordination is often referred to as moving *in-phase*. However, for figure 2.11b, notice that the temporal phasing of one finger is always nearly exactly opposite that of the other finger. That is, when one phase angle is at  $0^\circ$ , the other is at  $180^\circ$ ; then when the first is at  $180^\circ$ , the other has reached  $360^\circ$  (or  $0^\circ$ ). The relative phase for this series of estimates produces an average relative phase of about  $180^\circ$ , which is sometimes referred to as moving in an *anti-phase* pattern of coordination.

But notice also that there is some variability in the plots presented in figure 2.11. Thus, researchers often calculate the standard deviation of these relative-phase samples in order to supplement the description of a pattern’s average relative phase with an estimate of its *stability*. The measure of relative-phase variability is determined in a way similar to that for the measures of VE, discussed earlier in the chapter. Both the mean and standard deviation measures of relative phase will be used to describe important features of coordination in chapter 8.

### *Movement Measurement Devices*

Measurement recording systems, used to collect data about human movement, have undergone many changes over the years. Just as “moving picture” technology evolved from the efforts of Muybridge and others to capture on film the moment-to-moment changes in body positions, new developments in measurement technology have often been created to satisfy the needs of researchers to make recordings with increased precision and economy (in terms of time and effort).

One of the simplest methods to collect body position information is to acquire the information directly through various means. For example, a *goniometer* is a hinged device that, when strapped to the side of a body joint, physically changes in angle along with changes in the joint angle. Goniometers can be wired with potentiometers that send voltage information (proportional to the joint angle); this can be accumulated and analyzed by a computer. Potentiometers are also used in many other direct measurement devices, such as a *computer mouse*, that signal changes in position when physically moved by the participant. A *graphics tablet* is another device that records the changes in contact positions with the surface.

Muybridge (see “Movement Photographs of Eadweard Muybridge”) is often credited with initiating the analysis of human movement through imaging techniques. High-speed cinematography introduced a way to capture images of moving limbs many times each second. However, frame-by-frame analysis methods were tedious ways of

examining changes in locations over time (Bernstein & Popova, 1930/2003). Fortunately, technology has introduced more automated ways of performing these analyses. Such instruments have relieved the scientist of the time-consuming job of reading locations from each frame of film, a method that also made the cost of such analysis systems prohibitive for many years. Computer systems that analyze such data are now more powerful and much cheaper, and the use of these measurement techniques is now the norm.

The most common imaging devices use *video* and *optoelectric* methods. Video methods were straightforward, as movements could be captured on relatively inexpensive videotape using VHS and 8 mm formats. Typically, the performer was recorded on videotape wearing pieces of tape or fluorescent “markers.” The locations of these markers were later digitized for analysis. For optoelectric methods, tiny light bulbs (called light-emitting diodes, or LEDs) are attached to the participant on various body parts. Light-sensing devices then detect and record automatically the locations of the LEDs during the movement. With advances in technology, newer systems have the capability to record information in three dimensions, providing greater information about movements and greater flexibility in the types of actions that can be studied in experiments.

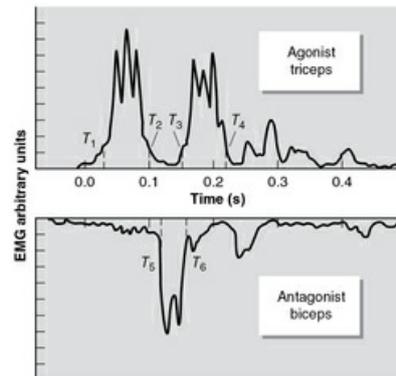
More recent advances in movement recording technology have combined the use of robotics and virtual reality environments. These systems not only record movement with fine precision but also have great flexibility to provide diverse perceptual inputs. For example, the robotic system can induce different types and magnitudes of haptic feedback (information about touch) during movement. When combined with virtual reality feedback information, these robotic systems can simulate the look and feel of complex skills (e.g., surgical techniques) without the dangers that might otherwise be present if practice were undertaken in the “real world” (e.g., on a patient).

### *Electromyography*

Another method for describing movement characteristics is to measure the involvement of a muscle in a movement by recording the electrical activity associated with its contraction. The simplest method is to attach (with adhesive collars) recording electrodes to the skin surface over the involved muscle; then, this weak signal from the muscle is amplified and recorded on a polygraph recorder or computer for later analysis. Occasionally subcutaneous electrodes are used; the electrode is placed just under the skin but above the muscle belly. Or a small wire electrode can be embedded *within* the muscle so that electrical activity in small portions of the muscle can be recorded.

A record of transformed EMG activity, taken during a rapid elbow extension (from Wadman et al., 1979), is depicted in [figure 2.13](#). A number of changes were made in the raw EMG signals before they were plotted. First, the EMGs were *rectified*; that is, the negative voltage values were given positive signs so that the resulting record would be completely positive. (Notice that [figure 2.13](#) has two such records, with the biceps record inverted so that the two patterns can be compared more easily.) When the EMG is rectified, the pattern of electrical activity can be seen more readily than if only the raw signals were examined. Second, these records were *averaged* for a number of similar movements, mainly so that the important patterns of contractions could be seen over and above the trial-to-trial variations. These patterns are more reliable than are those for a single trial.

Figure 2.13 Rectified and averaged electromyogram signals from the triceps and biceps muscles during a rapid elbow extension.



Reprinted from W.J. Wadman et al., 1979, "Control of fast goal-directed arm movements," *Journal of Human Movement Studies* 5: 10. By permission of W.J. Wadman.

Such records are useful in that they provide one kind of description of what the central nervous system "tells" the muscles to do. In the example shown, it appears that the triceps muscle contracted for about 100 ms; then it turned off and the biceps muscle contracted for about 50 ms; and then the triceps muscle came on again for another burst of about 100 ms. These records are even more helpful if they are superimposed on other records of kinematic information, so that the changes in the muscle actions can be associated with the resulting actions of the limbs.

### *Measures of Eye Movements*

Motor skills involving the use of the upper limbs constitute a large proportion of our daily activities. How we use our hands and fingers to press the buttons to make a phone call, pick up a cup from the table, or move a mouse-controlled pointer across a computer monitor depends considerably on our visual system. We use vision to determine where we want the hand to go and then to update the relative success of that movement as it approaches the target. Researchers have used eye movement recording systems in their investigations to determine where someone is looking (that is, where the eyes are directed), for example during an aiming movement of the hand or in making a left turn in an automobile. These recording systems can provide accurate measures of what the person sees, through two video imaging techniques. One camera mounted on the head or helmet of the performer provides an image of the person's line of vision. This visual gaze is then coordinated with an eye-tracking device that measures the movements of the eyes by means of corneal reflection. The calibration of the two recording devices provides an accurate measure of where the eye is directed during the performance of a motor task, sometimes referred to as point-of-gaze information. One caveat here is that what the person "sees" (i.e., perceives visually) is not perfectly related to where the eye is pointed. In some situations, even though the eye is directed at an object, the object is for various reasons not actually "seen." The mere fact that a person is looking at an object does not guarantee that he or she actually perceives it.

## Describing Expert–Novice Differences

Comparing performances in people with varying skill levels has become a growing area of individual-differences research (Ericsson, 1996; Starkes & Allard, 1993; Starkes & Ericsson, 2003). The fundamental question concerns the ways in which experts perform *differently* than novices. This expert–novice research is characterized by various methodological approaches, each contributing unique information about the ways in which distinctions can be made among people of varying levels of skill in certain activities (Abernethy, Burgess-Limerick, & Parks, 1994; Chamberlin & Coelho, 1993). Following is a summary of some of these approaches.

### *Recall of Briefly Presented Information*

Early work in cognitive psychology (Chase & Simon, 1973; deGroot, 1946/1978) revealed that master chess players had excellent recall of games they had played previously. To examine this apparent superior memory under controlled experimental conditions, expert and novice chess players were briefly shown chessboards of games that had been partially completed; they were then asked to recall the information by reconstructing the pieces' locations on the game board after the pieces had been removed from view. As expected, the experts were much better than the novices at this recall task. However, when the "game" that was shown was in actuality a series of randomly arranged chess pieces, the experts were no better at reconstructing the board than were the novices. The arrangement of the pieces in an actual game had meaning and relevance to the expert but not so for random patterns. The recall advantage was specific to the domain of the performer's expertise.

These important findings have been replicated in experts in other intellectual games, such as Scrabble (Tuffiash, Roring, & Ericsson, 2007), and in sports. For example, using a paradigm similar to the chess work, Abernethy, Neal, and Koning (1994) compared expert and novice snooker players' recall of ball positions during an actual match. Although the experts were better at the task than the novices for recall of a partially completed game, no differences were found when the balls were scattered randomly on the table. Similar patterns of findings, in which the recall advantage for experts is specific to the nature of the expertise, have been reported for many other sports (see reviews in Chamberlin & Coelho, 1993; Starkes, Helsen, & Jack, 2001; Williams, Davids, & Williams, 1999).

### *Occlusion Methods*

Two methods of studying expertise involve adapting the visual displays that the participant sees. Although this research paradigm began many years ago with the use of film and videotape (e.g., Jones & Miles, 1978), more recent opportunities afforded by digital displays have provided researchers with precise methods of preventing the participant from viewing certain parts of a display. *Spatial occlusion methods* involve masking certain relevant and irrelevant parts of a display, such as the various parts of the arm and racket of a badminton opponent (Abernethy & Russell, 1987). *Temporal occlusion methods* are used to stop a display at critical points during an action (e.g., Salmela & Fiorito, 1979). A frequent experimental approach compares experts and nonexperts under these occlusion methods to assess a key temporal marker or an important spatial location in the display that differentiates each participant's performance. The nature of the specific skills that define expertise for that sport underlies observed differences in performance (Williams & Ward, 2003).

Müller and colleagues (2006, 2010) provided a good example of this research. They recorded videos of cricket bowlers from the perspective of the batter. Edited videos were shown to groups of expert, intermediate, and novice players, who made predictions about where the ball would land under varying conditions. Temporal occlusion was manipulated by stopping the video at time markers during the bowler's delivery—either well before or shortly before ball delivery, at the point of release, or with no occlusion. Müller and colleagues found that only the experts could make use of the earliest time-occlusion information. Intermediate players showed some moderate success (relative to the novices) when the video was occluded at the point of ball release, but novices improved their accuracy only well after the ball had been released. Spatial occlusion involved editing out parts of the display during the ball delivery up to the temporal marker of ball release, at which point the entire video was stopped. The features that were spatially occluded included relevant parts on some trials (e.g., hand and ball; bowling arm) and irrelevant parts on other trials (e.g., nonbowling arm; lower body). The results revealed that a complex relationship existed for the pickup of advanced information; in impoverished viewing conditions, only the experts were able to predict with accuracy when relevant viewing data were available. The differences in performance between experts and nonexperts in occlusion experiments of this kind suggest that the acquisition of perceptual skills in sport is not a simple, quantitative change that occurs with practice. Rather, the acquisition of expertise requires the learning of specific perceptual cues to which information is acquired with increasingly earlier temporal landmarks.

## Measuring Brain Activity

The most dramatic advances in measurement in recent years have been the various methods of measuring brain

activity. Their use in describing the brain activity that underlies motor performance is still in development; and the promise of faster, more flexible, and more accurate advances in technique remains a technological challenge. Each of these techniques has advantages and disadvantages, although changes in methodology are occurring at a rapid pace and many of the current disadvantages may yet be overcome.

Electroencephalography (EEG), which has been around the longest, involves the recording of electrical changes that occur in the brain as recorded from the scalp, more or less as EMG measures electrical activity of a muscle via the skin adjacent to the muscle. Another type of encephalography is known as magnetoencephalography (MEG). As the name suggests, this technique measures changes in the magnetic fields involving brain activities. Both techniques have the advantage of working very quickly, providing precise measures of the timing of mental events. However, their capacity to allow inferences about localized anatomical structures is significantly less than that of other, albeit slower, methods (Haynes & Rees, 2006).

In contrast, methods such as (a) positron emission tomography (PET), (b) single-photon emission computed tomography (SPECT), and (c) functional magnetic resonance imaging (fMRI) are all neural imaging techniques that provide much more detailed information about the localization of brain structure and activity. The latter technique (fMRI) is based on the fact that when a specific part of the brain is active in the processing of information, neural activity increases and consequently oxygenated blood to that region of the brain increases. The fMRI records the “BOLD” (blood oxygen level dependent) signal as vectors of three-dimensional pixels (called “voxels”), allowing researchers to map the location and volume of brain regions that are actively processing information during task performance. While the spatial resolution of fMRI is poor, a high-resolution MRI structural scan is acquired first. Then the fMRI data are superimposed on the structural MRI image to obtain a functional activity map with high spatial resolution. Diffusion tensor imaging (DTI) techniques can be used to characterize the structural integrity and microstructural characteristics of key tracts and pathways, such as the corticospinal tract. This information is particularly useful when studying the relationships between brain and behavior in pathological conditions affecting the central nervous system or neuromuscular system. The use of new brain functional and structural recording techniques in motor control and learning experiments has increased dramatically in the past decade, although some challenges remain, such as temporal resolution and the nature of tasks that can be used with these devices.

Although not a brain activity “measurement” device, an approach to studying brain function that is frequently used today is called transcranial magnetic stimulation (TMS). The TMS method sends a brief pulse through a magnetic coil that has a temporary effect on the region of the brain above which the coil has been positioned. Depending on where the magnetic coil is positioned, the brief pulse can either excite or inhibit the activity of that brain area. In contrast to what happens in nonstimulated trials, the TMS-stimulated locations of the brain are assumed to be active if a change in task performance is observed (see Hallett, 2007, for an excellent primer on TMS). Recent investigations have combined TMS with fMRI so that the effects of stimulation on both behavioral and brain responses can be observed (Sack & Linden, 2003).

These neural imaging and stimulation techniques are useful in localizing the parts of the brain that are active during the performance and learning of many activities. Indeed, many motor behavior researchers are including these techniques as routine components of their investigations to provide neural substrate evidence that augments the motor behavior data obtained in their experiments. In addition to allowing researchers to localize putative brain regions for motor behavior, recent developments have allowed researchers to quantify networks of connected regions using signal-processing techniques. The three connectivity networks used to investigate communication within and across the brain are structural, functional, and effective (Bowyer, 2016). Well-established techniques from other fields, such as machine-learning methods, are beginning to show promise, advancing knowledge about relationships between the central nervous system and motor control and learning.



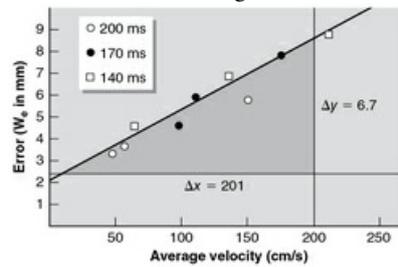
## Measuring and Evaluating Relationships

An important process for evaluating the outcomes of various experimental procedures begins after the main performance measures are generated from the experiment. This process involves determining the relationship between some independent variable and a dependent variable on the basis of the empirical data. One important kind of relationship is linear. In a graph, the dependent variable plots essentially as a straight line with the independent variable.

### Linear Relationships

In [figure 2.14](#) we have plotted data from an experiment by Schmidt and colleagues (1979), for which the error (measured as VE and called effective target width,  $W_e$ ) in hitting a target with a handheld stylus is plotted as a function of the average velocity of the movement. A quick examination of the plot in [figure 2.14](#) indicates that the relationship between these two variables is essentially linear. A line has been placed through the points that seems to represent their general direction, and this line is called the *line of best fit*. The actual placement can be done accurately by various statistical techniques (e.g., regression) or can be done “by eye” for a rough approximation.

Figure 2.14 Graphical method for determining constants for linear empirical equations.



Reprinted, by permission, from R.A. Schmidt et al., 1979, "Motor-output variability: A theory for the accuracy of rapid motor acts," *Psychological Review* 86: 427. Copyright 1979 American Psychological Association.

The goal in this section is to express this line of best fit in terms of what is known as an *empirical equation*, a kind of shorthand that enables us, with but two numbers, to convey information about a linear relationship for an empirically determined set of data points. These two numbers also will have special meaning in terms of various theories; that is, these numbers will be measures of certain hypothetical constructs. We begin with the general equation for a line:

$$Y = a + bX \quad (2.8)$$

In this equation,  $Y$  represents the values on the  $y$ -axis (error),  $X$  represents the values on the  $x$ -axis (average velocity), and  $a$  and  $b$  are constants (figure 2.14). The constant  $a$  is termed the  $y$ -intercept, and it refers to the value of  $Y$  when the line crosses the  $y$ -axis; here the value is about 2 mm. The constant  $b$  is called the *slope* and refers to the amount of inclination of the line. The slope can be *positive* (upward to the right, as in this example) or *negative* (downward to the right), associated with either positive or negative values of  $b$ , respectively. Once these values are specified from a given set of data, the empirical equation that describes the linear relation between values of  $X$  and  $Y$  can be written.

## Computation of Constants

Computation of the constants needed for the empirical equation is simple. After the line of best fit has been applied to the data points, extend it leftward until it crosses the  $y$ -axis and read off the  $y$ -intercept, or  $a$ . In the data shown in figure 2.14,  $a$  equals 2.08 mm.

Next, draw two lines, one perpendicular to the  $y$ -axis and one perpendicular to the  $x$ -axis, forming the shaded triangle as shown. The length of the line forming the base of the triangle will be called  $\Delta X$ , and the length of the line forming the side of the triangle will be called  $\Delta Y$ . The symbol  $\Delta$  means "change in"; measures of the changes in  $Y$  (6.7 mm) and the corresponding changes in  $X$  (201 cm/s) can be seen. Then, the slope of the line is defined as

$$b = \Delta Y / \Delta X \quad (2.9)$$

That is, the slope is defined as the change in  $Y$  divided by the corresponding change in  $X$ . Here, the slope ( $b$ ) is computed as  $6.7 / 201 = +0.033$ . The interpretation of this slope is that each time the value of  $X$  increases by 1 cm/s, there is a 0.033 mm increase in the  $Y$  value (error).

### Uses of Empirical Equations

The slope and intercept are the only two values needed to determine the linear relationship. Putting the slope and the intercept together into the general equation for a straight line results in the empirical equation for these data:

$$Y = 2.08 + 0.033X$$

Having been provided the calculated values of  $a$  and  $b$  found by a person in California, someone in Munich can

reconstruct the line of best fit by using the linear equation. This is done by picking any two arbitrary values of  $X$  (say, 50 and 250 cm/s) and calculating the values of  $Y$  for these values of  $X$ :

$$Y = 2.08 + 0.033 (50) = 3.73 \text{ mm}$$

$$Y = 2.08 + 0.033 (250) = 10.33 \text{ mm}$$

Then, on a new graph, these data points ( $X = 50, Y = 3.73$ ;  $X = 250, Y = 10.33$ ) can be plotted, and the line in [figure 2.14](#) drawn between them. Thus, saying that the intercept was 2.08 and the slope was 0.033 can convey a great deal of information about the experimental results to someone who does not have access to the nine actual data points.

In addition, this relation can be used to predict *new* values of error before they are found. If we wanted to choose a velocity value so that the error was only 5.00 mm, we could take the empirical equation and substitute the value of the error as follows, then solve for the value of the velocity:

$$5.00 = 2.08 + 0.033X$$

$$X = (2.08 - 5.00) / (-0.033)$$

$$X = 88.48 \text{ cm/s}$$

Thus, if we wanted the error to be about 5 mm, we would use a velocity of about 88 cm/s. Having an empirical equation makes it possible to predict this result without actually going into the laboratory to measure it directly.

### *Interpreting Empirical Equations*

In addition to the benefits provided by empirical equations in terms of description of experimental results and prediction of new findings, the values of the constants  $a$  and  $b$  often have special theoretical meaning, depending on the nature of the data collected and the kind of independent variable studied. In the present example, the meaning of the constant  $a$  (the intercept) is related to the amount of error for the slowest movement possible, and thus the intercept seems to represent a kind of “background” or “baseline” error. On the other hand, the value of the slope ( $b$ ) refers to the amount of *increase* in error as the velocity increases, and it represents a measure of the “difficulty” of the task. In this and other similar situations to be discussed later, the slope and intercept describe two distinct features of the task or the performer’s behavior.

## Correlation and Regression

A statistical tool that is used often in motor behavior research, and that has mathematical properties similar to those of the simple linear regression method, is the *correlation*. The correlation and regression methods are used to establish the degree of *association* between two measures, as seen in the study of individual differences, discussed earlier for expert versus novice differences. For a relatively large group of participants (e.g., 50), we begin with two different tests administered to each person. The degree to which the performances by individuals on one test are related to the performances of the same individuals on the other test is reflected in the size of the correlation coefficient. The correlation coefficient expresses the amount of shared association that exists between the two data sets, with no implications about whether or not one variable caused the other to change.

### *Scattergrams*

One of the ways in which data from two tests can be described is by a special kind of graph called a *scattergram*. Consider the data shown in [table 2.3](#), which have been plotted on the scattergram in [figure 2.15](#). The two axes in [figure 2.15](#) are the scales of the two tests, respectively; and each of the participants is represented as a dot, located according to his scores on the two tests. The data are hypothetical scores that might be obtained on a common

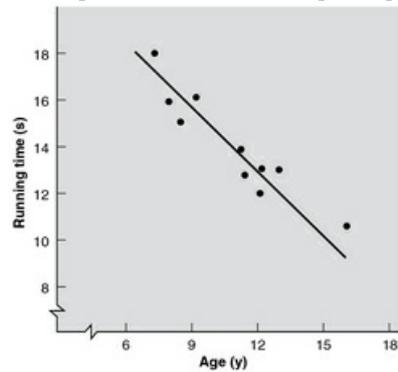
playground and consist of age (in years) and the time for a 100 m dash (in seconds). In [figure 2.15](#), the scores for these 10 people are plotted, so that each of the 10 dots on the graph represents each person's joint scores on the two variables (age and running time).

Table 2.3 Hypothetical Data for Age and 100 m Dash Performance

100 M DASH			
Participants	Age (years)	Time (s)	Average speed (km/h)
1	13.1	13.5	26.6
2	11.6	12.8	28.1
3	12.2	12.0	30.0
4	16.1	10.5	34.3
5	9.2	16.1	22.4
6	8.5	15.2	23.7
7	8.1	16.0	22.5
8	11.3	14.1	25.5
9	12.2	13.0	27.7
10	7.3	18.0	20.0

Note: Speed data were computed from the time data.

Figure 2.15 A scattergram showing the relationship between age and running time. (Data are from table 2.3, and each dot represents one of the 10 participants.)



A relationship apparently exists between the score on the age variable and the score on the running test, indicating that as the age score becomes larger, the number of seconds on the running test tends to become smaller, with some exceptions. In general, the 10 participants showed a relationship between these two variables, and a line could be drawn through the points to represent the “direction” in which the “cloud” of points is oriented. This “line of best fit” can be determined in exactly the same way as discussed earlier for empirical equations and often involves computing regression equations.

### Direction of the Relationship

In this example, as the value of the age variable increases, the value of the running time variable tends to decrease. This kind of relationship is called an inverse, or *negative*, relationship, and the equation representing this relationship has a negative slope constant ( $b$ ). In other situations, we might find that as one of the variables increases, the value of the other variable tends to increase as well; this is a direct, or *positive*, relationship. In such cases, the slope constant of the regression equation has a positive value, with the line of best fit sloping upward to the right.

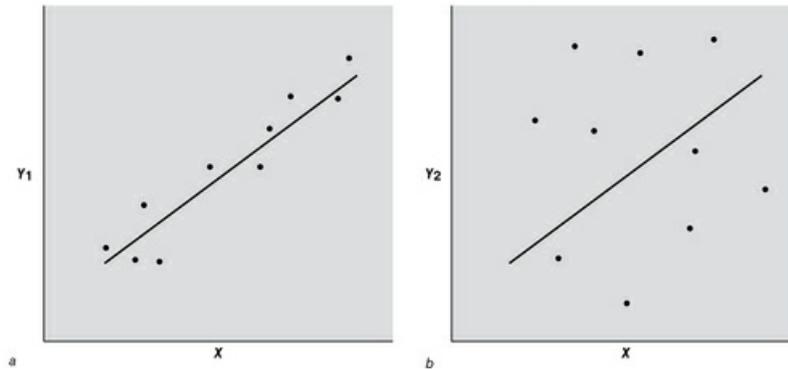
The direction of the relationship shown in such data is often dependent on the scoring system used. Consider the data in [table 2.3](#). In the fourth column we have expressed each participant’s 100 m dash scores as average running *speed* (km/h) rather than as the *time* required to travel 100 m. This change in scoring system “inverts” the group of scores, so that the person who had the largest time score has the smallest speed score, and so on. When the age data are plotted against the average running speed scores, the relationship becomes positive, and the empirical equation would now have a positive slope constant ( $b$ ) rather than a negative one. You can verify this for yourself by plotting the age data by the average speed data from [table 2.3](#). Thus, a positive relationship is not any “better” than a negative one; the sign simply indicates the direction in which the line of best fit is sloped.

### Strength of the Relationship

A second characteristic of the relationship between two variables is its *strength*. By strength, we mean the extent to which the relationship is perfectly linear, or the extent to which all of the performer’s points fall exactly on the line of best fit. [Figure 2.16](#) shows two scattergrams that represent relationships of different strengths. In [figure 2.16a](#), the relationship can be considered quite strong because nearly all the points fall close to the line of best fit. In [figure 2.16b](#), however, the relationship is not very strong, because the points tend to fall away from the line of best fit. These two aspects, direction and strength, are the primary descriptors used to characterize relationships. They are *independent*, in that a relationship can be either positive or negative *and* either strong or weak.



Figure 2.16 Hypothetical scattergrams for (a) a strong and (b) a weak relationship.



### Predicting From a Relationship

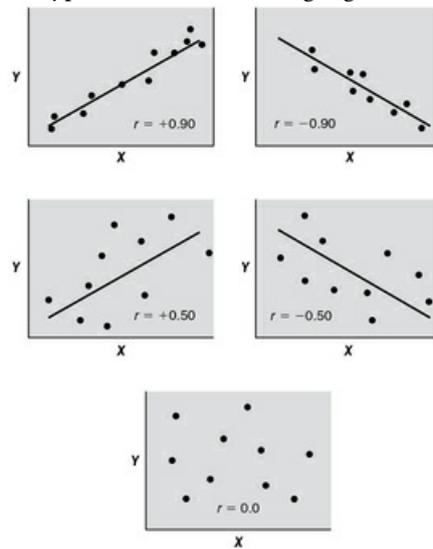
One of the most important reasons scientists want to know the nature of the relationship between two variables is for the purpose of *prediction*. For example, if we know that the relationship between age and running time has been found to be as described in [figure 2.15](#), then on a new group of children we can estimate (or predict) the 100 m time given the age of a person not in the original data set without actually measuring running speed, just as with the linear equations discussed earlier. Such procedures are used extensively in everyday situations, as in predicting the probability of having an automobile accident from one's age, or predicting success in graduate school from achievement test scores.

As the strength of the relationship increases, the predictability of one variable from the other increases as well. When the relationship is perfect and all the individual data points fall exactly on the line of best fit, perfect predictions with no error can be made. When the data are related less perfectly, as in the example shown in [figure 2.16b](#), then more error is introduced into the predictions. Thus, the strength of the relationship—but not the direction—is the primary determinant of the extent to which a relationship can be used to predict.

### *Correlation Coefficient*

These concepts of strength and direction of relationships can be quantified using a statistic called the *correlation coefficient*. The correlation, abbreviated  $r$ , ranges from +1.0 through zero to -1.0. The two important aspects of the correlation are the sign and its absolute size. The sign of the correlation indicates the direction of the relationship, exactly as described in the previous sections. The absolute size of the correlation indicates the strength of the relationship and hence is critical for evaluating the extent to which one can use the relationship to predict. [Figure 2.17](#) shows five hypothetical examples of correlations and the associated scatterplots. Both a +0.90 and a -0.90 correlation are strong relationships, as all the data points fall almost exactly on the lines, although the lines are sloped in opposite directions. Correlations of +0.50 and -0.50 are moderate in strength, and the points fall considerably away from the lines of best fit. A correlation of zero is weakest, indicating that no predictive capability is possible between these two variables. Formulas for the calculation of correlations can be found in most statistics textbooks (e.g., chapter 8 in Thomas, Nelson, & Silverman, 2012; chapter 8 in Vincent, 2012).

Figure 2.17 Scattergrams for hypothetical data showing high, moderate, and low relationships.



A convenient method for comparing the strength of relationships between tests is to square the correlation coefficient and multiply by 100 to convert it into a percentage score. Generally, the square of the correlation coefficient indicates the extent to which two tests can be considered to measure the same thing, and represents the percentage of *shared* variance (or, the percentage “in common”) between the two variables. This fits nicely with the earlier discussion of the strength and direction of relationships. The shared variance for two tests that correlate positively (+0.90) or two others that correlate negatively (-0.90) is the same (e.g.,  $+0.90^2 \times 100 = -0.90^2 \times 100 = 81\%$ ), indicating that the direction of the relationship (positive or negative) has no effect on the amount of shared variance.

The  $r^2$  value is useful for interpreting the strength of two relationships. For example, suppose two variables correlate with a value of  $r = 0.50$  and two other variables correlate with a value of  $r = 0.25$ . In this case, the  $r^2$  value of the first relationship ( $0.50^2 = 0.25$ ) indicates approximately four times more shared variance than for the second relationship ( $0.25^2 = 0.063$ ), or that the first two tests had approximately four times more in common than did the second pair.

### *Differential Methods*

The differential methods contrast starkly with the experimental methods just described; they rely substantially on correlational (also called associational) techniques whereby the *relationships* between variables are studied. In its simplest form, the differential approach uses one group of people and at least two tests measured on each person. Remember that the simplest “true” experiment often uses at least two groups of people and one test (dependent) variable. The primary concern is the extent to which one test (e.g., height) relates to another test (e.g., accuracy) in the same people; the nature of the relationship is determined by the size and sign of a statistic called the *correlation coefficient* (discussed earlier). With these correlational methods, the chief concern is the relationship between the two tests, or between several tests if more than two are used. Sometimes the relationship is computed between a group of tests (called a test battery) and some other single measure. An example is the relationship between a fitness battery (consisting of five subtests) and some other measure, such as probability of becoming a successful firefighter.

A second major method of individual-differences research uses essentially the same logic, but the appearance of the procedures may make it seem that the methods are experimental. Consider a study to determine the relationship between age and throwing accuracy. Typically the researcher chooses one group of people at one age and another group at another age and compares the group means on some dependent variable, such as throwing accuracy. It appears to be an experiment, because it includes two groups and one dependent variable and the focus is on the

group means. However it is not really experimental, because the level of the independent variable (*age*) is not *manipulated* by the experimenter; that is, the ages of the people in the group were already established when the participants were chosen. Such a procedure is a study of the *relationship* between age and throwing accuracy. Such variables (*age*, in this example) are usually called *individual-difference* variables. Thus, studying which individual-difference variables are related to certain kinds of performances is a primary concern of the differential approach. Indeed, people have written textbooks solely about individual-difference variables, such as life span motor development (e.g., Haywood & Getchell, 2009; Piek, 2006), aging (e.g., Spirduso, Francis, & MacRae, 2005), individuals with various movement disorders (e.g., Weeks, Chua, & Elliott, 2000), and expert–novice differences in sport skill (Farrow, Baker, & MacMahon, 2008; Starkes & Ericsson, 2003).

With the differential approach, conclusions about the results tend to be phrased in language quite unlike that with the experimental approach. In experiments, one might conclude that the independent variable *caused* changes in the dependent variable (because other variables were held constant or, controlled). In differential studies, however, causation can seldom be inferred logically. The major reason is that many other things may differ or they intervene in the causal nature of the relationship. For example, consider the relationship between children’s height and their throwing accuracy. Weight is usually associated with height, so one cannot be certain that a relationship between height and accuracy is really not an indication of the relation between weight and accuracy. Also, taller children are usually older, and one could easily confuse the height–accuracy dependency with an age–accuracy dependency. The primary limitation in these studies is that the level of the variable of concern is not *manipulated* (artificially determined by the experimenter). Rather, the variable is allowed to vary naturally, and the scientist measures its value and attempts to understand how it relates to some other variable that is also varying naturally. Such procedures are often called *natural experiments*.

People can differ from each other in at least two fundamental ways. First, two people might be consistently different from each other in some stable characteristic, such as height. Such differences will be enduring and constant across both time and testing conditions. But they might also be different in other ways. For example, if on only a single trial one person makes a successful pool shot and another does not, we might not be willing to say with certainty that the two people are different in pool-shooting capability; on the next shot the performance success may be opposite. Finding differences between two people on some measure of performance does not necessarily indicate that these differences are *reliable*. The stable, enduring differences are the subject of individual-differences research. In fact, the definition of individual differences is “*the stable, enduring, and underlying differences among people*” (Henry, 1959; Schmidt, 1975a). It is critical that measures used in the study of individual differences be reliable, and various methods to assess reliability have been devised.

## Reliability and Individual Differences

The reliability coefficient provides a way to evaluate the extent to which observed differences between people on some tests are because of individual differences (i.e., stable, enduring differences) or to chance or transitory effects. Reliability is really another use of the correlation, but in this instance the concern is with the correlation of a test “with itself.” For example, assume that five participants each perform six trials on a reaction-time task. These six scores for each person are divided to form two scores (“halves”) for each person according to one of a number of different methods. One common method is called the *odd-even method*, the sum of the odd-numbered trials is computed as one of the scores for each person, and the sum of the even-numbered trials is taken as a second, separate score for each person. The extent to which the odd and even sums for each person tend to deviate from each other is one measure of the random variations in the individual trial data. Indeed, if there were no random variation at all, the sum of the odds and evens would be exactly the same for a given participant. Next, the across-participants correlation is computed between the odd and even scores; this correlation is typically called the *reliability coefficient*. Theoretically, reliability can take on any value between +1.0 and -1.0. However, in practical situations, reliability is seldom negative and usually ranges from 0 to +1.0.

One way to interpret reliability is to multiply it by 100 to express it as a percentage. The observed variation among people is made up of (a) differences between people in their stable, enduring traits (termed *individual differences*) and (b) random (or other) fluctuations that tend to make people only *appear* to be different. If so, reliability is the percentage of the observed variability due to individual differences. With low reliability of, say, 0.20, only 20% of the observed variation is due to individual differences; about 80% is due to random and other variations.

A primary concern of individual-differences research is the correlation between pairs of tests. Statistically, the size of the correlation between two tests is limited by the reliability of either (or both) of the tests being correlated,<sup>1</sup> so one must be certain that the reliability of each of the tests being correlated is reasonably high. Reliability also represents a measure of the stability of the test under different applications. As the number of trials administered to each participant increases, the performances become more stable and reliability increases. The number of trials that make up a test is a strong determinant of reliability; indeed, if the number of trials is increased enough, the reliability can actually be brought to 1.0 (e.g., Gullicksen, 1950). As easy as this is to do (usually), there is seldom a good excuse for a test with low reliability.

## Summary

Motor behavior can be classified according to several dimensions, such as (a) *continuous/serial/discrete*, referring to the extent to which the movement has a definite beginning and end, and (b) *open/closed*, referring to the extent to which the environment is predictable. Most of the tasks used in motor control work fall into one or the other of these basic categories. In measuring movement, experimenters devote attention to a measure's *objectivity* (the extent to which two independent observers achieve the same score), its *sensitivity* to changes in skill, its *reliability* (the extent to which the score is repeatable), and its *validity* (the extent to which the test measures what the experimenter intends it to measure).

The outcome of movements in terms of the environmental goal can be measured in essentially four ways: in terms of errors, speed or time (or both), or magnitude, or with various secondary tasks. There are many ways to measure errors in movement; chief among these are *constant error* (CE, a measure of average error or bias), *variable error* (VE, a measure of inconsistency), *total variability* (E, a measure of overall error), and *absolute error* (AE, also a measure of overall error). Each error measure has a different meaning and is used in different aspects of the measurement process. Measures of speed are used when accuracy is less important (or is controlled) and when rapid actions are critical. Measures of magnitude are used when the *amount* of behavior is critical. A fourth but related measure is based on the analysis of simultaneous secondary tasks, providing a measure of the spare capacity of the performer after he or she has devoted attention to a primary task.

Movements can be measured in many ways, but common methods involve the calculation of kinematic variables (position, velocity, acceleration) and the recording of the electrical activity from muscles (EMG). Methods used to assess kinematics have changed dramatically with digital technology, and precise measures of sensory–motor control are now the norm. Studies of brain activity are also becoming increasingly popular, and their use in motor behavior research continues to grow. *Linear empirical equations* provide a description of a linear relationship between two variables. The parameters of the equation can be easily estimated, and they provide a means by which the relationship can be used to predict facts that are yet unknown. The parameters can also be useful in describing the direction and strength of the relationship between two variables as indicated by the correlation coefficient.

Differential methods contrast with experimental methods most notably in what each tells us about relationships between variables. In experiments a cause-and-effect relationship can be determined, in that the independent variable (artificially determined by the experimenter) caused changes in the dependent variable. In differential studies, however, causation can seldom be inferred logically. The primary limitation is that the level of the variable of interest that is not manipulated by the experimenter. Instead the variable is allowed to vary naturally. Differential methods are best used in these kinds of natural experiments.

### Student Assignments

1. Answer the following questions and bring the information to class for discussion:
  - a. Compile a new list of examples from activities of everyday life that fit each of the following task categories: discrete/open, discrete/closed, serial/open, serial/closed, continuous/open, and continuous/closed.
  - b. Close your eyes and draw 10 lines as close as possible to 10 cm in length. Do not open your eyes until you are finished. Calculate the following error measures: CE, |CE|, VE, E, and AE.
  - c. Discuss the relative importance of reaction time in the following Olympic events: 100 m run, 10,000 m run, 100 m butterfly swim, and 400 m relay.
2. Find a research article published in the past five years that uses functional magnetic resonance imaging (fMRI) or transcranial magnetic stimulation (TMS) to better explain basic motor control processes.

### Notes

<sup>1</sup> A quantitative analysis of error scores in two dimensions is provided by Hancock, Butler, and Fischman (1995)

but is beyond the scope of the present discussion.

## Chapter 3

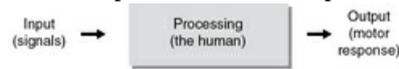
# Human Information Processing

Imagine you are a baseball player standing in the batter's box. A baseball is coming at you at 90 mph, and you have to organize a swing to contact the ball and propel it away from the fielders. The information you need in order to accurately hit the ball resides in the ball; that information is visual. However, the action of swinging the bat requires motor information, namely, the exquisitely controlled contractions of your muscles. Thus, you take in visual information and transform it into motor information; you process the information. The term *human information processing* is based on a computer metaphor. According to this metaphor, we “take in” information from outside sources, just as a computer takes in information via input devices. That information undergoes transformations, uses other information stored in memory, and is subject to certain limitations based on the amount processed and the speed of processing that is available; again, this is similar to how a computer processes information. And lastly, the process by which information is “output” has many analogies to the computer—the processed information can result in various kinds of movement, just as a computer displays the results of its processing on a monitor or sends it elsewhere as an output. Our goal in this chapter is to discuss information processing as it relates to human motor behavior (see also Marteniuk, 1976)—specifically how information is processed for the specific purpose of producing skilled movement. Although the tenets of information processing are well accepted by many scientists, a strong and growing position states that these assumptions are not correct. Chapter 8 on motor coordination outlines this alternative view (see Kelso, 1995; Turvey 1990, for these accounts), which denies the usefulness of the computer metaphor. With this caveat in mind, following is a description of classical information processing.

## Information-Processing Model

The model begins with the input of information from the environment through one or more of the sense organs, and then considers what happens to this information once it is inside the system. A typical “black box” model of the process is shown in [figure 3.1](#). The individual’s brain is considered to be the box, and information enters the box from the environment. This information is then processed in various ways, eventually resulting in output as observable motor activity. This *black box model* prevailed in the stimulus–response (S-R) tradition (see chapter 1), in which researchers were primarily concerned with the relationship between what went into the box (the information, or stimuli) and the output from the box (the response). With the emergence of *cognitive psychology*, however, interest began to focus on the processes that occur *within* the box. Obviously, this is an abstract way to study human behavior because it concerns processes and events that are not directly observable. Knowledge about these processes is inferred from the overt behavior of the human under various experimental conditions. Events occurring inside the box can be studied in a variety of ways through use of the cognitive–psychological perspective.

Figure 3.1 The simplified information-processing model.



The most common approach to the study of information processing is to consider the durations of these various processes. This *chronometric approach* (see Posner, 1978 and Sternberg, 1969) makes considerable use of the reaction-time (RT) measure, defined as the interval between the presentation of a stimulus and the beginning of the response (see chapter 2). Many different information-processing activities occur during RT; but if the experiment is designed properly, so that the durations of most other processes are held constant, one can usually infer that an increase in RT resulting from some experimental variable was caused by the lengthening of the duration of a *particular* process. This chapter presents many examples of this type of research and thinking, and the chronometric approach to studying information processing constitutes a large portion of it. Later in the chapter we consider other aspects of information processing that are not necessarily studied using the chronometric approach but are particularly important in the performance of motor skills.

## Three Stages of Information Processing

Although the notion of separate stages or processes between a stimulus and a response has been popularized by the cognitive–psychological viewpoint, the general concept of stages of processing is quite old, dating back to the research of Donders (1868/1969; see “Donders’ Subtractive Method”). This thinking, coupled with efforts from cognitive psychology (e.g., Kellogg, 2003; Sanders, 1980; Schweickert, 1993; Sternberg, 1969), has led to the view that various processing stages can be defined and that these stages can be organized in a *serial* (sequential) or *parallel* (overlapping in time) structure.

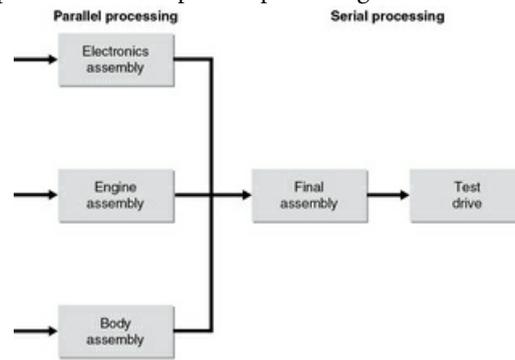
Donders argued that with use of these methods, the durations of the stages of processing involved in stimulus discrimination and response selection, which are not directly observable, could be estimated in the laboratory. It is remarkable that these insights were developed in 1868, long predating the cognitive revolution in experimental psychology that made use of these and similar concepts.

Donders’ general methods and assumptions would later be revived in a classic paper by Saul Sternberg (1969) that generated considerable interest and further research, some of which was involved in understanding motor behavior (e.g., Sanders, 1980). Later thinking and research identified a number of flaws in Donders’ subtractive method (see Massaro, 1989, for an analysis of Donders’ and Sternberg’s logic and methods). But even so, Donders’ basic idea that we could examine the changes in the duration of stages by subtracting RT in various conditions was remarkable, given the time of his work, and served as the foundation for more modern analyses of human information processing.<sup>1</sup>

### Nature of Serial and Parallel Processing

Imagine an automotive plant as a model of information processing, as in [figure 3.2](#). Some stages occur in parallel in different places, such as the fabrication of the electronics, the assembly of the engine, and the assembly of the chassis. But at various times during the overall process, these components are combined to complete the final assembly stage. After final assembly, imagine a test-drive stage, in which the drivers search for problems before the car is sent to the dealers, as yet another stage. This simple analogy contains an example of both parallel processing (overlapping in time the assembly of the electronics, engine, and body stages), and serial processing (nonoverlapping stages of final assembly and test drive). Thus, this system has both serial and parallel processing but at different times in the total sequence. Another useful analogy for understanding serial and parallel processing is the preparation of a meal. Many aspects occur in parallel (e.g., you can boil noodles in water while sautéing vegetables for a sauce), but other aspects have to start only after other processes have been completed (e.g., you must chop the vegetables before sautéing them). In human behavior, many have thought that the total RT has various stages, some of which can be performed in parallel and some of which are performed serially.

Figure 3.2 Examples of serial and parallel processing in an automobile assembly plant.



## Donders' Subtractive Method

Over a century ago, the Dutch physician F.C. Donders (1868/1969) made the first attempts to measure the time required to complete certain thought processes. Donders' *subtractive method* assumed the existence of a series of separate, nonoverlapping information-processing stages between a stimulus and a response. The notion was that the processing that occurs in stage 1 is separate and distinct from the processing that occurs in stage 2, and that stage 2 processing cannot begin until stage 1 processing is completed. Donders studied this idea using three RT methods that differed in systematic ways.

In the simplest method, termed the *a*-reaction task, the participant was presented with a single, unanticipated stimulus that required a single response (e.g., pressing a key using the right hand in response to the illumination of a red light). This reaction task is now commonly referred to as a *simple-RT* task. In a more complicated task, termed the *c*-reaction task, a participant was presented with two different light stimuli and asked to respond by pressing a key with the right hand if a specific stimulus was illuminated. For example, if the two stimuli were red and blue, then the task might be to respond if the red stimulus was illuminated but *not* to respond to the blue stimulus. This reaction task is today called a *go/no-go* task because the participant is to respond if the specific stimulus is illuminated ("go") but not if the nonspecified stimulus is illuminated ("no-go"). In the third task, called the *b*-reaction task, the participant was again presented with more than one stimulus and asked to make a response that depended on which particular stimulus was presented. For example, a red light might require a key press with a finger on the right hand whereas a blue light would require a left-hand response. This reaction task is known today as a *choice-RT* task.

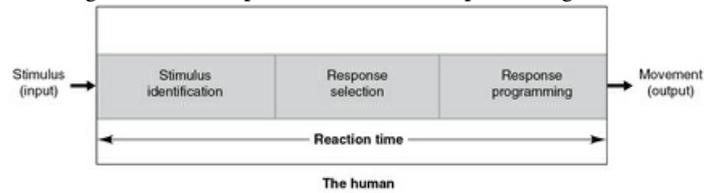
The logic of Donders' subtractive method was that the three tasks differed in the number of stages involved. All three tasks require stimulus detection (e.g., noting that a stimulus light has appeared). In addition, however, the *b*-reaction involves the processes of discriminating the stimulus that was detected from the possible alternatives that could have appeared, as well as the selection of a specific response. The *c*-reaction, however, requires only discrimination of the stimulus, and no response selection (because the specific response is always the same in the *c*-reaction). Thus, the difference in RT between a *c*-reaction and a *b*-reaction reflects the time to perform response selection. In a similar way, the *c*-reaction involves stimulus discrimination whereas the *a*-reaction does not; only one stimulus is presented in the *a*-reaction, and both of these tasks involve only one response (i.e., no response selection is needed for either). Therefore, the difference in RT between the *a*-reaction and the *c*-reaction should reflect the time for stimulus discrimination. This can perhaps be seen more clearly in [table 3.1](#), which presents an example using these ideas.



Table 3.1 Work Table for Computing Various Stages of Processing					
Donders' description	Common term	Number of stimulus choices	Number of response choices	Stages of processing	Hypothetical reaction time (RT)
<i>a</i>	Simple RT	1	1	Stimulus detection, response execution	200 ms
<i>b</i>	Choice RT	2	2	Stimulus detection, stimulus identification, response selection, response execution	285 ms
<i>c</i>	Go/no-go RT	2	1	Stimulus detection, stimulus identification, response execution	230 ms
Processing stage	Subtraction	Example			
Stimulus identification	$c - a$	$230 - 200 = 30$ ms			
Response selection	$b - c$	$285 - 230 = 55$ ms			

At least three stages can be proposed that intervene between the presentation of a stimulus and the production of a response (see [figure 3.3](#)). First, the individual must detect that a stimulus has occurred and identify it. This stage is frequently called *stimulus-identification*. Second, after a stimulus has been properly identified, the individual must decide *which* response to make. The decision can be to do one of a number of possible actions, or the stimulus can be ignored in favor of no action at all. This stage is usually called *response-selection*. Finally, after the response has been selected, the system must be prepared for the appropriate action and then initiate that action. This stage is called *response-programming* or *response-execution* to represent the preparations of the motor apparatus and the initiation of the action. More detailed discussion of these stages is presented in the remainder of the chapter.

Figure 3.3 An expanded information-processing model.



“Information Processing and Traffic Intersections” presents an example of the potential information-processing activities involved in the decisions needed to respond to a yellow (caution) light at an intersection. Although many of the experimental methods and research issues discussed in this chapter may seem quite removed from this example, it is probable that the processing of information in lab tasks and many examples of everyday life involves similar activities.

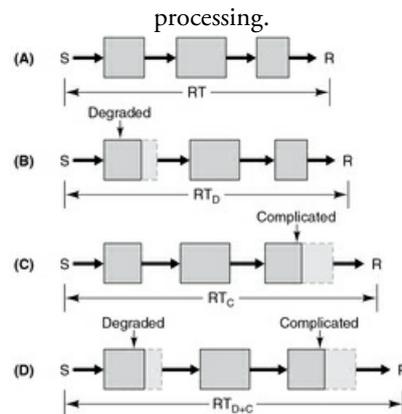
### Sternberg’s Additive Factors Method

In 1969 Saul Sternberg, an experimental psychologist working at AT&T Bell Laboratories, developed a method to ascertain how mental processes are organized in time. He observed which processes are organized in a serial fashion (sequential) and which processes overlap in time (parallel; Sternberg, 1969). Sternberg’s insight was that a mental process called a *stage* could have its duration manipulated.

Sternberg assumed that RT was equal to the sum of the durations of all of the nonoverlapping stages. He also assumed that the work product of a stage (called *output*) was unaffected by the duration of the process. To understand his idea, imagine that three stages exist. If one increases the duration of a stage, for example by making the stimulus quality degraded (compared to a vivid image), RT will be greater in the degraded condition. Now suppose that one increases the duration of response execution by requiring one movement to be simple (e.g., simple finger key release) and the other task to be more complicated (e.g., two sequential taps). RT is longer in the complicated task compared to simple because the duration of the response execution stage increases.

What happens when the complicated movement is to be executed *and* the stimulus is degraded? The duration of stimulus identification increases, and the duration of response execution increases. Because these stages are sequential (assumed) the total increase in RT is equal to the sum of the individual effects of stimulus degradation and response complexity. Thus, these factors are called *additive*. Figure 3.4 shows additive factors in three stages—stimulus identification, response selection, and response execution. When the stimulus is degraded (case B) the dotted line represents the increase in the duration of the stimulus identification stage. Likewise in case C, you can see the hypothetical increase in response execution for the complicated response. In case D, both stimulus identification and response execution are increased in duration, thus RT is increased by their sum compared to case A when the stimulus is not degraded and the response is not complicated.

Figure 3.4 Depiction of an additive factors approach for discovering sequential stages of information



Sternberg was not as clear about why, if two factors affect a common stage, the sum of the individual effects is greater than their effects individually (termed *over-additive*). One way to conceptualize this effect is to posit that the efficiency of a stage is affected by the demands placed on that mental operation, and the combined effect on a stage becomes greater than the individual effects when effecting a common stage, presumably because the efficiency and duration relation is not linear.

Although the Sternberg additive factors approach, coupled with a cognitive science revolution (Posner, 1978) is not without problems (Schweickert, 1979; Townsend, 1976), the conceptualizations of human performance as a set of nonoverlapping mental processes has served both the scientific and the applied community well. This framework will be the major scaffolding on which to hang various theoretical concepts concerning human motor learning and control.

## Stimulus-Identification Stage

Think of the stimulus-identification stage as beginning with the presentation (or onset) of an environmental stimulus that must be detected; this stimulus information must then be recognized as a part of an identifiable pattern. These two substages are considered in the following sections.

### *Stimulus Detection*

The occurrence of an environmental stimulus (e.g., light entering the retina of the eye or sound entering the ear) results in neurological impulses that are received by the brain. The stimulus is presumably processed further at different levels of analysis until it *contacts memory*, meaning that some memorized aspect of the stimulus is aroused, such as its name or an attribute with which it has been associated in the past (e.g., its red color, as with a stop sign). Considerable processing must occur in order for the stimulus to arouse the proper association in memory (rather than an improper associate or all possible associates). Scientists working in this area have assumed that the *variables* affecting the stimulus-identification stage relate specifically to the nature of the stimulus. For example, an experimental variable called *stimulus clarity*, which refers to the extent to which the visual stimulus is well defined and “sharp” (vs. out of focus) has been used. With increased clarity, the overall RT is shorter, and this change is attributed to the increased processing speed in the stimulus-identification stage. A variable called *stimulus intensity* (e.g., the brightness of a light stimulus or the loudness of a sound stimulus) is also assumed to affect information-processing time in this stage. Early research that has been replicated many times also revealed that RT is greatly affected by the *modality* of the stimulus—the latency in responding to a visual stimulus is somewhat slower than the time to respond to an auditory or a tactile stimulus. Further, stimuli presented simultaneously in more than one modality (e.g., combined visual + auditory stimuli) will shorten RT relative to either modality

presented alone; this is called intersensory facilitation (Nickerson, 1973; Schmidt, Gielen, & van den Heuvel, 1984). An excellent summary of the effects of the properties of the stimulus on RT has been provided by Woodworth and Schlosberg (1954).

### *Pattern Recognition*

In more realistic tasks, the stimuli that enter information processing are seldom as simple as they are in lab RT tasks, and we must usually extract a pattern or feature from the stimuli presented. Often these patterns have to do with such things as the shape of a face—or in sport, with where a baseball is going, how fast it is traveling, and what kind of spin has been put on it. Some of these pattern detections are genetically defined (e.g., related to survival). Others may depend heavily on learning, such as recognizing a developing play in volleyball.

Important studies of chess players demonstrate the influence of learning on pattern detection (deGroot, 1946/1978; Chase & Simon, 1973). In one such study, deGroot required chess masters and good-to-average chess players to reconstruct the locations of the chess pieces in a half-finished game after viewing the board for 5 s. As one might imagine, the chess masters were far superior to the good-to-average players. It could be argued that the superiority of the chess masters in this task was not necessarily evidence that they had learned to remember chess patterns, but rather that they were just superior, generally, in their inherent perceptual abilities. This last hypothesis is doubtful, however, as a later experiment by Chase and Simon (1973) included an important condition in which the chess pieces were placed on the board in random fashion. With this random arrangement, the chess masters and the average players were about equal in their ability to reposition the pieces (see also Vicente & Wang, 1998). One interpretation is that the processes involved in the stimulus-identification stage were improved in the masters through years of experience in *game* situations and that considerably more information could be accumulated in a single view of the board, but only as long as that information conformed to the normal patterns of chess play.

## Information Processing and Traffic Intersections

An activity that drivers face often while navigating city traffic concerns how to respond when an intersection signal changes color from green to yellow. Experiments in human information processing mirror this example in many ways. The traffic signal represents one of many sources of environmental information to which a driver must attend. A change in the traffic signal from green to yellow is a sensory event that the driver must identify and respond to with a decision. In the simplest case, the response to be selected involves making one of two choices—either to continue on through the intersection or to stop before entering the intersection. In making that decision, the driver quickly must process how fast his or her car is traveling relative to the distance to be covered (Senders, 1998). In addition to this environmentally available information, the driver must also access information in memory. Recently acquired information might include the proximity of the car behind. More remotely acquired information might include information learned about this particular traffic intersection (such as the width of the intersection and the duration of the yellow phase of the traffic signal) and the quality of the brakes of the car being driven. If the decision is to carry on through the intersection, then a typical driver response is to continue at the same speed or even to accelerate. If the decision is to stop, then the driver must remove the foot from the accelerator and apply it to the brake. In both of these selected responses (accelerate or apply the brake), an action is required that must be generated in the brain and sent to the appropriate musculature for implementation (see Green, 2000, for further discussion).

All of these information-processing activities—identifying that the signal has changed color, selecting which response is appropriate, and programming the response to be made—take *time*, during which the car continues to approach the intersection. It is quite understandable, therefore, why a great deal of

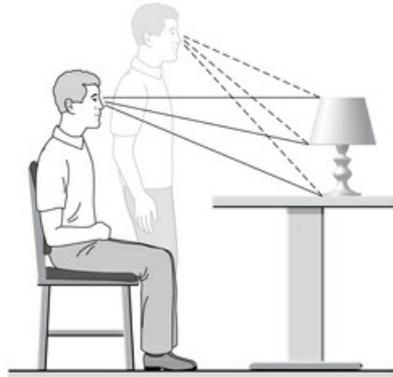
research activity has dealt with the temporal components of information processing, an approach some have referred to as the chronometric approach (Posner, 1978).

Two other factors involved in this traffic example are also important components of information-processing activities and are discussed in this chapter. One of these entails *anticipation*, the use of information to prepare a response in advance of the critical stimulus. For example, a driver who saw the traffic light turn green just a short time ago may anticipate that a yellow light will not occur before he or she enters the intersection, especially when this information is combined with prior information in memory that the green phase of the light is fairly long. The other factor relates to the potential results if the driver makes an incorrect decision in response to the light (going ahead when a stop was the appropriate response; or stopping when proceeding through the intersection was the correct response). Making the decision to go and making the decision to stop both carry two possible outcomes, one correct and one incorrect. The ability to process information in a way that optimizes the outcome of this decision is the domain of research called *signal-detection* (or *decision*) *theory* (*SDT*). All of these various issues (processing stages, memory, anticipation, and decision theory) represent features that influence indirectly how we control movement.

Analysis of such static situations seems important to many activities; but even more important from the point of view of motor behavior involves extracting patterns of movement from the environment. In many situations, how the environment changes from moment to moment will determine which movement (an action) is most appropriate.

A great deal of environmental movement information is represented as changes in the visual field, and it seems clear that an individual can use this information to provide an unequivocal analysis of movements in an environment or of the environment's movements. Gibson (1966), for example, referred to "optical-flow patterns," which are the patterns made up of the rays of light that strike the eye from every visible part of the environment ([figure 3.5](#)). As the individual or the environment moves, the angles of these rays change predictably to allow the participant to extract a pattern of movement from the changing visual array. For example, you *know* that a ball is coming directly toward your eye if the rates of change of the angles of the rays of light from all edges of the ball are the same. This *looming* can elicit strong avoidance reactions even in children and young animals who have presumably never been hit in the eye, suggesting that at least some kinds of pattern recognitions may be genetically defined. We will discuss these various aspects of visual information processing in more detail in chapter 5.

Figure 3.5 Optical arrays vary as the location of the observer changes in the environment.



These interpretations are important for many fast-action sports and games. Patterns of opponent position or action arouse meaningful responses that lead to fast action in highly skilled players, while they may go nearly unnoticed by novices. For example, certain patterns of linemen and backfield movement in American football mean the difference between a running and a passing play, and an effective response to this action by the defensive player often depends on recognizing such a pattern quickly and accurately (for reviews see Ericsson, 1996; Starkes & Allard, 1993; Starkes & Ericsson, 2003; Williams, Ward, & Smeeton, 2004).

## Response-Selection Stage

As a product of the stimulus-identification stage, the information in the stimulus input has been analyzed, and the individual now has a basis for “knowing” what happened in the environment. In the next stage, response selection, the participant decides what response to make. A baseball outfielder must make rapid decisions about whether to attempt to field a batted ball either before or after it bounces, what direction to move in order to catch it, and what to do with the ball if it is fielded successfully. Such decisions are important and apply to a wide variety of activities in sport, industry, driving, and so on.

### *Number of Stimulus–Response Alternatives*

For over a century and a half, scientists have believed that the processing of information relevant to the selection of a response requires more time when the number of *possible* alternative responses is *greater*. The idea is that if increasing the number of response alternatives causes an increase in the choice RT, then the increased RT is associated with changes in the way the information was processed in the response-selection stage.

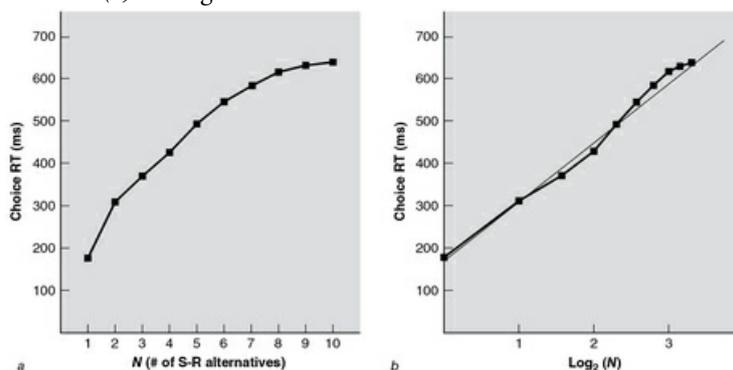
In the choice-RT paradigm, the participant is presented, for example, with four stimulus lights and instructed that one of the four will be illuminated randomly on a particular trial. Each of the four lights is associated (via instructions from the experimenter) with one of four different responses (e.g., the four stimulus lights are assigned, or “mapped,” to buttons located under the four fingers of the right hand). The task is to press the appropriate button as quickly as possible after one of the stimulus lights is illuminated. Usually participants are not able to predict exactly when the stimulus will occur and are thus prevented from initiating the response in advance. The time interval from stimulus onset to response initiation represents the speed of information processing responsible for the selecting the appropriate finger.

Merkel conducted one of the earliest studies addressing this question in 1885 (described by Woodworth, 1938). The digits 1 through 5 were mapped to the fingers of the right hand, and the Roman numerals I through V were mapped to the fingers of the left hand. In one set of trials, Merkel used all 10 possible stimulus–response S-R pairings, so there were 10 possible stimuli for these trials. On other sets of trials the participant knew which, from the set of 10 stimuli, would be possible (e.g., if there were three possible stimuli, they might be 3, 5, and V), yet only one of these stimuli was actually presented. (On this set of trials, only 3, 5, and V would be presented, and none of the other stimuli would be involved.) Other sets of trials might involve 1, 3, 5, and VI (four possible

stimuli) or 2, 4, VII, VIII, and X (five possible stimuli). Note that, on any given trial, only one of the set of possible stimuli would occur. Merkel studied the relationship between the number of possible S-R pairs (ranging from 1 to 10) and the choice RT.

His basic findings are presented in the left side of [figure 3.6](#), which plots the choice RT against the number of S-R alternatives (or  $N$ ). As the number of alternatives increased, so did the choice RT taken to respond to any one of them. This relationship was *curvilinear*, as is clearly illustrated in the data on the left side of [figure 3.6](#). Note, for example, that as the number of alternatives was increased from 1 to 2, the increase in choice RT was about 130 ms, whereas when the number of alternatives was increased from 9 to 10, the increase in choice RT was less than 5 ms. Even though there was an increase by one in the number of alternatives in both cases (i.e., 1-2 vs. 9-10 alternatives), the effects on choice RT were very different.

Figure 3.6 (a) Choice reaction time (RT) as a function of the number of stimulus–response (S-R) alternatives and (b) the logarithm of the number of S-R alternatives.



Data from Merkel 1885.

This relationship between number of alternatives and choice RT has been studied a great deal since Merkel made his original observations. The overall conclusion has not changed, although there have been some refinements in technique and much additional theorizing about the causes of the relationship. The most widely known findings and explanations of the effect were apparently produced by two people at about the same time—Hick (1952) and Hyman (1953). The relation they discovered between the number of S-R alternatives and RT has since been termed Hick’s law, or sometimes the Hick-Hyman law (Keele, 1986; Proctor & Dutta, 1995).

### Hick’s Law

Hick (1952) and Hyman (1953) studied the relationship between choice RT and the number of S-R alternatives in much the same way Merkel had, using various numbers of lights that were associated with an equal number of keys to be pressed when the appropriate light appeared. As Merkel had found, choice RT increased as the number of possible S-R alternatives increased. The RT values, as well as the overall shape of the function, were consistent with Merkel’s findings in [figure 3.6](#). However, what Hick and Hyman discovered was that choice RT appeared to increase by a nearly constant amount (about 150 ms) every time the number of S-R alternatives *doubled*. This suggested that the relationship between choice RT and the *logarithm* of the number of S-R alternatives should be linear.

The logarithm (base two) of the number of S-R alternatives is a measure of the amount of *information* that had to be processed, suggesting that more alternatives required more information processing. In the right side of [figure 3.6](#) we have replotted Merkel’s data as a function of the logarithm of the number of alternatives, and we see that these data demonstrate a linear fit too. The formal relation that has come to be known as *Hick’s law* states that choice RT is linearly related to the logarithm to the base 2 ( $\text{Log}_2$ ) of the number of S-R alternatives. In equation form,

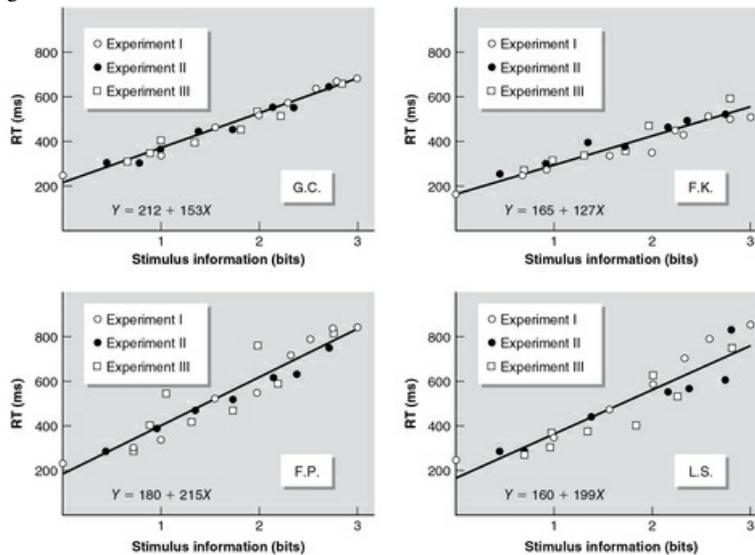
$$\text{Choice RT} = a + b[\text{Log}_2(N)] \quad (3.1)$$

where  $N$  is the number of (equally likely) S-R alternatives and  $a$  and  $b$  are the empirical constants. Notice that equation 3.1 is somewhat different from the “typical” linear equation discussed in chapter 2, where  $Y = a + bX$ ; but if  $X$  is  $[\text{Log}_2(N)]$ , then equation 3.1 means that choice RT is linearly related to  $\text{Log}_2(N)$ .

The data from four participants in Hyman’s (1953) study are presented in [figure 3.7](#); the data of interest at this point in our discussion are the open circles, referring to experiment 1, in which the number of S-R alternatives was varied (plotted as the  $\text{Log}_2[N]$ , or the number of bits of information to process—more on that later). For each participant there was a strong linear trend between the  $\text{Log}_2(N)$  and choice RT. The individual linear equation is shown on each participant’s graph; for example, for participant G.C., the intercept ( $a$ ) was 212 ms and the slope ( $b$ ) was 153 ms. Notice that these empirical “constants” were considerably different for different participants.

Nevertheless, in each case the RT was linearly related to the amount of stimulus information (or  $\text{Log}_2 [N]$ ).

Figure 3.7 Choice reaction time (RT) as a function of stimulus information.



Reprinted from R. Hyman, 1953, "Stimulus information as a determinant of reaction time," *Journal of Experimental Psychology* 45: 192.

That the relationship between the choice RT and the logarithm to the base 2 of the number of alternatives should be so clearly linear is of considerable interest in its own right. A linear relationship is the most simple of relationships, and scientists become excited about the possibility that complex behaviors of human beings can be described by such simple expressions. But of even more importance is one interpretation of this relationship: that the time required making a decision (or making a choice) about a response is linearly related to the amount of information that must be processed in coming to that decision.

### Measuring the Amount of Information

For Hick, and other scientists at that time, the notion of *information* was used in a very special way. Information is related to uncertainty and to the amount of uncertainty that is reduced by the presentation of a stimulus. Specifically, the amount of information contained in some signal is measured in *bits* (short for *binary digits*). One bit is defined as the amount of information that reduces the original uncertainty by half. For example, your friend tells you that she is thinking of one of four numbers (1, 2, 3, and 4), and you are to guess which it is. Then she tells you that the number is even. This last message has reduced the number of choices from four to two (i.e., by half) and has conveyed 1 bit of information. See "Uncertainty and Information Theory" for more details and an example about measuring information.

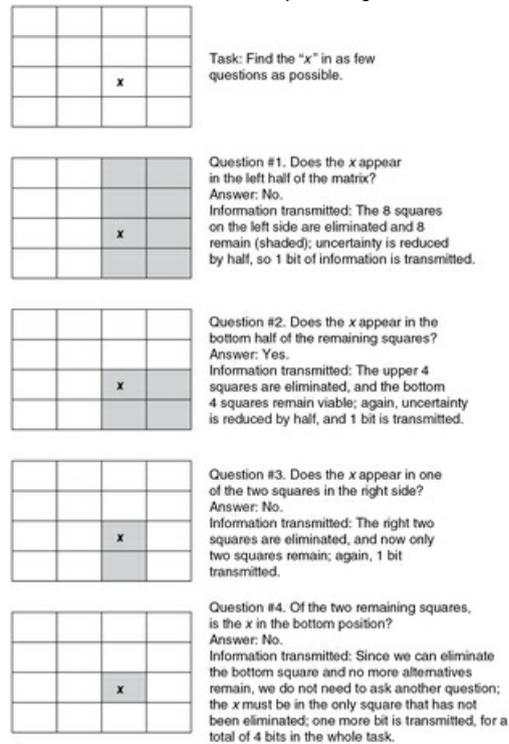
## Uncertainty and Information Theory

Scientists who study information processing use the term *information* to refer to the amount of *uncertainty* that has been *reduced* by a signal that was presented. If during a walk in the rain your friend says that it is raining, that *signal* conveys little information because there was little original uncertainty available to be reduced further. But if your friend says that it is raining in the Sahara desert, that signal conveys a great deal of information because (a) the probability that it is raining there is low and (b) you had no previous knowledge that it was raining there. Thus, the amount of information *transmitted* is affected by both (a) the amount of uncertainty prior to the signal's being presented and (b) the amount of reduction of uncertainty. Generally speaking, the amount of information ( $H$ ) is given by a simple equation:

$$H = \text{Log}_2(1 / P_i) \quad (3.2)$$

where  $P_i$  is the probability that a given event ( $i$ ) will occur. As the probability of an event ( $P_i$ ) decreases, the amount of information conveyed by a signal describing that event increases; this is why a signal about a rare event (it is raining in the desert) carries more information than a signal about a common event (it is raining in Eugene, Oregon). [Figure 3.8](#) provides a concrete example about how the information in a given situation can be reduced by asking a series of uncertainty-reducing questions (from Attneave, 1959). In the figure is a 4 by 4 matrix of squares, comprising 15 empty squares and 1 square with an  $x$  inside. If you did not know which of the 16 squares the  $x$  appeared in but wanted to find out, you could do so by asking four questions (because  $\text{Log}_2 16 = 4$  bits, and because  $2 \times 2 \times 2 \times 2 = 16$ ), designing each question to reduce the uncertainty by one-half (1 bit). Notice also that it does not matter whether the answer to each of the questions is yes or no—the information gained allows the uncertainty to be reduced by one-half, regardless of the answer.

Figure 3.8 Guess the location of the *x* in only four questions (from Attneave, 1959).



Adapted from F. Attneave, 1959, *Applications of information theory to psychology: A summary of basic concepts, methods, and results* (New York: Holt, Rinehart & Winston).

## Interpreting Hick's Law

Now we will connect the notion of information as the reduction of uncertainty to the logarithm involved in Hick's law. First, the logarithm to the base 2 of some number  $N$  is defined as the power to which the base 2 must be raised in order to obtain that number. For example, the  $\text{Log}_2(8)$  is 3, since 2 must be raised to the third power to obtain 8 ( $2^3 = 8$ ). Other examples are shown in [table 3.2](#) (with a more comprehensive table of log values in the appendix). Notice that every time  $N$  is doubled (say from 4 to 8, or from 8 to 16), [table 3.2](#) shows that the  $\text{Log}_2$  of the number increases by 1.

**Table 3.2 Relation Between Number of Alternatives ( $N$ ) and the  $\text{Log}_2(N)$**

Number ( $N$ )	$\text{Log}_2(N)$
1	0
2	1
4	2
8	3
16	4
32	5
64	6
128	7
256	8

Now, as applied to the RT situation, if  $N$  is the number of equally likely S-R alternatives, resolving the uncertainty about  $N$  things can be interpreted as processing  $\text{Log}_2(N)$  bits of information. In terms of Hick's law, we can say that choice RT is linearly related to the amount of information needed to resolve the uncertainty about  $N$  S-R alternatives. Stated differently, every time the number of S-R alternatives is doubled, the amount of information to be processed is increased by 1 bit, and the time required for choice RT is increased by a *constant* amount. This constant amount is the slope of the Hick equation,  $b$ .

To this point, we have considered only the circles in [figure 3.7](#) (Hyman, 1953, experiment I); in that experiment, the number of S-R alternatives was varied in order to change the amount of information to be processed. In Hyman's experiment II (the filled circles), the amount of information was varied by changing the *probability* of the stimulus. Remember, as the event becomes less probable, having to process a signal about it conveys more information, as in equation 3.2 (see "Uncertainty and Information Theory"). When information was increased by decreasing the stimulus probabilities, RT again increased linearly. In experiment III, Hyman varied information by changing the sequential dependencies (the probability that a given event [or stimulus] is followed by another event [or stimulus]). The effect was to make a particular stimulus more or less probable just before the presentation of the stimulus for a given trial. The squares in [figure 3.7](#) again show a linear relationship between amount of information and choice RT. If this interpretation is correct, the response-selection stage can be thought of as being involved in reducing uncertainty about alternative responses when a given stimulus is presented.

### Interpreting the Intercept and Slope

How should we interpret the intercept ( $a$ ) and the slope ( $b$ ) in Hick's law? From the earlier discussion of empirical equations (see chapter 2), recall that the intercept ( $a$ ) was that value of choice RT associated with  $\text{Log}_2(N) = 0$  (this is simple RT, a one-choice RT task), or the value of choice RT when the line crossed the vertical axis. In the data from various participants in Hyman's (1953) study (see [figure 3.7](#)), the average of these intercepts was 179 ms (mean of 212, 165, 180, and 160 ms). Consequently, it has been reasonable to interpret the intercept ( $a$ ) of Hick's law as a measure of the overall "speed" of the perceptual and motor system exclusive of any time required for a decision about which response to make. Comparing participant L.S. in [figure 3.7](#) ( $a = 160$  ms) with participant G.C. ( $a = 212$  ms) might be roughly analogous to comparing one of the original desktop computers with super computer to surf the Internet (Seow, 2005)—the basic processing speed is different.

Also from Hyman's (1953) data, the slopes of the relation ranged from about 127 ms/bit to 215 ms/bit for the various participants (see [figure 3.7](#)). Remember that the slope ( $b$ ) is a measure of the slope of the line; alternatively  $b$  represents the amount of increase in choice RT as  $\text{Log}_2(N)$  is increased by one unit (1 bit). So, one additional bit of information resulted in from 127 to 215 ms of additional choice RT for the different participants. Thus, the slope is the "speed" of decision making by the response-selection stage of processing, measured in units of milliseconds per bit. Seen in this way, the slope and intercept measure two different underlying processes in human performance.

The practical implications of the slope are important and probably obvious. For games in which rapid reaction is important, if the player can double the number of likely alternatives to which the opponent must respond (and the opponent cannot anticipate them), then the player increases by 1 bit the amount of information that must be processed in order for the opponent to respond, and thereby increases by a constant amount the opponent's choice RT in initiating the appropriate response. These kinds of effects are seen in most fast ball games, as well as in reaction situations involved in driving a car, performing various industrial tasks, and so on.

### Exceptions to Hick's Law

Whereas Hick's law does hold very generally over a wide variety of situations and people, other variables also affect choice RT, and a few situations exist in which the law does not appear to hold at all. The key variable is the participant's *familiarity* with responding to a particular stimulus by means of a specific response. These familiarity effects have been studied in various ways, most notably by examining (a) practice or experience with the task and (b) the nature of the relationship between the stimuli and the associated responses.

In one of the first studies to investigate the role of practice in relation to Hick's law, Mowbray and Rhoades (1959) used a two- and four-choice RT task and found, as had been observed previously by many researchers, that early in practice the four-choice task showed a much slower choice RT than did the two-choice task. However, their study is unique in that they provided their participants with an incredible 42,000 trials of practice! After this amount of practice, the four-choice RT was reduced to a level essentially equal to that of the two-choice RT. Thus, the slope of the choice-RT function between 1 and 2 bits (i.e., two and four alternatives) was reduced by practice, eventually becoming essentially flat (where  $b = 0$ ). Similar findings were also reported by Seibel (1963). These effects of practice have been the basis for the important notion of automaticity in responding, which we discuss more fully in chapter 4 (see Schneider & Shiffrin, 1977).

Another set of data that can be similarly interpreted was generated by Mowbray (1960). When the task involved digit naming (the number of possible digits was varied, and the RT was measured by a voice microphone), increasing the number of possible digits to be named did not increase the choice RT. The interpretation is that the names of digits are so highly practiced that the association between the digit and the name is nearly direct (i.e., automatic), not requiring further reduction in uncertainty (see also Fitts & Seeger, 1953; Hellyer, 1963).

Similar findings of essentially zero slope for highly overlearned S-R relationships were provided by Leonard (1959). In this study, choice RT with one, two, four, and eight alternatives was examined, but the situation was quite different from those studied earlier. The participants placed their fingers on the appropriate number of keys and were instructed to press as quickly as possible on the one key that *vibrated*. The relationship between the stimulus (vibrations) and the response (pressing *that* finger on the key) was very direct. As the number of S-R alternatives increased from two to eight, Leonard found no further increase in choice RT. That is, the relationship was flat (with  $b = 0$ ). When the finger was vibrated, the relation between it and the response was so direct that no additional time was required for decision making about which finger to activate (see also Keele, 1986, for a good review).

Another exception to Hick's law is seen in responses involving rapid movement of the eyes to targets. In experiments by Kveraga, Boucher, and Hughes (2002), participants responded to stimuli that occurred at from one to eight locations by making either a manual key press, an eye movement (saccade) toward the target, or a saccade away from the target. The authors found that RT to initiate manual key presses and saccades away from

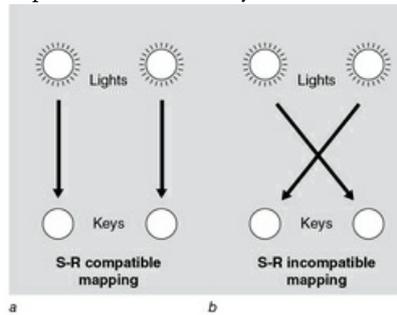
the target corresponded well to Hick's law. However, saccades toward the target were completely unaffected by the number of stimulus alternatives. This finding agrees well with the ideas just discussed, as the saccades toward targets are much more "natural" (and biologically important) than either manual responses or saccades away from a stimulus.

These findings illustrate the importance that the relationship between the stimulus and response can have to response selection. The exceptions to Hick's law suggest that highly overlearned S-R relationships, or relationships that are in some sense biologically "natural," can *facilitate* response selection when multiple alternatives are available. It seems impossible to remove that difference between simple RT and two-choice RT, because choice RT requires a response-selection process not needed in simple RT, thus the increase between simple and choice RT reflects the added duration of the response-selection stage. In the next section we examine how this same influence of S-R familiarity can also have *detrimental* effects on response selection.

### *Stimulus–Response Compatibility*

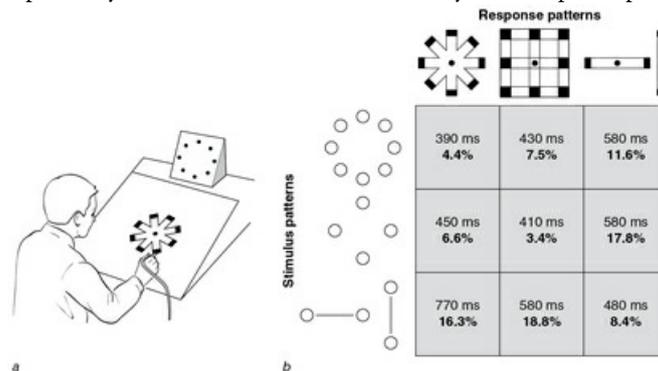
The association between (or the degree of "naturalness" between) a stimulus (or set of stimuli) and the response (or set of responses, called the S-R *ensemble*) has a very important influence on information processing, and was given the term *stimulus–response (S-R) compatibility* (or S-R compatibility) in 1951 by Small (see Small, 1990). For example, when a right-positioned stimulus requires a right-hand response and a left stimulus signals the left hand, the situation is said to be S-R compatible, as in [figure 3.9a](#). *However*, when a left signal indicates a right-hand response and a right signal a left-hand response ([figure 3.9b](#)), this is said to be S-R incompatible, or at least less compatible than the arrangement in [figure 3.9a](#).

Figure 3.9 Stimulus–response (S-R) compatibility is defined by the relationship between the stimuli and the responses to which they are associated.



The pioneering work on S-R compatibility was conducted by Fitts and his colleagues. An example is illustrated in [figure 3.10, a and b](#) (Fitts & Deininger, 1954; Fitts & Seeger, 1953). [Figure 3.10a](#) illustrates the basic experimental setup used in these studies. The participant was to move rapidly and accurately from a center home position to one of eight target locations available on the response panel. The specific target was identified by the stimulus pattern on the display visible to the participant. [Figure 3.10a](#) illustrates the general layout, where the stimulus information about which response to make is provided via lights, and the participant makes a response with a hand movement on the response panel. Fitts and Seeger used three different stimulus patterns and three response patterns in all nine combinations, illustrated in [figure 3.10b](#).

Figure 3.10 (a) A participant performing in Fitts and Seeger's (1953) experiment and (b) stimulus–response (S-R) compatibility effects for various stimulus arrays and response panels.



The organization of the *stimulus* patterns (the left side of [figure 3.10b](#)) to indicate which of the eight responses the participant was to make worked as follows. For the top stimulus pattern in [figure 3.10b](#), the light that was illuminated indicated the response—such as “up-left,” or “down-right” ([figure 3.10a](#)). In the second row, the stimulus was presented in a different way. If the upper light was lit, it meant “up,” and the right light meant “right.” But if the lower *and* right lights came on, this meant “down-right.” The third configuration was again different. Here, if the upper light of the vertical pair came on, it meant “up,” and the right light of the horizontal pair meant “right.” Here, the left light in the horizontal pair *and* the upper light in the vertical pair meant “up-left.”

The working of the *response* panels is shown on the top of [figure 3.10b](#). In the example at the left, the participant always started in the middle. If the display signaled “up,” the response was up; if it signaled “left,” the move was left. If “down-right” was signaled, then the movement was along the path downward to the right.

In the second response panel, the participant again started in the middle, but this time could move only along the perpendicular pathways. “Up” meant to move straight up to the center of the upper line, and “left” meant to move to the center of the left line. “Down-right” meant to move to the lower-right corner, either by moving down and then right or by moving right and then down.

Finally, the response panel on the right used two hands, the right hand on the right half and the left hand on the left half. Each hand started at its respective center point. The stimulus pattern “up” meant to make a vertical response up with the right hand (and not move the left hand), and “left” meant to move the left hand to the left (and not move the right hand). Here, though, “down-right” meant to move the right hand down *and* the left hand to the right, similarly for “up-left.”

Now, consider the data shown in the body of the table in [figure 3.10b](#)—RT for the correct responses under that combination of stimulus and response arrangements, and the percentage error where the participant moved initially in the wrong direction. Consider first RT. It is interesting to ask which *stimulus* display pattern is fastest across all the combinations of response arrangements. It is clear that the fastest stimulus pattern is different for each of the response arrangements; the shortest RT for the first pattern (390 ms) is for the first response pattern; the shortest RT for the second pattern (410 ms) is for the second response pattern; and the shortest RT for the third pattern (480 ms) is for the third response pattern. The fastest stimulus pattern depended on which response pattern was paired with it.

Next, what is the fastest *response* pattern? The shortest RT for the response pattern on the left (390 ms) is for the top stimulus pattern; the shortest RT for the response pattern in the center (410 ms) is for the center stimulus pattern; and the shortest RT for the right response pattern (480 ms) is for the lower stimulus pattern. Again, the fastest response pattern depended on which stimulus pattern was paired with it.

This is the essential idea of spatial S-R compatibility. The pattern of the stimulus arrangement seems to be closely linked with the pattern required for the response. The pattern with lights arranged in a circle was fastest when the

hand had to make responses radially but was relatively slow when a two-hand response had to be made. That is, the fastest responses were always on the diagonal in this matrix, where the stimulus requirements seemed aligned with the response requirements.

Next, consider the percent error, shown also in [figure 3.10b](#), for each of the nine combinations. Again, the stimulus pattern that had the fewest errors depended on the response that was paired with it. Also, the response pattern with the fewest errors depended on which stimulus pattern was paired with it. Note again that the smallest errors were on the diagonal in the matrix where the stimulus and response requirements seemed to be matched. Also notice that some combinations resulted in a *very* high percentage of errors.

Finally, note that these effects cannot be explained by a speed–accuracy trade-off, i.e. error rates are negatively related to RT, with some of the combinations having low RT only because errors happened to be large. To the contrary, with only minor exceptions, the combinations that made the participants fastest also made them the most accurate—the opposite of a speed–accuracy trade-off. This was truly a remarkable demonstration of the power of having the stimulus and response patterns “go with” each other. This general principle of S-R compatibility has become one of the cornerstones of the field of human factors and ergonomics, and it pervades the design of countless real-world devices for which participants must make responses based on the patterning of stimuli. In the following sections we describe some of the areas in which S-R compatibility research has been conducted.

## Population Stereotypes

Many S-R relationships that were originally quite arbitrary “become natural” through practice and experience (e.g., moving a light switch up to turn on a light) and are called *population stereotypes*. Different populations often have their own unique stereotypes, however, resulting in S-R relationships that are quite different from others and sometimes even opposite, such as the movement of the light switch down to turn on the lights in Germany. This relationship seems clumsy to Americans, but it is perfectly natural to Germans who have experienced this relationship throughout their lives.

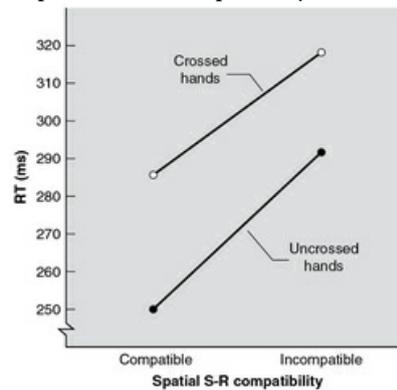
## Spatial and Anatomical Relationships

A high degree of S-R compatibility seems to suggest that there is an overlap of the mental representation of the task dimensions associated with the stimuli and the mental representation of the possible responses (Kornblum, Hasbroucq, & Osman, 1990; Weeks & Proctor, 1990). Data of the type shown by Fitts and Seeger (1953) and many others suggest that S-R compatibility occurs because of spatial similarities in the stimulus and response sets. One possible reason for the S-R compatibility effect in [figure 3.9](#) could be that the right limb responds to the right light faster than to the left light because of some anatomical or neural advantage. If this is so, then imagine what would happen if the hands were crossed, so that a participant’s right hand was used to press the left button and the left hand used for the right button. This crossed condition is now compatible with respect to the spatial mapping of the stimulus and the *key* to select (as before) but incompatible with respect to the mapping of the stimulus and *hand* to select (i.e., the right stimulus is responded to with the right key but using the left hand).

Experiments that have addressed this issue (Anzola, Bertolini, Buchtel, & Rizzolatti, 1977; Brebner, Shephard, & Cairney, 1972; Wallace, 1971) reveal that it is the spatial relationship between the location of the stimulus and the location of the response key that is crucial. Regardless of which hand is used (i.e., crossed or uncrossed conditions), performance is faster in the spatially compatible conditions (ensemble *a* in [figure 3.9](#)) than in spatially incompatible conditions (ensemble *b* in [figure 3.9](#)). This conclusion is supported well by the findings of Brebner and colleagues (1972), shown in [figure 3.11](#). In general, the crossed-hands procedure resulted in slower overall RT than did the uncrossed condition. However, regardless of the position of the hands, when the stimulus light was paired with its spatially compatible response-key position, RT was faster than in the incompatible positions ([figure 3.11](#)). We infer that response selection is more concerned with relations between stimuli and spatial locations than

with anatomical parts.

Figure 3.11 Effects of stimulus–response (S-R) compatibility and hand location on reaction time (RT).



Data from Brebner et al. 1972.

Earlier we discussed an exception to Hick’s law—making saccades toward visual stimuli (Kveraga et al., 2002). Directing the eyes in response to the presentation of a visual target represents another type of S-R compatibility effect. Reaction times are smaller and errors are fewer when the task is to make the natural response to look *at* the source of a visual stimulus as compared to an *anti-saccade* task, which can be thought of as an incompatible S-R relationship (see Munoz & Everling, 2004, for a review). In the case of the anti-saccade, the natural tendency—that is, to look at the source of the visual stimulus—must be actively suppressed, or inhibited, before the correct response can be made. Presumably, this inhibition requires time.

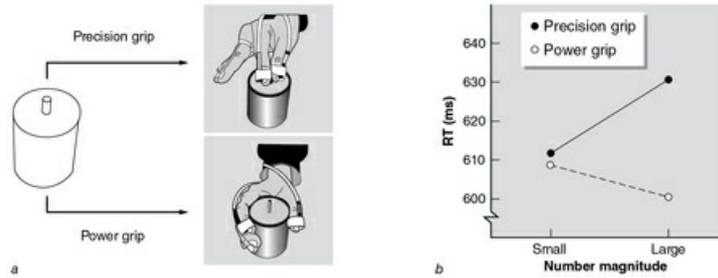
### Stimulus and Response Intensity

Another rather straightforward type of S-R compatibility relationship has been found when the force of a response is mapped to the intensity of the stimulus. Participants in a study by Romaiguère, Hasbroucq, Possamaï, and Seal (1993) were asked to make a weak or strong isometric thumb press in response to a visual stimulus that varied in intensity. There was a 50 to 75 ms RT advantage in the compatible condition (in which stimuli low in intensity were paired with weak thumb movements and strong stimuli with strong movements), compared to the incompatible S-R condition (low intensity paired with strong movements). Note, however, that the relation between the stimulus and the response here is more abstract than the more direct physical compatibility relationship that we have considered so far.

A related S-R compatibility effect occurs when different grip actions are made in response to numbers that differ in their magnitude. The left side of [figure 3.12](#) illustrates the two types of responses made by participants in an experiment by Lindemann, Abolafia, Girardi, and Bekkering (2007)—a precision grip (a pinching action used to pick up small or light objects) or a power grip (a whole-hand grip used to move large or heavy objects). Lindemann and colleagues used a clever design in which these specific grips were used to respond in a choice-RT task regarding the features of a number, presented as the visual stimulus. For example, if the number 2 or 8 was presented (both even numbers), participants in one condition were to respond with a precision grip; if the number 3 or 9 was presented (odd numbers), then a power grip was required. Quite incidental to making the response was the effect of the *magnitude* of the number and its “compatibility” with the response. As illustrated in the right side of [figure 3.12](#), RT was lower to initiate a precision grip in response to a low number (2 or 3) compared to a high number (8 or 9). Conversely, RT was longer to initiate a power grip to a low number compared to a high number. The compatibility of specific grips to the magnitude of a number may be an example of a more general type of conceptual S-R compatibility effect known as the SNARC effect (the “spatial–numerical association of response codes” effect), which describes a relationship between space and number magnitude (see Umiltà, Priftis, & Zorzi, 2009, for a review). Some of these types of S-R compatibility effects, which appear to be more “conceptual” than physical (by definition), are considered in the next sections.



Figure 3.12 (a) Participants in the study by Lindemann and colleagues (2007) were cued with a low or high number to pick up an object using either a pinch grip or a power grip; (b) reaction times (RTs) were fastest for large numbers using a power grip but were fastest for small numbers using a pinch grip.

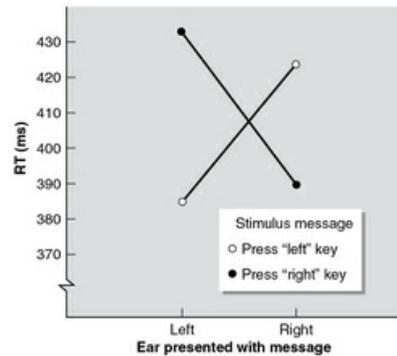


Reprinted, by permission, from O. Lindemann et al., 2007, "Getting a grip on numbers: numerical magnitude priming in object grasping." *Journal of Experimental Psychology: Human Perception and Performance* 33: 1400-1409. Copyright 2007 American Psychological Association.

### Simon Effects

We can also see the influence of S-R compatibility on response selection when the spatial dimension of the stimulus is *irrelevant* to response selection, not unlike the S-R compatibility effects discussed in the previous sections. In an early demonstration of what were later called *Simon effects*, participants responded by pressing a right key whenever the verbal stimulus "right" was presented via earphones, and by pressing the left key when the word "left" was presented (Simon & Rudell, 1967). The auditory stimuli were sometimes presented only to the left ear and sometimes only to the right ear. Note that regardless of the ear to which the stimulus was presented, participants were to respond to the *content* of the message; the spatial location (ear) to which the message was sent was irrelevant to making the correct response. However, the findings revealed that the irrelevant (spatial) feature of the stimulus had a profound effect on response selection and could not be ignored. As [figure 3.13](#) shows, choice RT was faster when the message of the signal and the response were compatible with the spatial origin of the stimulus. These findings, along with others reported since Simon published his initial series of studies, suggest that there is *interference* in selecting a response when the presumably irrelevant stimulus is incompatible with the response. The spatial dimensionality of the stimulus tends to attract the response toward it, which must be inhibited (thus taking extra time) before the correct response can be selected (see also Simon, 1969a, 1969b, 1990).

Figure 3.13 The Simon effect—the irrelevant stimulus (which ear receives the message) interacts with the information.



Adapted, by permission, from J.R. Simon and A.P. Rudell, 1967, "Auditory S-R compatibility: The effect of an irrelevant cue on information processing," *Journal of Applied Psychology* 51: 302. Copyright 1967 American Psychology Association.

Although the spatial layout of the S-R ensemble has a critical effect on response selection, this appears to be only a partial explanation of what is happening (Umiltà & Nicoletti, 1990). For example, choice RT to the stimulus word "right" or to a rightward-pointing stimulus arrow is faster when the participant responds with a button press with the right hand or with the word "right" in comparison to arrangements with incompatible relationships (e.g., McCarthy & Donchin, 1981; Weeks & Proctor, 1990). Thus, similar to the effects of number size, verbal stimuli that implicate a spatial relation and responses appear to have dimensions that produce compatibility relationships affecting response selection.

Together, these findings suggest that the response-selection stage exploits compatibility effects when the relationship between the set of stimulus alternatives and the set of response alternatives has a highly learned (or "natural") association (as in the word "right"). Interference is likely to occur when the response is inconsistent with the learned association (for in-depth discussion of theoretical interpretations of various S-R compatibility effects see Cho & Proctor, 2003; Hommel & Prinz, 1997; Kornblum et al., 1990; Proctor & Reeve, 1990; Proctor & Van Zandt, 1994).

### Compatibility and Complex Actions

When people respond to stimuli that require *complex* actions, the issue of S-R compatibility and response selection seems to be related to the *intentions* of the action. For example, Rosenbaum and colleagues (1990) describe the everyday task of a waiter who wants to turn over an upside-down glass with one hand so that he or she can pour water from a pitcher into it with the other hand. What will be the initial grasp of the hand—thumb up or inverted with the thumb down? Experiments show that the waiter's initial hand position is usually inverted so that when the glass is turned upright the hand is in the correct holding position, so that the glass is ready to receive poured liquid. The response initially selected by the waiter "trades off" an awkward early posture in order to achieve a posture that is more suited to filling the glass with water. In this case, compatibility between the stimulus (the glass) and the waiter's response (initial hand posture) is defined not in terms of the initial interaction, but rather in terms of the efficiency of the intended *final* position (what Rosenbaum and colleagues have termed the "end-comfort effect"). Also, selection of the method that maximizes the efficiency at movement completion is initiated faster than of one that is more efficient at the action's start (Rosenbaum, 2009; Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992; Rosenbaum, van Heugten, & Caldwell, 1996), especially if the final location has a stringent precision requirement (Short & Cauraugh, 1999). Thus, for more complex actions, S-R compatibility effects may influence the response-selection stage in terms of *how* an action is to be performed, rather than simply about where to move.

### Response-Programming Stage

The performer can organize and initiate an action only after having identified the stimulus and selected a response. After response selection, the performer must translate this abstract idea into a set of muscular actions that will achieve the desired action. These processes are thought to occur during the *response-programming stage*. Like the processes in the earlier stages, the events occurring in response programming are probably very complex—requiring that some program of action be *retrieved* from memory, that the program be prepared for activation, that the relevant portions of the motor system be readied for the program (called *feedforward*, or *tuning*), and that the movement be initiated. It is helpful to view the response-programming stage as the final set of processes that allows the individual to communicate with the environment—just as the stimulus-identification stage is viewed as the first stage that allows the environment to communicate with an individual.

Information about the response-programming stage has developed more recently than research regarding the other two stages. It was not until 1960, when Henry and Rogers performed an experiment on the nature of the movement to be produced in RT situations, that conceptualization about the response-programming stage began. The underlying motivation for their experiment was based on Henry's idea that motor programs are stored in memory. When a well-learned action is retrieved from memory, it is "read out" like a series of triggers on a conveyer belt (as in a player piano), with more triggers required for more complex movements (Klapp, 1996). Although the language and analogies have changed over the years, it is interesting and useful to read the theoretical arguments that Henry and Rogers (1960) presented in their paper and to understand why RT was considered a valuable measure of motor program retrieval and preparation (see "Henry and Rogers' 'Memory Drum' Theory of Neuromotor Reaction").

## Henry and Rogers' "Memory Drum" Theory of Neuromotor Reaction

### Research Capsule

In the following quote from Henry and Rogers (1960), the recall of information for movement is analogous to retrieval of information from a computer's memory buffer. The significance of these statements was probably not fully recognized at the time, even though they were published in the very same year as Miller, Galanter, and Pribram's (1960) book *Plans and the Structure of Behavior*. This book, regarded as one of the major factors leading to the fall of behaviorism, popularized the terms "plans" and "programs" as structures that must precede actions.

"A rich store of unconscious motor memory is available for the performance of acts of neuromotor skill. Added to this are innate neuromotor coordinations that are important in motor acts. The tapping of the store may be thought of broadly as a memory storage drum phenomenon, to use the analogy of the electronic computer. The neural pattern for a specific and well-coordinated motor act is controlled by a stored program that is used to direct the neuromotor details of its performance . . . there should be a longer reaction latency for a complicated movement than for a simpler movement. This is because a more comprehensive program, i.e., a larger amount of stored information, will be needed, and thus the neural impulses will require more time for coordination and direction into the eventual motor neurons and muscles." (pp. 449 and 450)

It was not until years later that Henry and Rogers' ideas became widely cited (Cardinal & Thomas, 2005; Ulrich & Reeve, 2005). These ideas about motor programs are quite prevalent and useful today, as will be evident in later chapters here.

### *Henry-Rogers Experiment*

Henry and Rogers (1960) studied the nature of the movement to be made using a simple-RT paradigm, in which

the participants knew, on any given trial, exactly which response was required. Over many blocks of trials, Henry and Rogers had the participants make different movements while keeping the stimulus for the movement, as well as the number of response alternatives, constant (i.e., there were *no* stimulus–response alternatives, or  $N = 1$ ; in other words it was simple RT). The first task version (movement A) involved merely lifting the finger from a key a few millimeters and had essentially no accuracy requirement. For the second version (movement B), the participant lifted the finger from the key and moved approximately 33 cm forward and upward to grasp a tennis ball suspended on a string, which stopped a timer that measured movement time (MT). The third task version (movement C) involved a second suspended ball mounted 30 cm to the left of the first ball. The participant lifted the finger from the key, moved upward to the right to strike the first ball with the back of the hand, moved forward and downward to push a button, and then moved upward to the left to grasp the second suspended ball.<sup>2</sup> Remember, for all three task versions, there was one stimulus and response alternative for a block of trials. Thus, the processing speed in the stimulus-identification and response-selection mechanisms should always be the same; the only variation in the three task versions was in the nature of the *movement* to be made. The primary measure, as before, was the (simple) RT, or the interval from stimulus onset until the movement began.

Henry and Rogers' data results are presented in [table 3.3](#). Movement B (single-ball grasp) resulted in a 36 ms longer RT than did movement A. The most complex movement (C) (ball strike, button press, ball grasp) resulted in an additional 13 ms increase in RT compared to movement B. Because the stimuli were neither changed for the different movements, nor was the number of choices, the increased RT as the movement complexity increased was due to an increased amount of time required to *program* the movement in some response-programming stage. Henry and Rogers' original idea was that a more complex set of motor commands, such as would be necessary to control the limb through several movement reversals and to produce striking and grasping actions, would require more neuromotor activities to be coordinated, in turn requiring more time for all of this neurological complexity to be organized during RT. In slightly modified form, this idea still has a great deal of support (see Christina, 1992; Henry, 1980; Klapp, 1977a, 1996).

Movement task	Number of movement parts	Movement accuracy requirement	Duration of movement	Latency to begin movement (RT)
A	1	No	Very brief	159 ms
B	2	Yes	95 ms	195 ms
C	4	Yes	465 ms	208 ms

How does one explain the result of the Henry and Rogers experiment? The obvious conclusion is that RT increased when the *complexity* of the *movement* was greater. But what was actually involved in making the movement more “complex”? The careful reader will notice a number of factors that came into play in this regard. [Table 3.3](#) also summarizes a number of potentially relevant factors that differed according to the three experimental conditions in the study. The differences between movements A, B, and C included additional movement parts, increased accuracy demands, and longer movement durations (and perhaps other factors as well). Research conducted since this pioneering experiment suggests that all of these factors played a role in producing the results seen in the Henry and Rogers experiment.

### Number of Movement Parts and Reaction Time

Results similar to the Henry and Rogers (1960) data have been obtained in a number of replications of their study, implicating the addition of movement parts as the primary reason for the increase in RT (e.g., Christina, 1992; Fischman, 1984). Corroborating evidence was obtained from experiments using different tasks. For example, Sternberg, Monsell, Knoll, and Wright (1978) observed that the latency in speaking the first word of a sequence increased by about 10 ms for each word that was added to the sequence (i.e., strings of one, two, three, four, or five words) and by 5 to 15 ms for additional letters to be typed (see also Canic & Franks, 1989). It would appear, however, that the additional movement must be performed as part of a whole ballistic response in order to have an effect on RT. A study by Franks, Nagelkerke, Ketelaars, and van Donkelaar (1998) compared the effect on initiation latency of a single-movement task (elbow extension) and a two-movement task (elbow extension and flexion) in which there was either no pause, a short pause (75 ms), or a long pause (260 ms) between extension and flexion. Increased RT was observed when the flexion movement followed without delay or with a very brief delay, but not when there was a long delay between the two movements. Thus, when there was sufficient time to program the second movement *following* completion of the first movement (and thus not during the original RT), the participant needed only to plan the first movement prior to movement onset, regardless of whether or not it was followed by a flexion. However, with no pause or a brief pause between the two parts, the entire response needed to be programmed in advance, resulting in the observed effect on RT of the additional movement part (see Klapp, 1996, for further discussion).

### Movement Accuracy Effects on Reaction Time

At about the same time as Henry and Rogers’ work (but quite separate from it), Paul Fitts was investigating movement complexity effects as well, using aiming tasks that varied in target distance and accuracy demands. Although Fitts’ primary concern related to the ongoing movement (as revealed by movement time; see chapter 7), he also found that RT increased as the precision requirements of the task increased (Fitts & Peterson, 1964). Findings that RT increases as the target size decreases (thereby increasing the accuracy demands) have since been reported in a number of experiments by Sidaway and his colleagues (e.g., Sidaway, Sekiya, & Fairweather, 1995).

### Movement Duration Effects on Reaction Time

In addition to complexity and accuracy demands, the three movements studied by Henry and Rogers (1960) varied in at least one other important respect—their *duration*. From Henry and Rogers’ data ([table 3.3](#)), notice that the most complex movement required much more time to produce (465 ms) than the simpler one (95 ms). This observation has led various scientists to suspect that the duration of the movement to be produced might be a

major variable in the response-programming stage. In Klapp and Erwin (1976) participants produced 10 cm movements of a slide along a track, with goal MTs of 150, 300, 600, or 1,200 ms. The number of actions and the accuracy demands of the movement were held constant, but the duration of the movement was varied. As the movement duration increased, the RT to initiate the response increased as well, especially when the movement durations were below 600 ms. Similar effects were reported by Rosenbaum and Patashnik (1980), who varied movement duration of the time a button had to be depressed, and by Quinn, Schmidt, Zelaznik, Hawkins, and McFarquhar (1980), who varied the movement time for aiming responses of a stylus to a target (see Klapp, 1996, for a review).

### *Response Complexity and Motor Programming*

The effect of movement complexity on RT occurs both when the person knows in advance what movement will be made (in simple RT) and when the choice of movement is not known until it is indicated by the stimulus (in choice RT) (see Klapp, 1995, 1996). Regardless of the variations in method and movements, the effect of movement complexity on RT has been interpreted as relating to the time necessary to prepare and initiate the movement during the response-programming stage of RT. Despite over 50 years of research on this topic, the ideas of Henry and Rogers about the process of movement organization during the motor-programming stage remain remarkably valid today.

# Anticipation

So far in this chapter, we have discussed information-processing activities in which the performer's task is to respond to generally unanticipated stimulus information. The processing speed, as measured by RT, tends to be relatively slow, giving the impression that humans have severe limitations in information processing. One problem with this line of thinking, though, is that RT is usually studied in highly unrealistic situations, and especially in situations in which the participant is seldom allowed to *anticipate* environmental information. In fact, experimenters go to elaborate lengths to prevent the participants from anticipating. They often use "catch trials," in which the stimulus is sometimes withheld to "catch" a participant who is anticipating; often use choice-RT tasks, preventing the participant from knowing *what* stimulus is going to occur; or randomize foreperiods (the interval from the preparatory signal to the stimulus presentation) so that the participant cannot predict *when* the stimulus will appear. By employing these methods, researchers try to ensure that participants are responding to an "unanticipated" signal. Clearly, under these conditions, humans find information processing very difficult indeed.

But in many "real" skills, suddenly presented and unexpected stimuli are the exception rather than the rule. Of course, unexpected events do sometimes occur—and sometimes we even try to make them occur (e.g., faking in sports); but many of the stimuli to which we respond in our daily activities are very predictable. During walking or driving, the stimuli emerge from a generally stable environment that allows us to preview upcoming events with plenty of time to do something about them. And when a signal does arrive, it is often not a discrete event, but rather a *pattern* of sensory information that unfolds before us. Gibson (1966) has emphasized that visual information is really an *optical flow* of stimuli, from which the performer detects important future environmental events (see chapter 5).

Poulton (1957) has described three different kinds of anticipation. One obvious type is *receptor anticipation*, in which the performer detects the upcoming events with various sensory receptors (e.g., the batter *sees* the ball coming). However, the performer must also estimate how long his *own* movement will take, and often he must allow for this interval in initiating the actions; the batter must time the bat swing's initiation so that the bat and ball meet at the proper location over the plate. This is called *effector anticipation*, because the duration of the effector's movement (the body, mainly the arms and bat) must be predicted. Finally, Poulton described what he called *perceptual anticipation*; here the environmental events are not perceived directly, but they are still predictable because the performer has had a great deal of practice with them, such as the regular timing of beats in music or in military drill. In the next sections, we consider important principles related to a performer's capability to anticipate.

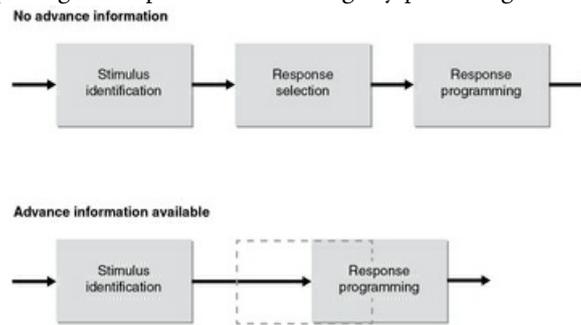
## Spatial (or Event) Anticipation

One way in which performers can anticipate future activities is by knowing what kinds of stimuli could be presented and what kinds of responses will be required for each of the anticipated stimuli. This class of anticipation has been called *spatial*, or *event*, anticipation. In an experimental study of these processes, Leonard (1953, 1954) and Jeeves (1961) used an apparatus that had trackways arranged as spokes of a wheel. Participants moved repeatedly from the center position toward lights at the ends of the spokes and back again as quickly as possible. The light indicated the spoke along which the participant was to move. If the next spoke was indicated only after the participant had arrived back at the center position from the previous spoke, participants could not anticipate which movement to make next, and performance was slow, jerky, and labored. But if participants were informed about the next spoke when they were at the peripheral end of the previous spoke, they could plan the next movement while they were moving back to the center. Overall, performance was smoother, less jerky, and more rapid. Analogous effects were found by Leonard (1953), whose participants used advance information to reduce a six-choice RT task to a three-choice RT task, with associated gains in speed as would be expected from reducing the number of S-R alternatives from six to three (conforming to Hick's law). Many other experiments led to a similar conclusion (see Schmidt, 1968, for a review).

Some experimenters have sought to determine what kinds of information about the upcoming *movement* can be used in advance and how much time can be “saved” by using it. Using the *precuing technique*, Rosenbaum (1980, 1983), Goodman and Kelso (1980), Zelaznik and Hahn (1985), and others have examined tasks in which various aspects of the response could be specified in advance, leaving other aspects unspecified until the stimulus actually arrived; the stimulus then provided the remainder of the information needed to produce the action, as well as the “go” signal. For example, Rosenbaum (1980) used a task in which the response involved up to three types of movement choices: (a) with the right or left arm, (b) toward or away from the body, and (c) to a target that was near to or far from the starting position—an eight-choice RT task ( $2 \times 2 \times 2 = 8$  alternatives). Rosenbaum found that providing advance information about any one of the three movement features (arm, direction, or extent) reduced the RT by about 100 to 150 ms. Apparently, when the participants had this advance information they could engage in some response processing before the stimulus arrived, thus “saving” processing time during RT. There seemed to be a greater advantage in receiving information about which arm was to be used (150 ms reduction in RT relative to the no-precue condition) as compared to information about the extent of the movement (100 ms reduction), suggesting that the situation is somewhat more complex than simply reducing the number of alternatives from eight to four. Klapp’s (1977b) work, using a different paradigm, makes a similar point.

One way to think of these effects is illustrated in [figure 3.14](#). If the participant receives advance information about a certain feature of the movement, some of the processing operations normally done during RT can be done in advance, and can be “bypassed” when the reaction stimulus finally arrives. If sufficient information is given so that all the aspects can be selected in advance (e.g., knowing arm, direction, *and* extent in Rosenbaum’s situation), then one can think of “bypassing” processing in response selection completely, resulting in what is essentially simple RT. The work of Rosenbaum and others suggests that portions of response programming can be done in advance as well.

Figure 3.14 Bypassing the response-selection stage by processing information in advance.



It is also interesting to note in Leonard's (1953, 1954) and Jeeves' (1961) studies that advance information allowing partial or complete selection of upcoming actions was presented while the participant was already moving back to the center position. The result should not be particularly surprising, but it does show that one movement can be planned while another is being executed. This is a very important feature of motor control, as it provides a mechanism by which a series of rapid movements can be executed with considerable speed and accuracy.

Anticipating the spatial location of a directed penalty kick in soccer is one example of a situation in which advanced information processing is necessary if a goalkeeper is to have any chance to be successful (Franks & Harvey, 1997). Analyses of the soccer penalty kick have shown that, if a goalkeeper waits until the ball is contacted before deciding which direction to dive, it is virtually impossible to intercept the ball, since the travel time for the ball to reach the goal line (about 600 ms) is roughly equal to the goalkeeper's own movement time (500-700 ms) *after* the decision to move has been made (Franks & Harvey, 1997). Therefore, if he or she is to be successful, the goalkeeper must pick up advance cues from the kicker regarding the direction in which the ball will travel and must use that information to decide on a response *prior* to the actual delivery of the stimulus (contacting the ball). Analyses of this task have revealed that expert goalkeepers focus on the position of the stance foot (the nonkicking leg) and the relation of both feet to the ball as advance cues, whereas novice goalkeepers use visual search strategies that are much less reliable and useful (Franks & Harvey, 1997; Savelsbergh, van der Kamp, Williams, & Ward, 2005; Williams, 2000).

## Temporal Anticipation

The evidence just reviewed on spatial anticipation suggests that the performer can, by knowing some specific information about the response to be produced, bypass or at least shorten some of the stages of information processing. This shortening of RT is rather modest, though, and the responder still has difficulty processing environmental stimuli quickly. The evidence presented in the next sections suggests that if the person can anticipate *when* the stimulus is going to arrive, rather large reductions in RT can occur. Under the proper circumstances, the performer can *eliminate* RT altogether!

### *Constant-Duration Foreperiods*

Imagine a participant in a simple-RT situation (one stimulus and one response) in which a warning signal is followed by a foreperiod, at the end of which is the stimulus onset. Foreperiods may be of a constant duration (e.g., always 3 s), or they may be variable and unpredictable (e.g., 2, 3, or 4 s in random order). It seems obvious that a constant-duration foreperiod will result in the shortest RT. If these constant foreperiods are relatively short (e.g., less than a few seconds), evidence shows that the participant can respond essentially *simultaneously* with the stimulus after some practice (provided that the participant knows which response to produce). Quesada and Schmidt (1970) showed that the average RT with a constant 2 s foreperiod was only 22 ms! It seems likely that the person anticipated the temporal onset of the stimulus and began the process of programming and initiating the response before the stimulus came on so that the overt movement occurred at about the same time as the stimulus.

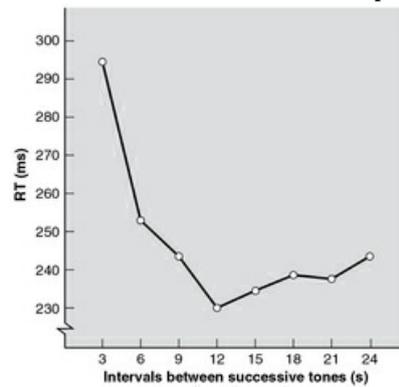
Thus, if the foreperiods are both regular *and* short, *and all* aspects of the response to be made are known in advance, then the participant can (with very little practice) perform the needed processes in advance and emit the overt response essentially simultaneously with the stimulus. This has been termed *early responding* in the literature because the response is triggered early—before the stimulus actually arrives.

On the other hand, when the foreperiod is regular but very long (a few seconds or more), and various features of the response are known in advance, participants apparently cannot shorten RTs to zero even with extensive practice. Under these conditions, Mowrer (1940) found RTs of about 230 ms. The RTs in these situations with long but regular foreperiods seem to be similar to those in which the foreperiod is short but irregular (thus preventing early responding). When the foreperiods are long (e.g., 12 s), early responding is prevented because the participant cannot anticipate the *exact* stimulus onset when it is so far in the future. The reason is that the internal “timing” for short durations is much less variable than that for long durations.<sup>3</sup> Attempts to anticipate the stimulus onset following a long foreperiod result in too many (very) early responses (by a second or so), which is usually not allowed by the instructions or by the experimenter. All the participant can do is engage in *preparation* and respond very quickly when the stimulus does arrive. Therefore, in situations involving anticipation, a common question is whether it is preparation *or* early responding that is taking place.

### *Variable-Duration Foreperiods*

In simple-RT situations, there is a great deal of evidence that irregular (variable duration) foreperiods averaging about 1 s produce shorter RTs than do longer ones of 2, 3, or 4 s (e.g., Klemmer, 1956; Welford, 1968). This effect seems to be quite small, however, and it is overshadowed by a larger effect that is apparently related to when the participant expects the signal. In these latter situations, the smallest RT is not associated with the shortest foreperiod as would be expected from Klemmer’s results, but rather either with the *most probable* foreperiod, or, if the foreperiods are all equally probable, with the center of the range of foreperiods (Aiken, 1964; Mowrer, 1940; Poulton, 1974). Participants in Mowrer’s (1940) study responded to tones presented every 12 s, but occasionally Mowrer presented tones at greater or less than 12 s intervals. The data in [figure 3.15](#) show that the shortest RT was at the interval that was most expected (12 s), and that longer and especially shorter intervals resulted in longer RT. It appears that as the end of the expected foreperiods draws near, the participant begins to prepare for the stimulus and response. Because maintaining a prepared state is effortful (and perhaps not possible during these longer intervals), this readiness begins to increase only when the first of the group of stimuli is expected, reaches a maximum at about the center (the most frequently occurring foreperiod), and declines toward the end. Presumably, the participant is most expectant for the signal when it is presented with an average foreperiod, and the RT is somewhat faster as a result. Clearly, this expectancy speeds RT.

Figure 3.15 Minimum reaction time (RT) occurs at the most probable interstimulus interval.

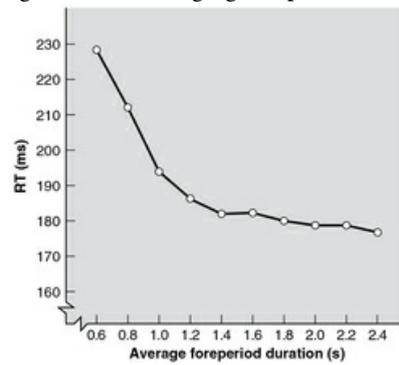


Reprinted from O.H. Mowrer, 1940, "Preparatory set (Expectancy): Some methods of measurement," *Psychological Monographs* 52(233): 12.

### *Aging Foreperiods*

We can see a notable exception to the findings on foreperiod duration in experiments that include *no catch trials* (again, in catch trials, the stimulus—though expected—never arrives; e.g., Drazin, 1961; Rothstein, 1973; Salmoni, Sullivan, & Starkes, 1976). Drazin's data are shown in [figure 3.16](#), which plots the RT against the average foreperiod duration. Here there were variable foreperiods and no catch trials, and the RT decreased as the stimulus was presented later and later in the group of foreperiods. At first, this result seems contradictory to the earlier conclusion that a stimulus presented at the center of the foreperiods elicits the most rapid RT (Aiken, 1964; Mowrer, 1940).

Figure 3.16 The aging-foreperiod effect.



Reprinted from D.H. Drazin, 1961, "Effects of foreperiod, foreperiod variability, and probability of stimulus occurrence on simple reaction time," *Journal of Experimental Psychology* 62: 45.

The critical difference is that the studies by Drazin (1961), Rothstein (1973), and Salmoni and colleagues (1976) did not employ catch trials. Without catch trials, the participant can become increasingly expectant for the stimulus as the foreperiod "ages" toward the last possible time of stimulus presentation. Consider an example with four possible (and equally probable) foreperiods (1, 2, 3, and 4 s) and no catch trials. Note that when only 0.5 s of the foreperiod has elapsed, the probability that the signal will appear at the 1 s point is one in four (0.25). After the 1 s interval has passed without presentation of the signal, the probability that the signal will arrive at 2 s is one in three (0.33), and so on, until beyond the passage of 3 s the probability of the signal's arriving at 4 s is 1.0. Thus, the participant has a basis for becoming increasingly expectant as the foreperiod "ages."

## Temporal and Spatial Anticipation: Implications

Essentially, anticipation is a *strategy* to reduce the time, or even the stages, of processing that would normally be involved in responding to an unanticipated stimulus. For this reason, in some situations people make attempts to either prevent or enhance such anticipation. For example, the starter in a sprint race attempts to prevent early responding by using a variable-duration foreperiod together with some "catch trials," which requires that the athletes wait for the signal before initiating their response (see "Foreperiods and False Starts in Sprinting"). On the other hand, the dance instructor or the drill leader in the military uses predictable foreperiods so that all the performers can respond simultaneously with the count and with one another. Dance instructors present a 1-2-3-4 count that the pupils know not to respond to, then a second 1-2-3-4; the "1" of the second count is the stimulus to begin. Drill leaders issue a command (e.g., "Left . . .") to provide the soldiers with event predictability and then later, at a very predictable time, give another command—"Face!"—which is the stimulus to perform the action (i.e., a 90° left turn); a good unit will respond as a single person, right on command. Anticipation is also very important in defensive driving skills. Young and Stanton (2007) provide a good review of various individual, vehicle, and situational factors influencing brake response times in driving.

### Foreperiods and False Starts in Sprinting

A rare event occurred in the 1996 Summer Olympic Games—a sprinter false-started *twice* and was disqualified from the 100 m final. In the second of his false starts, British sprinter Linford Christie appeared to explode out of the blocks with an excellent and legal start. Moments later the start was ruled invalid because Christie had apparently "jumped the gun." His RT, as indicated by the time from the starter's signal until the sudden rise in force of his foot against the blocks, was shorter than the 100 ms minimum value allowed by Olympic standards. Some raised arguments at the time that such standards place too fine a constraint on what might otherwise be an exceptional performance. Was this a fair judgment?

The starter's goal in the sprint is to have all the athletes *reacting* to the sound of the gun, and not responding before it. For this reason the starter attempts to *prevent* anticipations by using variable foreperiods and by sometimes aborting a start when the foreperiod ages too much (a type of catch trial). What the starter observes in the sprint start is forward movement of the athlete in relation to the sound. When that movement occurs before the sound or coincides with it, it is easy to infer that the athlete has anticipated, and the sprinter is rightfully penalized with a false start. The more difficult decision, however, concerns penalizing the sprinter who has initiated the start after the sound of the gun, but not in *reaction* to it. In other words, how fast is too fast?

Numerous experimenters have studied how to optimize RT under various experimental constraints. Simple RTs typically range from about 130 ms to 200 ms or so, depending on the intensity of the stimulus, the effector used in the response, and so on. In the case of the sprint start, however, the time measured is from the presentation of the stimulus until the first change in *force* against the starting block, and additional time is required to actually start the body in motion so that it is visible to the starting official. Also, consider that the laboratory RT values have been achieved under very controlled experimental conditions with responses involving very simple movements (such as finger lifts). The sprint start entails a much more complex coordination of effectors and much larger forces. Consequently, an even longer RT than is typical—not a shorter one—might be expected in the sprint situation.

Still, one could argue that the RTs of world-class sprinters might be expected to be faster than those of the average participants in an RT experiment. However, though sprint training does improve many speed-related factors, there is only so much that can be shaved off the stages of processing involved in simple RT. The minimum of 100 ms from stimulus to force change as an RT for a sprint start is a conservative criterion that still leaves plenty of time for some anticipation (perhaps up to 100 ms). Anything faster is most likely due to anticipating and "early responding," as discussed in this chapter. When all of the factors affecting sprint RT are combined, we must conclude that Christie was almost certainly guilty of a false start.

These concepts are also evident in American football, in which the quarterback provides a set of signals for his teammates just before the ball is snapped. The basic idea is for the quarterback to enable his team to anticipate and begin moving before the opposition can do so. According to the principles discussed in the previous sections, the signal count should be predictable, allowing temporal anticipation. For example, the quarterback could bark out distinctive, sharp sounds (such as "two, two, two, two, . . .") such that the timing between the sounds is regular and predictable. Earlier (in the huddle), the team will have been informed that the second "two" is the signal to start the play. This allows all of the offensive team to have nearly perfect temporal and spatial (event) anticipation because they know what is to be done and when to do it. The opposition does not have this capability, which forces them to be delayed by at least one RT before responding. The signal caller should be careful to avoid the aging-foreperiod effect, as an alert defense could predict the temporal onset of the "two" signal with increasing certainty as the count "ages," since the rules do not allow for "catch trials."

## Benefits Versus "Costs" of Anticipating

The previous sections have described benefits to performers when they correctly anticipate temporally, spatially, or both. However, the adage that "you don't get something for nothing" holds just as well in motor control laboratories as in anything else, and there are necessarily "costs" of various kinds that result from anticipating.

What happens if we anticipate incorrectly, as occurs when the batter anticipates a fastball but receives a curveball instead, or the boxer expects a blow from his opponent's left hand but receives one from the right hand? LaBerge (1973) and Posner, Nissen, and Ogden (1978) used a method of estimating the advantages and disadvantages of anticipating called a *cost-benefit analysis*.

In the study by Posner and associates (1978), the participant fixated on the center of a screen and received one of

three precues. One second after the precue, a signal would come on at one of two locations on the screen (which could be seen without an eye movement), and the participant's task was to lift a finger from a key as rapidly as possible after stimulus onset. Only one response was ever required (lifting a single finger from a key) regardless of the stimulus location. One of the precues was a plus sign, presented on one-third of the trials, indicating an equal probability that either of the two signal locations could be used (these were called "neutral-precue trials"). On the remaining two-thirds of the trials, however, the precue was an arrow pointing to the left or to the right, meaning that the signal would be presented on the side of the screen to which the arrow pointed; however, this precue was correct on only 80% of the trials. On the remaining 20% of the trials, the participant was "tricked"; the signal would arrive on the side of the screen opposite the one indicated by the arrow. The trials in which the signal arrived on the side indicated by the arrow were called *valid-precue* trials; those in which the arrow pointed away from the eventual signal location were called *invalid-precue* trials.

Posner and colleagues (1978) found that the average RT on the neutral-precue trials was 265 ms. On the valid-precue trials, the average RT was 235 ms, revealing a 30 ms *benefit* to performance for a correct anticipation, relative to the neutral-precue condition. However, when the signal was presented in the location opposite that indicated by the arrow (an invalid-precue trial), the average RT was 304 ms, revealing a 39 ms *cost* of anticipating the direction incorrectly, relative to the neutral-precue condition.

Notice that the cost in this study involved only the detection of the signal, because the response was always the same. But what happens when the task also includes different response alternatives? What are the costs involved in actually *moving* incorrectly? Schmidt and Gordon (1977) used a two-choice RT task in which the participant had to produce a correct amount of force on a lever in a direction indicated by a signal light. In one series of trials, the right and left signals were presented in random order, and participants could not successfully anticipate the direction of the upcoming response. But in another series of trials, the signals were presented in an alternating order (right, left, right, left, . . .), and the participants would develop strong spatial anticipation about the next response. In this alternating series, however, a few signals were embedded that were opposite to the direction expected; for example, a series might involve the following responses: left, right, left, right, left, right, left, right, *right*—an alternating series in which the participant was expecting the last signal to be a left, not a right.

On those trials in which the participant was anticipating one direction but was presented with the unexpected signal, there were errors on about 64% of the trials. These erroneous responses were initiated with a rapid RT (144 ms, on the average); the participant started moving in the incorrect direction (i.e., left) for 144 ms, and only then reversed direction to *begin* to move in the correct direction. Falsely anticipating appears to be a major cause of this kind of error.

Next, if the participant was anticipating left but the right signal came on, and the participant did avoid making an error, then the RT was somewhat longer (276 ms) than it would have been if the person had not been anticipating at all (235 ms). Thus, inhibiting an already planned (incorrect) movement does require time ( $276 - 235 = 41$  ms). This can be thought of as the *cost* of anticipating incorrectly and is very similar to the 40 ms cost found by Posner and colleagues (1978). Interestingly, though, in the Schmidt and Gordon study (1977), there was an 83 ms *benefit* (i.e.,  $235 - 152$ ) of anticipating correctly, which is somewhat larger than benefits found by Posner and colleagues.

However, more important is the finding that people actually *moved* in the incorrect direction on a majority of the trials (64%) in which they were falsely anticipating. Eventually, they did start moving in the correct direction, but not until 288 ms ( $144 + 144$  ms) had elapsed. This was *compounded* by the fact that the person now had farther to go to reach the correct target, so that arriving at the target was delayed even longer. And, in having to move farther to the target, the errant performer was less accurate in hitting the target, because the error in hitting a target is roughly proportional to the movement distance (see chapter 7). When we put together all these negative aspects of making an error, it is clear that the cost due to an incorrect anticipation can be quite high.

Many theoretical questions arise from these data on error production, but a major importance of these findings is in their application to various common activities. The pitch count in baseball is used by both batters (Gray, 2002, 2009a) and umpires (MacMahon & Starkes, 2008) to make predictions about the nature of the next pitch. A tennis player anticipating that a shot will be hit to her left moves to the left, only to experience that sinking feeling

when the ball is hit to her right. The defensive lineman in American football expects to be blocked to his left so leans or moves to his right, only to find that he is now being blocked to his right, making the task a very easy one for his opponent who was going to block him in that direction anyway. Effective coaching techniques employ the notion that anticipating has certain benefits and costs—and that one can determine whether or not to anticipate in a certain situation by weighing the probable gains against potential losses. In many situations, the benefit of correctly anticipating might be very small compared to the cost of a false anticipation (e.g., when a driver anticipates what another driver may do). In other cases, the reverse is true. Obviously, these factors will depend on the particular activity, as well as on the particular situation (e.g., the score of the game, position on the field, etc.).

## Signal-Detection Theory

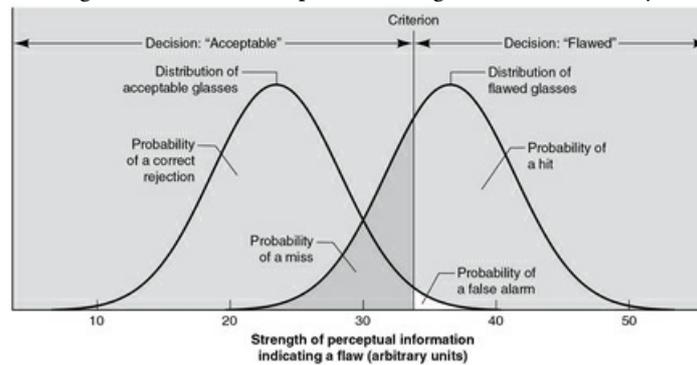
One of the most important components of motor performance occurs prior to any action at all. Taking in sensory information and making a yes/no decision on the basis of that information is often critical. Deciding whether or not to perform some action (e.g., “Should I turn left at an intersection or wait?”), and whether or not something occurred in the environment (e.g., “Did I see a warning signal or not?”), are examples of this kind of decision making. We discuss these issues further to illustrate a style of decision-making analysis that has been frequently referred to as *signal-detection theory* (Green & Swets, 1966; Swets, 1964).

Signal-detection theory assumes that we make decisions on the basis of what we perceived, and that such perceptual processes are participant to variability and error. As such, decisions are not based on what is actually happening but on what we *perceive* to be happening, which could be different. Consider the example in which a production-line employee’s job is to inspect glassware, searching for flaws or defects in color or shape. The employee examines each piece and, based on what she sees, accepts the good glasses and rejects the flawed ones, which are then destroyed. [Table 3.4](#) presents the four possible outcomes of making a decision about the glass. Here, the two possible decisions to be made by the employee are combined with two “truths” regarding whether or not the glass was actually flawed. In two situations the employee makes a correct decision: when she judges a flawed glass to be flawed (called a *hit*), and when she judges an acceptable glass as acceptable (termed a *correct rejection*).<sup>4</sup> However, in two other cases, the employee makes an error. In one case, she judges an actually acceptable glass as flawed (called a *false alarm*); in the other, she fails to detect the flaw in the glass and judges it as acceptable (called a *miss*).

Table 3.4 Four Possible Outcomes of a Decision to See a Flaw in a Glass			
		EMPLOYEE'S DECISION	
		No (no flaw)	Yes (flaw in glass)
ACTUAL (TRUTH)	Glass is not flawed	Correct rejection	False alarm
	Glass is flawed	Miss	Hit

Signal-detection theory assumes that the “strength” of the perceptual information about which a decision is to be made varies along a continuum, and has a *normal distribution* (i.e., has a dispersion of scores with known statistical properties) as seen in [figure 3.17](#); by convention, the area under these normal curves is taken to be 1.0. There are two curves here, one representing the situation with a (truly) flawed glass (curve on the right in [figure 3.17](#)) and one indicating an acceptable glass (curve on the left in [figure 3.17](#)); of course, for a given glass, only one of these curves can exist, depending on whether or not it is actually flawed, so only one of these two curves can actually exist at the same time. The *x*-axis represents a hypothetical measure of the “strength” of the sensory information pointing to the conclusion that a particular glass is flawed, with increased strength (moving to the right along the axis) indicating more (or “stronger”) information that a flaw exists. A particular glass has a particular strength for an observer, with some dispersion about the mean because the perceptual processes are variable or “noisy.” The *y*-axis refers to the probability that a certain strength will be perceived on some occasion when the mean strength is at the center of the curve. The *y*-axis refers to the probability that a particular perceptual strength will occur. In our example, for a given glass, sometimes the glass appears to be more flawed than it is and sometimes it appears to be less flawed. And, for an acceptable glass (left curve), sometimes the unflawed glass even *appears* to be more flawed than an actually flawed one, leading to errors in judgment by our employee.

Figure 3.17 Basic components of signal-detection theory.



## Setting the Criterion

According to signal-detection theory, the actual process by which humans make decisions occurs when a *criterion* (a kind of cutoff point) is set along the  $x$ -axis, as illustrated in [figure 3.17](#). The location of the criterion is usually described by a measure called  $\beta$  (beta; see Green & Swets, 1966, for a formal definition). Here we have the curves for the two glasses but have added the criterion at 33 “strength units.” This criterion is set by the employee as a result of the task instructions, his or her experience, and various biases he or she might have about the task. The criterion is a decision rule: Whenever the employee perceives the strength of the signal to be greater than 33 strength units, he or she makes the decision that the glass is flawed; if the signal is less than or equal to 33 strength units, he or she decides that the glass is acceptable. This provides a “rule” that the employee uses to make decisions as he or she examines the various glasses.

The setting of the criterion allows the employee to adjust the sizes of the various kinds of errors he or she is willing to make (see [table 3.3](#)). Suppose that the employee is biased by a perfectionist employer so he or she feels that a flawed glass should never go undetected. In this case the employee would set the criterion very far to the left (say, around 20—far to the left of the flawed-glass curve in [figure 3.17](#)), so that essentially *all* of the actually flawed glasses would be detected and destroyed. The problem with this is that many actually acceptable glasses would be destroyed as well (i.e., those glasses to the right of “20” on the acceptable-glass curve in [figure 3.17](#)). On the other hand, if maximizing production volume is the employer’s goal and some flaws are tolerated, then the employee would set the criterion farther to the right (say, around 40), so that an acceptable glass is almost never judged to be flawed. In doing so, however, he or she will accept some flawed glasses. Thus, this procedure allows the employee to “trade off” the quality of the glassware for the quantity of glassware produced—a classic issue in manufacturing. Another classic example in signal-detection analysis is the job of the radiologist, which is to detect the presence or absence of a tumor in an X-ray (Swets, Dawes, & Monahan, 2000). There are many other practical examples, especially in situations in which the individual must make a decision based on sensory information.

## Misses and False Alarms

Now, with the addition of the criterion, we can relate the curves in [figure 3.17](#) to the types of decisions represented in [table 3.4](#). Consider the rightmost curve, indicating that the glass being judged by the employee is actually flawed. Given the employee’s criterion at 33, the probability of detecting that this glass is flawed is represented by the area to the right of the criterion (light gray shaded area), which is about 60% of the area falling beneath the flawed-glasses curve. Note that this is the probability of a *hit*—correctly detecting that the flawed glass is flawed [i.e.,  $p(\text{hit}) = 0.60$ ]. On the other hand, the probability of judging this glass acceptable is the remaining 40% of the area under the flawed-glasses curve that lies to the left of the criterion (dark gray shading). This is the probability of a *miss*—judging that a flawed glass is acceptable [i.e.,  $p(\text{miss}) = 0.40$ ].

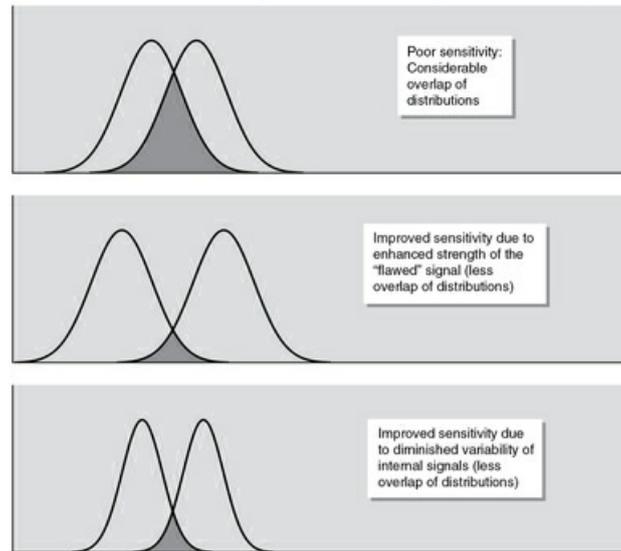
Next, consider the case in which the employee is examining an actually acceptable glass, represented by the curve on the left in [figure 3.17](#). Here, the probability of judging this glass as flawed is represented by the area under the

left curve lying to the right of the criterion (white section), which represents about 15% of the area under the acceptable-glasses curve. This decision is a *false alarm*, because the acceptable glass was judged to be flawed [i.e.,  $p(\text{false alarm}) = 0.15$ ]. Finally, the probability of judging the good glass to be acceptable is given as the area under the left curve to the left of the criterion (light gray shaded area), which represents the remaining 85% of the area under the acceptable-glasses curve. This was termed correct rejection, because the acceptable glass was correctly rejected as one being flawed [i.e.,  $p(\text{correct rejection}) = 0.85$ ].

### *Reducing Errors*

In this kind of analysis, the two types of errors in [table 3.4](#) occur because of *overlap* in the distributions seen in [figure 3.17](#). This overlap can be reduced in essentially two ways, as shown in [figure 3.18](#). We can see one way by comparing the top example in [figure 3.18](#) with the middle example, in which the classes of objects being evaluated are more physically different. Imagine a situation in which the manufacturing process produces glasses that either are essentially perfect or have a massive flaw (e.g., a severe discoloration). Now, the means of the “acceptable” and “flawed” distributions are far apart, resulting in very little or no overlap and essentially no misses or false alarms (middle example). Secondly, overlap can be smaller if the variability of the two distributions is reduced, as seen in the bottom example in [figure 3.18](#), while the means are kept the same distance apart as in the top example. Ways to accomplish this might be to enhance training for the employees, to select people who are very talented perceptually, or to provide more effective lighting or background conditions to facilitate visual detection. There are nearly countless real-world examples. One of these concerns the effect of viewing conditions on signal-detection errors when soccer officials make offside calls; the visual angle at which the play was viewed contributes greatly to the specific types of errors made (Oudejans et al., 2000; see also Baldo, Ranvaud, & Morya, 2002).

Figure 3.18 Effects of reducing variability in signal-detection judgments.

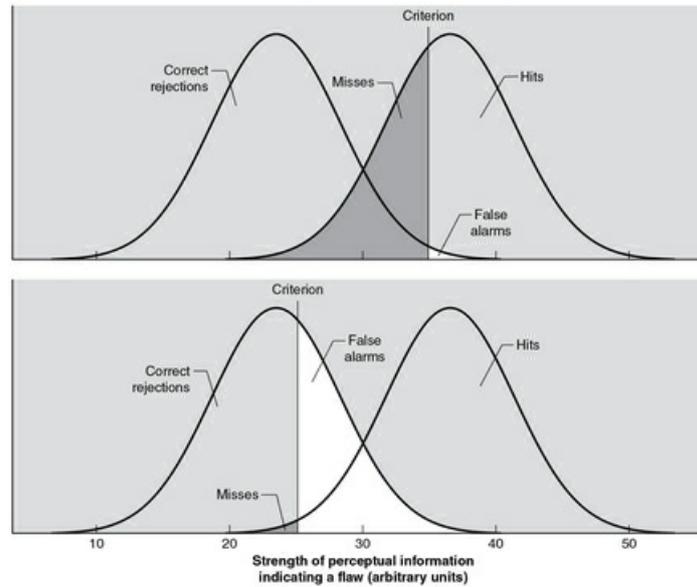


### *Nature of Decision-Making Errors*

One of the advantages of signal-detection methods has to do with evaluation of the nature of the errors that participants make, as well as evaluation of the effects of various experimental variables (e.g., lighting conditions) on detection. Benefits in accuracy can come in essentially two different ways.

First, consider our example with glassware-flaw detection under different lighting conditions. From [figure 3.19](#), assume that the employee chooses to enhance the lighting in his or her workplace, and that this enhanced lighting produces a shift in the employee's criterion (i.e., a shift in  $\beta$ ), say to the right from 25 to 35 units. This shift in  $\beta$  results in a reduction in false alarms, but at the same time produces an *increase* in misses. These kinds of changes, and the shift in the types of errors that result, reflect the participant's voluntary choice of criterion ( $\beta$ ), perhaps due to lighting choices, or perhaps because of a new directive from the company hierarchy, new ownership, or the like.

Figure 3.19 Effects of shifting the criterion on signal-detection errors.



Second, the effects of the lighting change might reduce the variability in his or her detections, as in [figure 3.18](#) (bottom example). This kind of shift reflects a fundamental change in detection *sensitivity* and is independent of a shift in criterion ( $\beta$ ). This kind of shift in sensitivity is reflected in a measure called  $d'$  (“d-prime”), which represents the amount of separation between the means of the two distributions.<sup>5</sup> Note that when this happens, the number of both misses and false alarms can be reduced because the participant has become a more sensitive “detector” of the flaws.

Finally, experimenters examining decision making usually report both  $\beta$  and  $d'$  in their experimental write-ups. In our example, we might have said that the lighting conditions not only produced a shift in  $\beta$  but also an increase in  $d'$ . The reader would then know that the improved lighting conditions not only increased the fundamental detection sensitivity ( $d'$ ), but also had an effect on the participant’s choice of criterion ( $\beta$ ).

# Memory

So far, our focus has been on what happens to information as it enters the system and is processed, eventually leading to a response. Many scientists believe that information must be stored like a file on a hard drive, to be called upon later; this storage is memory.

Memory is one of the most controversial and highly debated topics of information processing. Researchers tend to conceptualize ideas and experimental methods according to particular theoretical *frameworks*, which vary greatly among psychologists. In this book we take a neutral approach and briefly present one of these frameworks; for more complete discussions, consult one of the many books on this topic (e.g., Roediger, 2008a).

Memory is considered to be a consequence of information processing. In other words, when previously processed information influences current information processing, we assume that memory is the reason. Indeed, when viewed this way, it is obvious that everything humans do is influenced by memory. The current state of a person's skills and knowledge reflects previous information processing. Thus, we don't doubt that memories exist. Rather, the debate among psychologists concerns (1) how memory affects the performance of daily activities and (2) what form these memories might take. Furthermore, in the verbal-cognitive domain researchers have been interested in the function of memory rather than in describing the rules of remembering (see Nairne, 2001). In this latter framework, memory developed to provide a survival advantage; in other words, memory was crucial for evolutionary fitness.

## Direct Versus Indirect Influences of Memory

Memory seems to influence our daily activities in two rather distinct and separate ways. Memory has a direct influence when one makes a deliberate attempt to recollect past experiences for the purpose of facilitating current information processing (e.g., Richardson-Klavehn & Bjork, 1988). For example, one of life's awkward moments occurs when you meet an acquaintance on the street and cannot recall the person's name. In this case, there is a failure to recall a specific memory as a purposeful and explicit means to solve a problem (addressing the person by name). Scientists use terms such as memory *search* and *retrieval* to describe deliberate attempts to use memory in a direct way.

Memory can also have an indirect effect on information processing. For example, in the act of typing, the production of the letters on the computer screen is determined by coordinated actions of the two hands. In this case, the memory for past experience (i.e., learning) in typing is having an indirect impact on the ability to carry out this activity. You do not need to recollect specifically when you last typed, or even when you learned to type, in order for the memory of the skill to influence your performance. One does not have to be conscious that memory is being used in order for it to influence performance. Motor skill can be described mainly in terms of an indirect memory influence. Because this book is about the learning and control of motor skills, our interest in memory is in how it affects current information processing indirectly. However, much of what is known about memory comes from experiments in which participants are asked to recall or recognize information in a direct manner (i.e., consciously).

In the remainder of this chapter, we describe a rather traditional distinction that psychologists have made among various memory systems, customarily labeled *short-term sensory store (STSS)*, *short-term memory (STM)*, and *long-term memory (LTM)*. In the last chapter of the book (chapter 13, "Retention and Transfer"), we focus on the indirect influences that memory for motor skill has on our daily activities.

Psychologists sometimes refer to these ideas as "box theories" of memory, because the storage systems are often discussed as if they were *places* in which information is stored, which is a common metaphor for memory (e.g., like a computer hard drive or a university library). However, one should note that this is just one way to conceptualize memory—other views discuss memory simply as the persistence of the products of information processing,

without taking a stand about memory's location. This reflects one of the many controversies that make the study of memory so interesting (see Roediger, 2008b, for a compelling historical review of the memory literature).

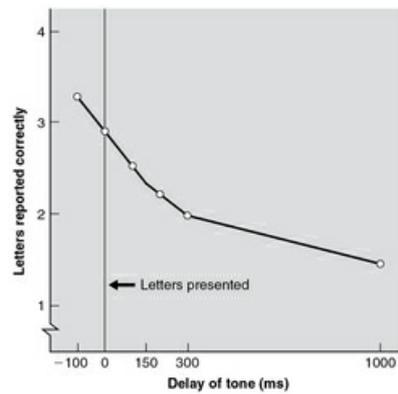
## Short-Term Sensory Store

The most peripheral memory is thought to hold massive amounts of information, but only for brief periods of time. When information is presented to the system, STSS accepts it without much recoding and then loses it rather quickly as new information is added. Just as the redness of a burner on an electric stove fades when the burner is turned off, the information in the STSS is thought to fade or *decay* with the passage of time. Such a system can be proposed for each of the stimulus modalities—vision, touch, audition, kinesthesia, and so on.

Some of the earliest and strongest evidence about STSS came from the work of Sperling (1960). Sperling presented a matrix of three rows of four letters very briefly and under controlled conditions. The matrix was presented for 50 ms so that the participant's impression was a bright flash of the letters. One of three tones was also presented, indicating which row of four letters the participant was to recall. The tone could be presented 100 ms before the letter matrix was flashed on, simultaneously with the letter matrix, or 150, 300, or 1,000 ms after the matrix appeared.

The number of letters recalled in Sperling's experiment is plotted as a function of the temporal location of the tone in [figure 3.20](#). When the tone was presented before the letters, the recall was about 3.3 letters (out of 4). When the tone was presented 150 ms after the letters, recall was only about 2.3 letters. When the tone was presented after a full second, recall was only about 1.5 letters.

Figure 3.20 Number of items correctly recalled as a function of the delay of the tone indicating which row should be recalled.



Reprinted from G. Sperling, 1960, "The information available in brief visual presentations," *Psychological Monographs* 74: 498.

The concept revealed in Sperling's experiment is that all of the letters are delivered by the flash to STSS and are stored briefly. However, the participant does not know which of the rows to attend to until the tone is presented. If the tone is presented immediately, the letters are still available and the participant can recall them. But if the tone is delayed, the letters have begun to decay from STSS, and the participant cannot report as many of them. This evidence suggests that (a) STSS is capable of holding all the information presented to it (because the participant could report any of the letters in the row if the tone was presented immediately) and (b) STSS loses information very rapidly with time.

On the basis of later experiments, the information in STSS is thought to have a maximum duration of about 1 s, with a more practical limit of about 250 ms. Also, it involves rather *literal* storage of information, in that the stimulus is recorded in the same way it came into the system in terms of both spatial location and form; this is analogous perhaps to how film records images that enter the lens of the camera ([table 3.5](#)). Contents of STSS are then available for further processing.

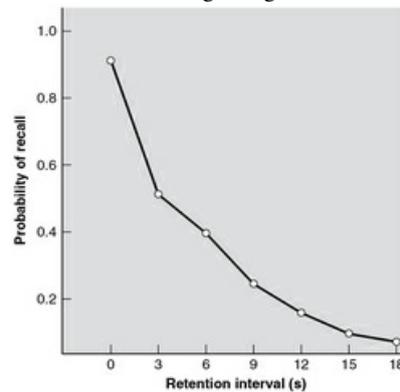
Attribute	MEMORY SYSTEM		
	STSS	STM	LTM
Storage duration	Less than 1 s	1 s to 60 s	Seemingly limitless
Type of coding	Very literal	More abstract	Very abstract
Capacity	Seemingly limitless	$7 \pm 2$ items	Seemingly limitless

## Short-Term Memory

Short-term memory is thought to be a storage system for information delivered either from STSS or from LTM. It has a limited capacity and a relatively short duration. Originally, STM was thought of as a kind of “work space” for processing, and one where *control processes* such as decision making, rehearsal, coding, and so on are performed (Atkinson & Shiffrin, 1971). Peterson and Peterson (1959) and Brown (1958) provided evidence for this kind of system that was to have a strong influence on research in memory for the next two decades. In the paradigm developed by Peterson and Peterson, participants were provided with a single *trigram* (three unrelated letters, e.g., XBF) for a period of study time; then the letters were removed, and the participants had to count backward by threes from a three-digit number until recall of the trigram was requested, from 0 to 18 s later. The backward counting was intended to prevent the participant from rehearsing the trigram during the retention interval. Thus, the participant only had to remember the trigram after counting backward for up to 18 s.

Peterson and Peterson’s results are shown in [figure 3.21](#), where the probability of successfully recalling the trigram is graphed as a function of the length of the retention interval. When the recall was nearly immediate, the probability of recall was about 0.90; but when the retention interval was increased only by a few seconds, there was a marked decrease in the recall. This persisted until, at 18 s, almost no trigrams could be recalled. The evidence suggests the existence of a memory system that loses information rapidly (in about 30 to 60 s) unless the information is *rehearsed* in some way.

Figure 3.21 Probability of correct recall of a single trigram as a function of the retention interval.



Reprinted from L.R. Peterson and M.J. Peterson, 1959, "Short-term retention of individual verbal items," *Journal of Experimental Psychology* 58: 198.

### *Short-Term Memory Versus Short-Term Sensory Store*

A major difference between STSS and STM ([table 3.5](#)) relates to capacity. Previously we mentioned that the capacity of STSS is very large—practically limitless. However, on the basis of experiments in which participants have been asked to remember as many members of a list of items as they can, evidence suggests that STM has a capacity (often called the *span* of memory) of only about seven (plus or minus two) items (Miller, 1956). This conclusion, however, depends on the definition of an "item." Sometimes participants organize separate items into larger groups, so that each group may contain five "items" of its own; this process has been termed *chunking* (Miller, 1956). The idea is that if there are 55 letters to remember (e.g., the number of letters in the first sentence in this paragraph), it would be difficult to remember them as completely separate items without chunking. By chunking the letters into larger, more meaningful groups (words or sentences), one can recall the items more easily. In this sense, the capacity of STM is thought to be seven chunks. Ericsson, Chase, and Faloon (1980) showed that after 175 days of practice with a technique for chunking effectively, a participant was able to increase the capacity of STM from 7 to 79 items by creating larger and larger chunks. Therefore, there were probably only about seven chunks or groups of items held in storage at any one time.

Another distinction between STM and STSS ([table 3.5](#)) is in the nature of the coding processes. In STM, coding is considered to be abstract. For example, stimuli are given names, and the separate stimuli are often combined in various ways to produce chunks that can reduce the number of separate items in STM. Although many theories of STM do not directly say so, the implication is that STM is related to consciousness; those things in STM are essentially things of which we are consciously aware.

### *Working Memory*

Atkinson and Shiffrin's (1971) earlier notion was that STM comprised a kind of limited capacity "work space" where various operations were performed. More recently, this view of STM has been expanded and incorporated into the notion of *working memory* (e.g., Baddeley, 2003). Although there are differing viewpoints, the essential idea is that working memory is a part of STM where (a) information from STSS can be stored for processing, (b) information from LTM can be retrieved for processing and integrated with information from STSS, and (c) effortful and limited-capacity conscious processing (*controlled processing*, see chapter 4) can be performed. Working memory is thought to contain items in a high level of activation for rapid access, but these are lost relatively quickly unless they are attended to, rehearsed, or allocated some of the limited capacity (Anderson, 1990).

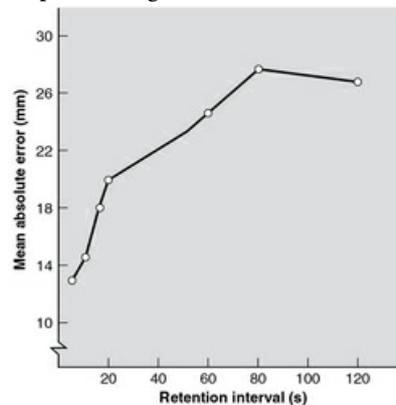
For motor behavior, the most important idea is that information processing entailing the choice of actions is involved in working memory, which suggests that working memory is closely related to the response-selection stage mentioned earlier in this chapter. Also, during the response-programming stage, information in the form of stored motor programs—described more fully in chapter 6—or other well-learned information about a task can be retrieved from LTM. In working memory, presumably, environmental information from STSS (such as the

locations of seen objects, speed of a flying ball) can be integrated with information from LTM, creating what some term an “action plan” that takes into account one’s stored capabilities and the specific environmental demands. The prepared movements are then triggered from working memory to generate muscle contractions and actions.

### *Motor Short-Term Memory*

In a motor analog of verbal STM, Adams and Dijkstra (1966; Posner & Konick, 1966) required blindfolded participants to move a slide along a trackway until it struck a fixed stop that defined a criterion target position. Then the participant moved back to the starting position to wait for the remainder of the retention interval (from 10 to 120 s), after which the participant attempted to move the slide to the criterion position with the stop removed. The absolute error in recalling the position increased sharply as the retention interval increased from 10 to 60 s and changed very little thereafter ([figure 3.22](#)). These findings closely paralleled the early findings of Brown (1958) and Peterson and Peterson (1959) with verbal materials, in that nearly all the forgetting of the position occurred within the first 60 s, which is interpreted as the approximate upper limit for retention in short-term verbal memory. Chapter 13 presents more about short-term motor memory studies. Long ago, James (1890) proposed the distinction between “primary memory” (what is today called STM) and “secondary memory” (today’s LTM), described next.

Figure 3.22 Absolute error in positioning recall as a function of the retention interval length.



Reprinted, by permission, from J.A. Adams and S. Dijkstra, 1966, 'Short-term memory for motor responses,' *Journal of Experimental Psychology* 71: 317. Copyright ©1966 by the American Psychological Association.

## Long-Term Memory

When items are practiced (or rehearsed), which of course requires information-processing activities, they are in some way transferred from short-term storage to long-term storage, where they can be held more permanently and protected from loss. An example is learning a new phone number. The first time you hear it, you are likely to forget it quickly if you do not rehearse it. Practice results in the transfer of the number to more permanent storage. In some cases, this storage is indeed permanent. Can you remember what your home phone number was when you were a child? We can.

Long-term memory, of course, provides the capability for making movements that have been practiced before. Some of the variables that appear to determine retention of well-learned acts are discussed in chapter 13. For now we can say that practice leads to the development of "better" or "stronger" (or both) LTM for movement and that these memories are often present after many years, even without intervening use of that stored information. Riding a bicycle is the most often cited example, as people appear to be able to ride acceptably well after 40 years or more with *no* intervening practice.

Another major distinction between LTM and STM relates to the amount of information that can be held ([table 3.5](#)). Most argue that STM has a functional capacity of about seven chunks, whereas LTM must have a very large capacity indeed. In the motor realm, the analog of well-learned facts and principles is well-learned motor skills. Thus, the functional capacity of motor LTM must also be very large if it is capable of retaining all of the movements that humans can typically perform on demand.

The cognitive psychology of memory might not be applicable to motor skills. Imagine you are a skilled football (soccer) player. Do you store the memory of your free kick that occurred in the first half of the third game of the season? If the kick was memorable (a goal was scored), you might remember the event but not the actual movement. Skilled movements appear to be produced without much conscious awareness (Fitts & Posner, 1967), but the consequence of the movement does access your conscious awareness. Thus, you can recall many aspects of the kick but not the actual movement. The question of the nature of motor memory is at the heart of issues in motor control. In chapter 6 the generalized motor program construct (Schmidt, 1975) will serve as the vehicle for long-term memory of motor skills.

## Summary

We can describe a great deal about the way people move by considering the human as an information-processing system that takes in information from the environment, processes it, and then outputs information to the environment in the form of movements. Using the concepts of additive-factors logic first advanced by Sternberg (1969), *stages of processing* can be defined and studied through the use of RT methods. The first stage, called *stimulus identification*, concerns the reception of a stimulus, preliminary (preconscious) analyses of features, and extraction of patterns from the stimulus array. Variables like stimulus clarity and stimulus intensity affect the duration of processing in this stage. A second stage, called *response selection*, concerns the translation or decision mechanisms that lead to the choice of response. The duration of this stage is sensitive to variables such as the number of S-R alternatives and S-R compatibility (the extent to which the stimulus and response are “naturally” linked). The final stage, called *response programming*, is associated with changing the abstract idea of a response into muscular action. The duration of this stage is related to variables affecting the response, such as response complexity and response duration. Some of the processing in some of these stages can apparently be bypassed by anticipation. Providing both spatial and temporal predictability allows so-called early responding, whereas providing other information leads to increased readiness and faster response.

Another aspect of information processing that considers factors related to making decisions has been termed signal-detection theory and involves two separate types of information-processing activities: setting the criterion for making a decision, and the sensitivity of the system that is used to make the decision. Factors such as the relative importance of the type of error that would result from a wrong decision are major influences on setting the criterion, whereas the skill level of the participant and the nature of the environmental information are major factors in the sensitivity of the information upon which the decision is based.

Parallel to the ideas about stages of processing are concepts about information storage systems, or memory. Motor skills use memory in an indirect way, although much of what we know about memory involves directed remembering. In a common framework, memory can be thought of as consisting of three compartments: a *short-term sensory store (STSS)*, capable of storing a large amount of literally coded information for perhaps a second; a *short-term memory (STM)*, sometimes discussed as *working memory*, capable of storing only about seven (plus or minus two) abstractly coded items for perhaps 30 s, as well as providing a kind of “work space” for conscious information processing; and a *long-term memory (LTM)* capable of storing very large amounts of abstractly coded information for long periods of time.

### Student Assignments

1. Answer the following questions and bring the information to class for discussion:
  - a. Discuss an everyday-life example of uncertainty that illustrates the concept of information theory.
  - b. Choose any sport to illustrate the contributions of each of the three stages of information processing.
  - c. Using the same sport used to answer question 1b, describe examples of the various kinds of anticipation.
2. Find a research article that uses signal-detection theory to describe processes involved in decision making.

### Notes

<sup>1</sup> It is fitting that today, F.C. Dondersstraat (which would be translated as “F.C. Donders Street” in English) runs adjacent to Donders’ original lab in Utrecht, Holland.

<sup>2</sup> Note that our description of Henry and Rogers’ (1960) most complicated task (C) is slightly different than in earlier versions of this book, due to recent revelations about a small error in the describing the apparatus in the original article (Fischman et al., 2008).

<sup>3</sup> This finding is closely related to research on voluntary motor timing, which is discussed in considerable detail in

chapter 7. Essentially, the research concludes that producing a string of regular time intervals (e.g., as in drumming) is more variable as the duration of the intervals lengthens (e.g., the variability in producing 1 s intervals is greater than the variability in producing 500 ms intervals). The foreperiod duration effect is similar—anticipating the *end* of a regular foreperiod is more variable as the foreperiod duration lengthens.

<sup>4</sup> Perhaps the use of the labels “hit” and “correct rejection” in this example is confusing. Consider that the employee is searching for a flawed glass and, when he or she finds one, this is a hit. Accepting a “good” glass is then a correct rejection (i.e., a “good” glass is rejected as being a flawed glass).

<sup>5</sup> Students often find this confusing because the separation (in centimeters) between the means in the top and bottom panels in [figure 3.18](#) is the same. But these are actually measured in standard deviation ( $Z$ ) units based on the standard deviation of the distributions, and these units are smaller in the lower panel than in the upper panel because the variation of the distributions is smaller. The second panel has a larger  $d'$  than the top panel because the separation is greater with similar standard deviations; it is larger in the lower panel than the top panel because of the reduction of standard deviation with a constant mean difference.

# Chapter 4

## Attention and Performance

Attention has always been a topic of major interest to psychologists and motor behavior researchers. Early research and theorizing began in the 19th century (Cattell, 1886; Welch, 1898), and interest in the topic remains high today. Much of the early work involved introspection; for example, William James (1890), one of the most renowned experimental psychologists, wrote:

Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others. (pp. 403-404)

But does everyone *agree* on what *attention* is? Many theorists, such as Norman (1976) and Moray (1970), suggested that different definitions of attention exist, and people use the term in a variety of ways. Consider the task of driving a car. Drivers must be aware of a preplanned route, as well as where they currently are in relation to the route, in order to make appropriate turns at the right times. The driver must also be aware of other traffic (e.g., cars, pedestrians, and bicyclists) and be capable of responding to sudden changes. The control of movement requires another type of attention, although we spend less time and energy thinking about how to coordinate our limbs in time and space as skill develops. Still other types of attention are required to offset the mental drowsiness that accompanies long periods of driving without rest, or to talk on a cell phone. So, as we read in the quote from William James' description of attention, a number of features of the phenomenon are considered important and reflect various ways to think about the different *types* of attention that may exist.

# Types of Attention

There are many different ways to view the concept of attention. One of these is the notion that attention is *limited*: We can attend to only one thing at a time, or think only one thought at a time. In terms of motor behavior, we seem strongly limited in the number of things we can do at a given time, as if the limits to some maximum “capacity” would be exceeded if too much activity were attempted. Another important feature is that attention is *selective*: We can concentrate on one thing or on something else and can freely shift attention back and forth among numerous things. Here we discuss a few of the types of attention that are particularly relevant in the control of motor skills. Note, however, that the topic of attention entails a very broad research area—much more than can be covered in this chapter. The interested reader is encouraged to seek out some of the many excellent recent reviews for more in-depth discussion of attention (e.g., Baddeley & Weiskrantz, 1993; Folk & Gibson, 2001; Neumann & Sanders, 1996; Pashler, 1999; Shapiro, 2001; Wickens & McCarley, 2008).

## Attention and Consciousness

Early in the history of research on human performance, as implied by James’ (1890) statement, attention was linked to the notion of consciousness, which is defined loosely as “what we are aware of at any given time.” The term “conscious,” and in particular the concept of *unconscious behavior*, fell out of favor during the growth of behaviorism after the turn of the 20th century. The measurement of consciousness was troublesome because at the time the only way to understand what was “in” participants’ consciousness was to ask them to introspect, or “search their own minds,” and this was far too subjective for the behaviorists’ approach to accumulating data and theorizing.

Toward the end of the 20th century, however, the concept of consciousness saw a resurgence in popularity among cognitive neuroscientists, and that interest continues to grow (Cohen & Schooler, 1996; Posner & Petersen, 1990). Examining brain function using methods such as fMRI (functional magnetic resonance imaging) and TMS (transcranial magnetic stimulation) (see chapter 2) has allowed scientists to measure patterns of brain activity, revealing much more objective types of information than had previously been available through methods of introspection (Baars, 1997; Chalmers, 1995; Crick & Koch, 2003; Haggard, Clark, & Kalogeras, 2002). Consciousness has also been linked to the concept of *controlled versus automatic* processing (discussed later in this chapter). Performance on various memory tests (Roediger & McDermott, 1993), and the use of process-dissociation measures (Jacoby, Ste-Marie, & Toth, 1993), suggests an independence between conscious and unconscious influences on behavior. For example, automatic (unconscious) processing appears to be preserved well in older adults, whereas controlled (conscious) processing is quite susceptible to decline with aging ( Craik & Jacoby, 1996; Hasher & Zacks, 1988). Performance errors such as *action slips* (Norman, 1981) are often explained as situations in which an unconscious or automatic action has not been successfully inhibited or counteracted by conscious, controlled processing (Hay & Jacoby, 1996; Reason, 1990; Reason & Mycielska, 1982).

## Attention as Effort or Arousal

Another way to operationalize the notion of attention is based on the idea that when people perform attention-demanding tasks such as reading a challenging scientific article or diving in competitive swimming, they are expending mental *effort* that is revealed in various physiological measures. For example, Kahneman (1973) and Beatty (Beatty & Wagoner, 1978) have used pupil diameter, measured by special techniques that do not interfere with eye movement, as an indirect measure of attention. When participants are asked to perform various memory tasks, pupil diameter increases when they are under pressure to provide an answer; the increase is larger for more “difficult” tasks. Similarly, it is useful to consider attention as reflected by various physiological measures of *arousal*, a dimension indicating the extent to which the participant is activated or excited. Kahneman (1973) used physiological measures of skin resistance (resistance to a weak current passed between two electrodes on the skin decreases with increased arousal) and heart rate as indirect measures of the attention demand of various tasks.

## Attention as a Capacity or Resource

Another view of attention, and one that is an important component of the information-processing concepts discussed in chapter 3, suggests that humans possess a *limitation* in the *capacity* (or resources) available to handle information from the environment. The idea for the concept of a limited capacity of attention is illustrated in the ability to perform two tasks simultaneously. If one activity (*A*) requires attention, then some (or perhaps all) of the “pool” of limited capacity of attention must be allocated to its performance. Because the amount of this capacity is thought to be limited, some other activity (*B*) that also requires a certain amount of this capacity will compete with *A* for these limited attentional resources. When the combined need for resources exceeds the total amount of attentional capacity available, then *B* will *interfere* with the performance of *A*, and vice versa. Interference could be demonstrated in many ways: (a) *B* could suffer in performance speed or quality while *A* was relatively unaffected; (b) *B* could be unaffected while *A* suffered; (c) both *A* and *B* could suffer; or (d) *B* could be prevented from occurring altogether while *A* was in progress. These patterns of “interference,” or competition for attentional resources, could presumably tell us something about the nature of the limitations in capacity.

### *Interference as a Measure of Attention*

If two tasks can be performed as well simultaneously as each can be performed individually, then at least one of them does not require attention, or a portion of the limited capacity. We would say that at least one of the tasks is “automatic.” On the other hand, if one task is performed less well when it is combined with some secondary task, then both tasks are thought to require some of the limited capacity. In this instance, both tasks are *attention demanding*. Over the past few decades, this *interference criterion* became the critical test of whether or not a certain task “required attention.” Although this test for attention achieved popularity during the cognitive revolution, it is not really a new research method (Welch, 1898).

### *Structural Interference and Capacity Interference*

The simultaneous performance of two tasks can result in interference between them for a variety of reasons, only some of which would be interpretable as interference due to limitations in some central capacity (attention). To confront this problem, researchers have defined two kinds of interference: structural and capacity. *Structural interference* results when physical (or neurological) structures are the source of the decrement. For example, the hand can be in only one place at a time, and interference between using a touchscreen in a car dashboard to make a phone call and shifting gears in a car with the same hand would be due, at least in part, to this kind of limitation and not necessarily to a limitation in some central capacity. Also, the eyes can focus at only one signal source at a time, and thus detecting two simultaneous visual signals presented in widely different locations could suffer in processing speed because of a structural limitation, again not necessarily due to limitations in attentional capacity. On the other hand, when one can reasonably rule out the possibility that structural interference between two tasks is occurring, then a *capacity interference*—or a decrement in performance due to some limitation in central capacity (i.e., attention)—is inferred.

The concerns about “distracted driving” provide a good example of the difference between structural and capacity interference. Many laws dealing with distracted driving ban the use of *handheld* communication devices, the argument being that the perceptual and motor requirements for communicating with the device create structural interference with the hand and eye movements required for driving. The more important problem, however, is that the task of communication is not simply a structural interference issue—*hands-free* communication devices also interfere with the task of driving because of the attention (capacity interference) required to use them.

## Selective Attention

Very closely related to the limited-capacity view is the concept that we can direct (or *allocate*) attention to different inputs or tasks. Selective attention can be either *intentional* or *incidental*, depending on how a specific allocation

has been achieved (Eimer, Nattkemper, Schröger, & Prinz, 1996). Intentional selection occurs when we purposefully choose to attend to one source of information (e.g., listening to the radio) while avoiding or inhibiting attention to other sources (e.g., the television or someone talking to us). An involuntary capture of attention usually occurs as a response to an external stimulus—for example, when you suddenly pay attention to a loud or pertinent sound (e.g., the sound of two cars colliding). Theorists sometimes refer to intentional selection as “top-down” processing, and involuntary selection as “bottom-up” processing, to indicate that the orienting of attention is conceptually versus perceptually driven.

Selective attention is readily observed in the patterns of interference already mentioned in dual-task situations. Directing attention toward activity *A* may reveal deficits in the performance of task *B*, although no performance deficit is observed for *A*. However, by shifting the attention to activity *B*, you may observe that activity *A* is now the one that suffers and that performance of *B* is very proficient.

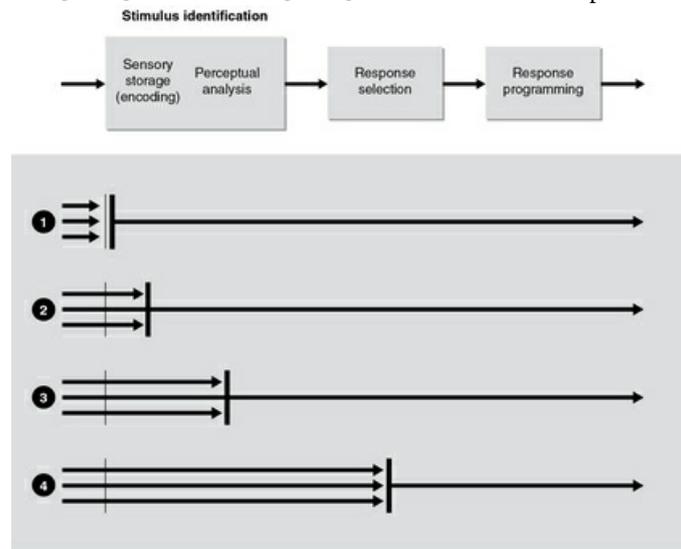
# Theories of Attention

If attention is defined as, or measured by, the degree of interference between two tasks, then which kinds of tasks do and do not interfere with each other, and under what conditions might these patterns of interference be expected to occur? Most of the everyday tasks we perform can be thought of as collections of processes involving stimulus input and encoding, response selection and choice, and motor programming and movement control. The fact that two complex tasks interfere with each other (or do not) might not be very meaningful by itself, because it would not be clear what the cause of the interference was or where in the information-processing activities the interference occurred (Jonides, Naveh-Benjamin, & Palmer, 1985). Did the two tasks require response-selection activities at the same time, or did they require movement programming at the same time? As a result, simpler laboratory tasks are used often in this research so that the various processing stages can be more specifically identified and studied. The following theories of attention attempt to explain the patterns of interference found in performing these types of tasks, using various hypothetical structures and processes.

## Single-Channel, Filter Theories

Some of the first few theories of attention (e.g., Broadbent, 1958; Deutsch & Deutsch, 1963; Keele, 1973; Norman, 1969; Treisman, 1969; Welford, 1952; see also B. Kerr, 1973), while different in detail, had some important features in common. They all assumed that attention was a *fixed* capacity for processing information and that performance would deteriorate if this capacity was approached or exceeded by the task requirements. These were single-channel theories of *undifferentiated capacity*, in that attention was thought of as a single resource that could be directed at any one of a number of processing operations. Theorists often described single-channel theories as *bottleneck* theories of attention, because the “neck” limits the information that can be later processed and its location determines when interference is likely to occur. Here, as shown in [figure 4.1](#), information flow is left to right, and many operations can occur at the same time in the large part of the bottle; but, at some point, a “bottleneck” is encountered, which allows only one operation at a time. A major question for these attention theorists was where (e.g., early or late) such a bottleneck, or “filter,” was located. These filter theories differed in terms of the kinds of information processing that required attention and, therefore, the location of the bottleneck during the stages of information processing.

Figure 4.1 Limits of attention in various stages of processing, according to various theories. (Line 1 represents the original single-channel theory [Welford, 1952]; line 2 represents Broadbent's [1958] filter theory; line 3 represents the Deutsch and Deutsch [1963] and Norman [1969] theories; and line 4 represents Keele's [1973] theory.)



### Early-Filter Theories

Welford's (1952) theory assumed that *all* processes require attention; in other words, the human could be regarded as a single information channel that could be occupied by one and only one stimulus–response operation (or “channel”) at a time. As illustrated in [figure 4.1](#), line 1, Welford's theory located the bottleneck at the earliest stage of information processing. Of course, if only one operation can be done at a time, then *any* task attempted at the same time as another task will interfere (or even be blocked altogether). Thus, this single-channel idea viewed a secondary task as a rather severe source of interference. For this reason, processing in the single channel is defined as attention demanding on the basis of the interference criterion described earlier.

Weaker versions of the single-channel theory denied that *all* the stages of processing require attention, especially the earliest stages, and therefore the location of the bottleneck was moved to a later stage in the sequence of processing. Thus, these other theories (Broadbent, 1958; Deutsch & Deutsch, 1963; Keele, 1973; B. Kerr, 1973; Norman, 1969; Treisman, 1969) presumed that early stages of processing occurred without attention but that attention was required at the later stage(s) of processing. Processing without attention implies *parallel processing*, such that a number of separate signals can be processed simultaneously without interfering with one another. For example, processes that translate sound waves into neurological impulses in the ear, and those that change mechanical stimuli into neurological activity in the movement receptors in the limbs, can occur together, presumably without interference. In other words, these theories assumed that peripheral (mainly sensory) information processing occurs simultaneously and without interference, but the theories differed with respect to the exact information-processing stages at which the interference occurs.

Broadbent (1958) and Deutsch and Deutsch (1963) theorized that a kind of *filter* is located somewhere along the series of stages of information processing ([figure 4.1](#), lines 2 and 3). According to these theories, many stimuli can be processed in parallel and do not require attention prior to reaching the filter. When the filter is reached, however, only one stimulus at a time is processed through it (the others being “filtered out”), so that the information processing from then on is sequential, requiring attention in the single channel. The decision regarding which stimuli are filtered out and which one is processed further into the single channel presumably depends on which signal arrives first to the filter, the nature of the activity in which stimuli are expected, and which stimuli are relevant to the task in question.

Lines 2 and 3 in [figure 4.1](#) show the locations of the proposed filter for these two theories. The sensory storage stage is considered the most “peripheral,” involving the translation of the physical stimuli into neurological signals.

The perceptual analysis stage involves the process that abstracts some preliminary, simple meaning from the stimuli (e.g., perception of right angles, or verticality). (Notice that the stages labeled *sensory storage* and *perceptual analysis* in the language of these theorists can be readily combined to yield the stimulus-identification stage discussed in chapter 3.) Broadbent viewed perceptual analysis and later stages as requiring attention, while Deutsch and Deutsch (1963), Treisman (1969), and Norman (1969) saw perceptual analysis as automatic (i.e., not requiring attention), with later stages requiring attention. Thus, these theories are similar, but they differ with respect to where the proposed filter is located in the chain of processes.

### *Keele's Late-Filter Theory*

Keele's (1973) theory of attention places the bottleneck even later in the sequence of stages than the Deutsch and Deutsch theory. According to Keele's concept, information is processed in parallel and thus is attention free through the stimulus-identification and response-selection stages. At this point, *memory contact* is made, in which certain associates of the stimuli are activated, such as items in related categories, items closely associated with the stimulus, or even certain aspects of early preparation for a movement that is to be triggered by the stimulus. In this view, because all such stimuli "contact memory" at about the same time, selective attention must determine which of these memory contacts are to receive further processing. These subsequent operations, such as memory searches, rehearsal, recoding, or readying a movement for production, are the ones that are attention demanding, according to Keele. If two such processes are required at the same time, decrements in performance will occur. Thus, Keele's view is represented as line 4 in [figure 4.1](#), indicating that processing can be in parallel and without interference even through response selection, with subsequent operations requiring attention.

## Flexible Allocation of Capacity

In contrast to filter theories, an argument presented by Kahneman (1973) was that the *capacity* of attention could change as the task requirements change. For example, as the "difficulty" of two simultaneous tasks increases, more capacity is used in processing the information. Eventually, when task requirements for processing two streams of information begin to exceed maximum capacity, decrements occur in one or more of the simultaneously presented tasks; that is, interference occurs. Kahneman's theory also differed from the earlier views by suggesting that parallel processing could occur in all of the processing stages but with some demand on attention at the same time. Kahneman's view that the amount of allocated attention is not fixed creates a number of difficulties for certain secondary-task techniques for measuring spare capacity (see chapter 2), which assume that capacity is fixed.

Other theories of attention have focused on issues of flexibility in information processing. For example, rather than assuming that processes requiring attention can deal with only one stimulus at a time, other theories suggest that these resources can be shared by parallel processing. How they are shared is presumably a function of the relative importance of the tasks, their relative difficulty, and other factors. Trade-offs between proficiency in two simultaneous tasks have been discussed by Norman and Bobrow (1975), Posner and Snyder (1975), and Navon and Gopher (1979).

## Multiple-Resource Theories

Some researchers have argued that attention should not be conceptualized as a *single* resource but rather as *multiple pools* of resources, each with its own capacity and each designed to handle certain kinds of information processing. In this view, for example, separate resources would be responsible for selecting the finger to make a movement and for selecting the movement of the jaw to say a word. Hence, these two operations could coincide without interference (e.g., McLeod, 1977; Navon & Gopher, 1979; Wickens, 1976, 1980; Wickens & Hollands, 2000).

Similarly, Shaffer (1971) and Allport, Antonis, and Reynolds (1972) argued that attention can be devoted to separate stages of processing at the same time. Such a position is inconsistent with fixed-capacity theories, in which the processing was thought to be confined to a single stage although it might be possible to perform one or more separate operations in parallel. These views help to explain skill in complex tasks, such as typing, simultaneous

translations, and sight-reading of music, for which attention is thought to be devoted to input (sight-reading) and output (muscular activation and control) stages at the same time.

## Action-Selection Views of Attention

In all of the viewpoints about attention that have been described, the basic assumption is that information-processing activities require some kind of capacity (or “fuel”) in order for behavior (skill) to occur. Decrements in performance result when various activities compete for this capacity. Some researchers, however, question the validity of this fundamental assumption. Scientists such as Neumann (1987, 1996; see also Allport, 1987, 1993) have criticized the various resource theories and presented a view that is considerably different. Neumann argued that when an animal or human has a certain momentary intention to obtain some goal (e.g., to run, to drink), many stimuli received at this time are processed in parallel in the early stages—the final product of this processing being the selection of a certain action. Then, *as a result* of this selection, certain other processes are *prevented* from occurring, or can occur only with great difficulty. Thus, in Neumann’s view, interference between two simultaneous tasks occurs not because attention (as a resource) is needed in order to perform various processes; rather, it occurs *because* an action has already been selected, and these other processes are completely or partially blocked. Thus, *selection* is the most basic and fundamental process of attention, not resources or capacity (see earlier discussion of Keele’s late-filter theory).

This theory has an interesting ecological aspect, in that if a particular action is important (e.g., escape from a predator) and is selected, then it would seem critical that other possible actions be prevented, at least for a while, until the original action has run its course. The selected action requires certain processes or structures for its completion, and preventing some other action from using them (and thus interfering with them) would ensure that the selected action would, in fact, have a good chance of being completed and of having its goal fulfilled. As we will see in the next sections, this theory is consistent with the general finding that very little interference occurs in processes related to stimulus processing, with most of the interference between tasks occurring in stages related to the planning or production of movements.

# Competition for Attention

It is beyond the scope of this text to do a thorough analysis of the extensive literature documenting the patterns of interference among tasks. For our purposes, however, some generalizations about the nature of these patterns, as well as about the situations in which the most and least interference seems to be produced, will enable us to have a reasonable insight into the nature of attention, at least as it relates to the selection and control of movement.

## Processing Unexpected Information

In this section, we examine the *competition* that exists for capturing attention—sometimes we are able to block or bypass things to which we do not want to attend, only to find that certain information is processed regardless of our intentions. Three specific research areas have arisen in the literature to demonstrate quite clearly that selective attention can be both *intentional* and *incidental*. The research areas discussed in the next sections include the Stroop effect, the “cocktail party phenomenon,” and inattentive blindness.

### *Stroop Effect*

A very interesting and powerful effect that helps us understand intentional and incidental information processing is the so-called *Stroop effect*, named after the psychologist who first identified the phenomenon (Stroop, 1935).<sup>1</sup> Many hundreds of research articles on the effect have been published since this classic article appeared, and the Stroop effect is now commonplace in numerous applications (MacLeod, 1991). The typical experiment involves at least two important conditions. In both, the participant is asked to watch a display and perform a simple task: to name the *ink color* in which a word is printed. In one condition, participants are presented with a neutral word and asked to name the color in which it is printed (e.g., for the word “house” printed in blue ink, the participant’s response would be “blue”). In the second condition, the word name is itself a color (e.g., for the word “blue” printed in blue ink, the participant’s response would be “blue”). Typically, the time to respond by naming the color is very fast when the word and target color are the same, or *congruent*. However, when the word name and the color in which it is printed are not the same, or *incongruent*, the participant’s response is typically delayed in time and quite prone to error (e.g., for the word “green” printed in blue ink, the participant’s response should be “blue,” but it is often incorrectly given as “green” or is delayed in time so that the error can be suppressed). This finding—namely that the color meaning of the word interferes with the naming of the ink color in which the word appears (if the two are incongruent)—represents the basic Stroop effect (many variations exist; see MacLeod, 1991, and MacLeod & MacDonald, 2000, for examples).

Why should an irrelevant dimension of the display (the name of the word) interfere with the intentional act of naming the color of the ink? Why can’t the participant simply focus on the color of the ink and ignore the word that the letters spell? One possibility is that since the processing speed for identifying the name of a color is slower than for naming a word (e.g., Fraise, 1969), the name of the word is more quickly readied as a response than is the name of the color. However, a clever experiment by Dunbar and MacLeod (1984) produced evidence that argued against this interpretation. In their studies, Dunbar and MacLeod presented the word names as you might see them in a mirror (reversed). Under these types of conditions, identifying the name of the word was much slower than naming the color. Nevertheless, the Stroop effect was still present when these mirror-oriented word names were presented in incongruent colors. Thus, the simple “speed of processing” explanation is insufficient to explain the Stroop effect. The resistance of the Stroop effect to conform to these and other theoretical predictions likely explains why psychologists have maintained a fascination with the nature of this attentional interference. A popular view is that the participant’s inability to ignore the irrelevant message is evidence that the irrelevant signal (color name) and relevant signal (ink color) are processed in parallel, perhaps without any interference in the early stages of processing.

### *Cocktail Party Phenomenon*

Another important illustration of the intentional and incidental effects of sensory-information processing is provided by the *dichotic-listening paradigm*. In a typical dichotic-listening experiment, the individual is presented (via headphones) with a different message in each ear. The participant's task is to ignore one of the messages and to concentrate on (and later report about) the other. Normally, participants are very skilled at concentrating on the intended message (termed "shadowing" the message) and ignoring the message being presented to the other ear. However, when a message cannot be ignored, the implication is that it is being processed through the stimulus-identification stage whether the individual tries to ignore it or not, perhaps without attention being required for that processing.

The dichotic-listening paradigm is a formal way to study the "cocktail party phenomenon" described by Cherry (1953). At large, noisy parties, attending to one conversation while ignoring the many other conversations is often quite difficult. But, with effort, the various potentially "interfering" conversations can be tuned out, just as they can in dichotic-listening experiments. Situations occur, however, in which the ongoing discussion in one of these unattended conversations cannot be ignored, such as when your name is spoken. In this case, some feature of the ignored message "gets through" to conscious processing—it captures our attention.

The findings from the dichotic-listening paradigm led to the suggestion that all of the auditory stimuli are processed through stimulus identification in parallel and without attention, and that some mechanism operates to prevent attention from being drawn to unwanted sources of sound. When the sound is particularly relevant or pertinent to us (e.g., our name or a danger alert, such as the sound of a car's horn), the stimulus is allowed to "pass through" for additional processing and attention. Perhaps stimuli from the environment had entered the system simultaneously and had been processed to some superficial level of analysis, with only those relevant (or pertinent) to the individual being processed further. Of course, this further processing will usually require attention, implying that two such activities cannot be done together without interference. Like the evidence from the Stroop effect, the evidence from these observations argues against the early-selection models of attention presented in [figure 4.1](#).

### *Inattentional Blindness and Change Blindness*

The "cocktail party phenomenon" is a nice illustration of how intentional and incidental human information processing coexist in daily activities. We can selectively filter out unwanted information yet be receptive to pertinent information when it arises. Another example of the competition for sensory-information processing illustrates a potentially dangerous consequence of selective attention—when intentional processing inhibits or prevents the processing of a critical sensory event. This failure to process incidental information is a frequent complaint in vehicle–bicyclist traffic accidents: The driver is looking for an available parking space or a specific street sign and fails to see the cyclist who is directly in front of the car. These are called "looked-but-failed-to-see" accidents (Hills, 1980) because the drivers often claim that they had been looking in the general direction of the accident victim but did not see the bicyclist at all (Herslund & Jørgensen, 2003; Koustanaï, Boloix, Van Elslande, & Bastien, 2008). Similarly, car drivers sometimes "overlook" motorcycles, especially during relatively attention-demanding driving maneuvers such as turning left (Wulf, Hancock, & Rahimi, 1989). In this scenario, the car driver violates the motorcyclist's right-of-way by making a left turn into the path of the oncoming motorcycle. Drivers frequently claim not to have seen the motorcycle.

One of the common reasons given for looked-but-failed-to-see accidents relates to the findings from studies using *selective-looking* paradigms. Essentially, these methods use the visual analog of the dichotic-listening paradigm (Neisser & Becklen, 1975) to investigate the cause of *inattentional blindness*—the failure to see certain visual stimuli when focusing on other stimuli. Typically, participants in a selective-looking paradigm are asked to focus on (and report on) the activities occurring in a visual display, but later are asked to report on other (normally obvious) visual events that occurred at the same time. For example, participants in a study by Simons and Chabris (1999) watched a video showing a basketball being passed among three players dressed in white shirts and another ball being passed among three players dressed in black shirts. The participant's task was to count the passes made by the team dressed in white and ignore the activities of the other team. What made this experiment particularly interesting was that an unusual event occurred about halfway through the video—a person dressed in a gorilla

costume walked through the middle of the two teams, stopped and faced the camera, then continued walking off screen. The “gorilla” was in perfect focus and was superimposed on the images of the ball game players—as if two separate movies were being projected onto a screen at the same time. After the trial, participants were asked how many passes were made, then questioned as to whether anything unusual had happened during the trial. Astonishingly, about half of the participants tested were completely unaware of the “gorilla.” An important additional finding was that if participants were not engaged in a primary task (e.g., counting the passes), then nearly all of them reported the unusual event. Also, individuals who have problems with *sustained attention*, such as people with multiple sclerosis, are more likely to see the gorilla (Feinstein, Lapshin, & Connor, 2012). The intentional task of processing specific information selectively in the visual-search task (the ball game information) made the participants unaware of other events that were occurring in the same visual field, even if the event was unusual (for other examples see Chabris & Simons, 2010; Driver, Davis, Russell, Turatto, & Freeman, 2001; Hyman, Boss, Wise, McKenzie, & Caggiano, 2010; Memmert & Furley, 2007; Simons, 2000).

A variant of this paradigm, illustrating what is called *change blindness*, reveals a similar effect. Participants in a change-blindness study are typically shown a series of still photos (or a video) of a scene in which a portion of the visual display disappears or changes significantly over time. Participants in the experiment often miss or fail to see the change (see Rensink, 2002; Simons & Rensink, 2005, for reviews). In one dramatic live demonstration of change blindness, an actor stops a person on the campus of a university to ask directions. While the participant (the person who is providing directions) explains the route to the actor, two people holding a large door walk between them. The actor is then *replaced* by one of the door carriers, who assumes the role of the lost actor after the door passes. Although the two actors look somewhat alike, they are clearly two different people. Yet nearly half of the participants in the study failed to recognize the change. The change-blindness phenomenon reflects a strong role of memory, and expectation, as to what we attend to and what we become aware of (consciously). Similar to what occurs with the inattentional-blindness effect, top-down processes play a very important role in attention and awareness.

Together, the results of experiments on the Stroop effect, the “cocktail party phenomenon,” and inattentional or change blindness illustrate that humans are capable of searching selectively and attending to specific information in the environment. Sometimes this intentional processing facilitates performance by filtering out unwanted information. At other times the process can have adverse consequences if the filtered information becomes important for task performance. Awareness appears to be a kind of confluence of top-down and bottom-up processes (Most, Scholl, Clifford, & Simons, 2005).

## Automatic and Controlled Processing

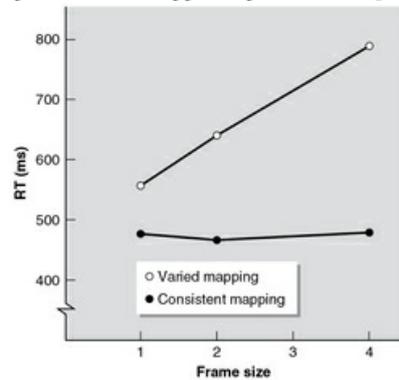
Whereas a number of “early” processes (stimulus encoding, feature detection, and so on) can apparently be conducted in parallel and without attention, it is clear that other processes prior to choosing an action cannot. For example, if you are asked to detect whether the name of your home town has a *t* in it, various mental operations are required in order for you to come to the answer, and common experience tells you that performing them would be detrimental to a number of other tasks that might be called for at the same time (e.g., remembering your friend’s phone number). This kind of processing is what Schneider and Shiffrin (1977) have called *controlled processing*. This type of processing is (a) slow; (b) attention demanding, in that other similar tasks interfere with it; (c) serial in nature; and (d) strongly “volitional,” in that it can be easily stopped or avoided altogether. But Schneider and his colleagues (Schneider, Dumais, & Shiffrin, 1984; Schneider & Fisk, 1983; Schneider & Shiffrin, 1977) have also argued for another class of information processing: *automatic processing*. This form of information processing is qualitatively different from controlled processing: Automatic processing (a) is fast; (b) is not attention demanding, in that other operations do not interfere with it; (c) is parallel in nature, with various operations occurring together; and (d) is not “volitional,” in that it is often unavoidable (Underwood & Everatt, 1996).

Schneider and his colleagues studied these processes using a variety of visual-search tasks. In one example, Schneider and Shiffrin (1977, experiment 2) gave participants two types of comparison stimuli. First, participants were presented with a memory set that consisted of one, two, or four target letters (e.g., *JD* represents a memory

set size of two). After the presentation of the memory set, they received a “frame” of letters that could also be composed of one, two, or four letters (e.g., *B K M J* represents a frame size of four). If either of the two letters in the memory set was presented in the frame (as *J* is in this example), the participant was to respond by pressing a “yes” button as quickly as possible; if none of the letters from the memory set was in the frame, a “no” button was to be pressed. Participants practiced under one of two conditions. In *varied-mapping* conditions, on successive blocks of trials the memory set would be changed. This meant that a given letter in the frame sometimes would be a target, and on other blocks of trials it would not be a target. Thus, seeing a *J* in the frame, for example, would in one block of trials lead to a “yes” response and in another block lead to a “no.” On the other hand, with *consistent-mapping* conditions, a given letter in the frame was either always a target or never a target, leading to a consistent response when it was detected (i.e., either “yes” or “no” but never mixed responses in different blocks of trials).

[Figure 4.2](#) illustrates the results for the “yes” responses from these conditions after considerable practice for a memory set size of four. The varied-mapping condition (open circles) shows a strong effect of the frame size, with reaction time (RT) increasing approximately 77 ms per item in the frame. On the other hand, there was virtually no effect of frame size on RT in the consistent-mapping condition. Both early in practice and later in practice, for the *varied-mapping* conditions, search of the frame for a target letter seemed to be slow, serial, and strongly influenced by the number of items to be searched; these features typify controlled processing. But after much practice with *consistent-mapping* conditions, the processing was much faster, appeared to be done in parallel, and was not affected by the number of items to be searched; this is typical of automatic processing. In other experiments using very similar tasks, Schneider and Fisk (1983) reported that after considerable practice with consistent-mapping conditions, participants could do these detections simultaneously with other secondary tasks without interference. However, sometimes these detections became unavoidable, as if they were triggered off without much control. One participant told of interference with her usual schoolwork (reading about history) after being in the experiment; an *E* (a target letter in the experiment) would unavoidably “jump out” of the page and distract her.

Figure 4.2 Reaction time (RT) to detect target letters in a letter matrix of one, two, or four letters (frame size) for varied- and consistent-mapping conditions; more letters to be searched led to no increase in RT for the consistent-mapping condition, suggesting automatic processing.



Reprinted, by permission, from W. Schneider and R. Shiffrin, 1977, "Controlled and automatic human information processing: 1. detection, search, and attention," *Psychological Review* 84: 20. Copyright © 1977 by the American Psychological Association.

For various reasons, however, the concept of automaticity is not perfectly clear. One problem is that if a process is to be truly automatic, then performance of *any* other simultaneous task should be possible without interference. Neumann (1987), in a review of this topic, argues that no information-processing activity has ever been shown to be interference free across all secondary tasks. Whether or not interference is seen—as well as the amount of interference—seems to depend on the nature of, or the relationship between, the two tasks (McLeod, 1977; Schmidt, 1987). Second, the findings of Schneider and colleagues showing no “resource cost” demands (i.e., no effects of frame size in [figure 4.3](#)), in fact, sometimes do show a very small, positive slope for the consistent-mapping conditions, suggesting that these tasks are not completely interference free. Recent thinking suggests that the controlled/automatic dimension may better be thought of as a *continuum* (MacLeod & Dunbar, 1988; Moors & De Houwer, 2006; Underwood & Everatt, 1996). Certain information-processing activities are attention free with respect to *certain kinds* of secondary tasks, and the problem is then to define which kinds of tasks will and will not interfere with what other kinds of tasks (Neumann, 1987). Various theoretical models have been developed that expand this view of automatic processing as a continuum, from memory-retrieval (Logan, 1988) and parallel-distributed processing perspectives (Cohen, Dunbar, & McClelland, 1990), for example.

The study of automatic processing, and of the ways in which it is developed with practice, has strong implications for understanding control in skills. Many processes in skills, whether they be the detection of individual letters or words as you read this sentence, or the recognition of patterns of automobiles in traffic, can, with extensive practice, become faster and more efficient. Such gains in skilled situations are of course extremely important, in that information-processing loads are reduced so that the performer can concentrate on other aspects of the situation (e.g., the meaning of a poem, navigation in driving), processing is much faster, and many processes can be done in parallel. On the other hand, such automatic processing can occur only with some “cost,” which is often seen when attention is drawn to the wrong place (distraction) or when an inappropriate movement is triggered (e.g., you respond to your opponent’s “fake” in tennis).

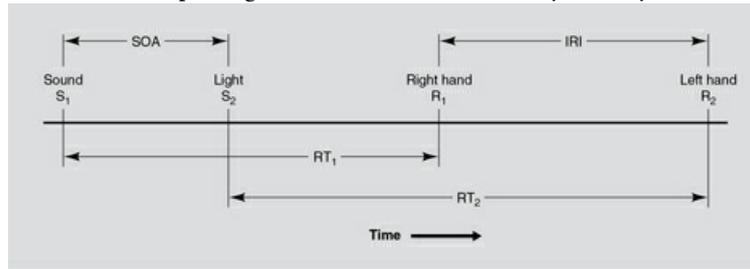
## Interference and Movement Production

Whereas the general findings are that many “early” stages of information processing can be done in parallel and without much interference from other tasks, the situation appears to be distinctly different with respect to the organization and initiation of movements. Research studies from various sources point independently to the view that *only one* movement can be initiated at a time. We turn next to the various lines of evidence for single-channel processing during these “late” stages of information processing.

### *Psychological Refractory Period*

Probably the most important evidence for single-channel processing emerges from the *double-stimulation paradigm*, in which the participant must respond to two closely spaced stimuli that require different responses. An example of this paradigm is shown in [figure 4.3](#). The participant is presented with a sound (stimulus 1, or  $S_1$ ) that requires a response by the right hand (response 1, or  $R_1$ ). After a very brief interval, a light is presented ( $S_2$ ) that requires a response by the left hand ( $R_2$ ). The two stimuli are presented in different modalities and require responses by different hands (to minimize structural interference). The stimuli are usually separated by at least 50 ms, and they may be separated by as much as 500 ms or even more; that is, the second stimulus could, in some situations, come well after the response to the first stimulus is completed. The separation between the onsets of the two stimuli is called the *stimulus onset asynchrony* (SOA). Further, the arrival of the signal onsets is usually randomly ordered, so that the participant cannot predict the occurrence or timing of a given stimulus (either  $S_1$  or  $S_2$ ) on a given trial. Thus, both stimuli must enter the information-processing system and be processed separately.

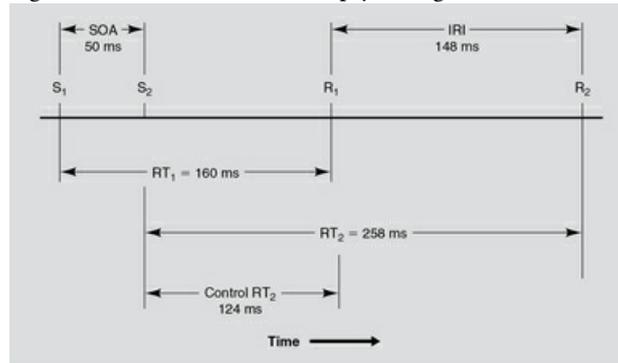
Figure 4.3 The double-stimulation paradigm (SOA = stimulus onset asynchrony, IRI = interresponse interval).



Experimenters have been interested especially in the RT to the *second* of the two stimuli (RT<sub>2</sub>) because it provides an indication about how the processing of the second stimulus has been affected by the ongoing processing of the first. The critical comparison is between RT<sub>2</sub> when preceded by a response to S<sub>1</sub> versus RT<sub>2</sub> when S<sub>1</sub> is not presented at all; that is, the “control RT<sub>2</sub>” is a measure of RT<sub>2</sub> when the participant does not have S<sub>1</sub> presented at all.

Using this method, experimenters have shown repeatedly that the processing of S<sub>1</sub> (through to R<sub>1</sub>) is generally *un*influenced by the presence of S<sub>2</sub>. However, the response to the second of the two closely spaced stimuli (i.e., S<sub>2</sub>) is influenced by the presence of S<sub>1</sub>. Here, the general finding is that RT<sub>2</sub> with S<sub>1</sub> present is considerably longer than RT<sub>2</sub> in the control condition (where S<sub>1</sub> is not present). Apparently the processing of S<sub>1</sub> and R<sub>1</sub> causes a great deal of interference with the processing of S<sub>2</sub> and R<sub>2</sub>. This important phenomenon was discovered by Telford (1931), who named it the *psychological refractory period (PRP)*.<sup>2</sup> The findings from Davis (1959), presented in [figure 4.4](#), are typical of the PRP effect. In this example, S<sub>2</sub> followed S<sub>1</sub> by an SOA of 50 ms. The control RT<sub>2</sub> (RT for S<sub>2</sub> in separate trials in which S<sub>1</sub> was not presented) was 124 ms. However, when S<sub>2</sub> followed S<sub>1</sub>, the RT<sub>2</sub> was 258 ms—about twice as long as the control RT<sub>2</sub>. Thus, the presence of S<sub>1</sub> and R<sub>1</sub> caused a marked increase in RT<sub>2</sub>. In other studies, the amount of increase in S<sub>2</sub> caused by S<sub>1</sub> and its processing can be 300 ms or more (Creamer, 1963; Karlin & Kestenbaum, 1968), making the RT for the second stimulus very slow—around 500 ms!

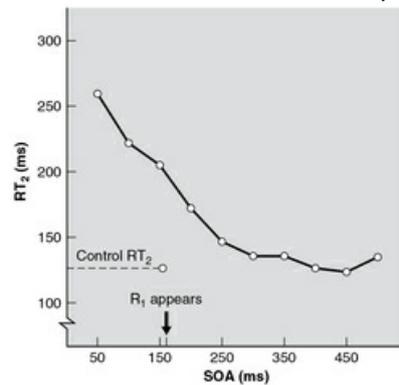
Figure 4.4 A demonstration of psychological refractoriness.



Adapted from Davis 1959.

Another important result in studies of refractoriness is the effect of the length of the SOA on  $RT_2$ . [Figure 4.5](#), also containing data from the Davis (1959) study, plots the values of  $RT_2$  for various values of the SOA, which ranged from 50 ms to 500 ms. Notice that, because the  $RT_1$  was about 160 ms in this data set, all the SOAs greater than or equal to 200 ms occurred when the second stimulus was presented after the participant had responded to the first (see also [figure 4.4](#)). In [figure 4.5](#), we see that as the SOA was increased from 50 ms to 300 ms,  $RT_2$  was shortened systematically, until there was no delay at all (relative to the control  $RT_2$  shown in the figure) with the longer SOAs. The most important points from [figure 4.5](#) are that (a) the delay in  $RT_2$  decreased as the SOA increased and (b) there was considerable delay even though  $R_1$  had already been produced (i.e., at SOAs of 200 ms or more).

Figure 4.5 Refractoriness decreases as the stimulus onset asynchrony (SOA) increases.



Adapted from Davis 1959.

One major exception to this generalization about the effect of the SOA should be mentioned. If the second signal follows the first one very quickly, with an SOA as short as, say, 10 ms, then the two signals are apparently dealt with as a single, more complex stimulus (called a *grouping* effect). The two signals elicit the two responses at about the same time but with a slightly greater RT for both than if only one of the responses had to be made to a single stimulus (see Welford, 1968). To explain this phenomenon, some writers (see Welford, 1968) have suggested the idea of a “gate” that “slams closed” about 50 ms after the presentation of  $S_1$ , presumably to prevent a second signal from entering the information-processing mechanisms and interfering with the response to the first signal. If a second signal comes before this point, the first and second signals are processed together as a unit, and the two responses are grouped.

### Single-Channel Hypothesis

A major contribution to the understanding of human information processing in motor tasks was made in 1952 when Welford proposed the *single-channel hypothesis* to account for the well-known findings about psychological refractoriness (see line 1 in [figure 4.1](#)). In his version of the theory, Welford hypothesized that if  $S_1$  entered the single channel and was being processed, then processing of  $S_2$  had to be delayed until the single channel was cleared—that is, until the response to  $S_1$  had been started. This was a strict serial-processing model, because  $S_1$  and  $S_2$  could not be processed together without interference.

How does this theory explain psychological refractoriness such as that seen in [figures 4.4](#) and [4.5](#)? Referring back to [figure 4.4](#),  $S_2$  was presented 50 ms after  $S_1$ , and  $RT_1$  was 160 ms. Thus,  $160 - 50 = 110$  ms remained before the completion of  $RT_1$  when  $S_2$  was presented. According to the single-channel hypothesis, processing of  $S_2$  must be delayed until the channel is cleared. Thus the predicted  $RT_2$  will be the control  $RT_2$  plus the 110 ms delay, according to the single-channel view. Note from the data that the control  $RT_2$  was 124 ms, which makes the estimate of  $RT_2$  in the double-stimulation situation  $124 + 110 = 234$  ms. If you look up the actual value of  $RT_2$  (258 ms) given in [figure 4.5](#), you will see that the predicted  $RT_2$  (234 ms) is fairly close. Thus, the duration of  $RT_2$  was thought to be the control  $RT_2$  plus the amount that  $RT_2$  overlapped with  $RT_1$  or

$$RT_2 = \text{Control } RT_2 + (RT_1 - \text{SOA}) \quad (4.1)$$

We can see in [figure 4.4](#) and equation 4.1 that, as the size of the SOA increases, there is less overlap between the two RTs, and the predicted value of  $RT_2$  decreases. This accounts for the finding that the  $RT_2$  decreases as the SOA increases, as shown in [figure 4.5](#) and in other research (Welford, 1968).

### Evidence Against the Single-Channel Hypothesis

While the original single-channel hypothesis accounts for some of the data, a considerable amount of evidence has suggested that the theory is not correct in its details. According to the single-channel hypothesis,  $RT_2$  lengthens as a direct function of the amount of overlap between  $RT_1$  and  $RT_2$ , as can be seen in equation 4.1. The first concern was that even when there was *no* overlap between  $RT_1$  and  $RT_2$  (that is, when  $S_2$  occurred after the participant had already produced a response to  $S_1$ ), there was still some delay in  $RT_2$ . Look at [figure 4.5](#). When the SOA was 200 ms, so that  $S_2$  occurred 40 ms after  $R_1$ , there was still some delay in  $RT_2$  (about 50 ms) that did not disappear completely until the SOA had been lengthened to 300 ms. How can there be refractoriness, according to the single-channel view, when the  $RT_1$  and  $RT_2$  do not overlap at all?

Welford (1968) suggested that after  $R_1$  is produced, the participant directs attention to the movement, perhaps to feedback from  $R_1$  to confirm that the movement was in fact produced correctly before processing  $S_2$ . Thus, according to Welford's view, attention was directed to feedback from  $R_1$  after the response, which delayed  $RT_2$ , just as the attention produced during the time from  $S_1$  to  $R_1$  did.

But this explanation could not solve other problems. In the double-stimulation paradigm, as the SOA decreases, say, from 150 to 50 ms (in [figure 4.4](#)), the overlap between the two stimuli increases by exactly 100 ms; the single-channel model assumes that the delay in  $RT_2$  is a direct function of this overlap, so the model predicts that  $RT_2$  should be increased by exactly 100 ms in this example. Generally, the increase in  $RT_2$  in these situations has been much smaller than expected on the basis of the model (Davis, 1959; Kahneman, 1973; see Keele, 1986, for a review). These effects are probably attributable to the fact that some processing of  $S_2$  was being completed while  $S_1$  and its response were being processed, which, strictly speaking, is contrary to the single-channel hypothesis.

### *Moderating Variables in Psychological Refractoriness*

Various factors act to change, or modify, the effects just seen in double-stimulation situations. Some of these variables are practice, stimulus or response complexity, and stimulus–response (S-R) compatibility (see also Pashler, 1993, 1994).

#### Effects of Practice

Practice has marked effects on the exact nature of the delay in  $RT_2$  in this paradigm. Gottsdanker and Stelmach (1971) used 87 sessions of practice, 25 min each, in the double-stimulation paradigm for a single participant. They found that the amount of delay in  $RT_2$  steadily diminished from about 75 ms to 25 ms over this period. But the delay was never quite eliminated, suggesting that refractoriness might have a permanent, structural basis in the information-processing system.

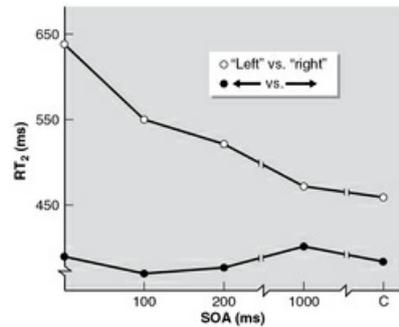
#### Complexity of Stimulus 1

Karlin and Kestenbaum (1968) found that the delay in  $RT_2$  was strongly affected by the number of choices involved in  $RT_1$ . When  $S_1$  was a simple RT (one stimulus, one response), with an SOA (until  $S_2$ ) of 90 ms, the amount of delay in  $RT_2$  was approximately 100 ms. However, when the first response was a two-choice RT, the delay was approximately doubled, so that  $RT_2$  was over 500 ms. A five-choice  $S_1$  produced an even larger delay, increasing  $RT_2$  to about 630 ms (Keele, 1986). Because increasing the complexity of  $S_1$  affects its processing time according to Hick's law (see chapter 3), the magnitude of the delay in  $RT_2$  apparently depends on the duration of processing for  $S_1$ .

#### Stimulus–Response Compatibility

An important moderating variable is S-R compatibility, or the relationship between the stimuli and responses to be made (see chapter 3). Greenwald and Schulman (1973) varied the compatibility of the first response ( $S_1$ - $R_1$ ). In a compatible condition,  $S_1$  was an arrow pointing to the left or right, and  $R_1$  was a hand movement in the indicated direction. In a less compatible (or less “direct”) condition,  $S_1$  was the visually presented word “left” or “right,” and  $R_1$  was again the manual response in the indicated direction. Thus, reading the word “left” or “right” required transformations from the stimulus to the response that were more complicated and less “natural” than seeing the arrows (see chapter 3). In both conditions,  $S_2$ - $R_2$  was unchanged;  $S_2$  was the number 1 or 2 presented auditorily, and  $R_2$  was the vocal response “one” or “two.” [Figure 4.6](#) gives the results; C on the horizontal axis refers to the control  $RT_2$  with no  $S_1$  or  $R_1$  required. When  $S_1$ - $R_1$  was not compatible (open circles),  $RT_2$  was lengthened considerably and refractoriness was increased as the SOA decreased, as we have seen before (e.g., in [figure 4.5](#)). But when  $S_1$ - $R_1$  was compatible (filled circles), there was no lengthening of  $RT_2$  at any of the SOAs. If the compatibility of the stimuli and responses is very high, the usually devastating effects of the first signal and its response can be reduced or even completely eliminated.

Figure 4.6 Reaction time (RT) to the second of two closely spaced stimuli at various stimulus onset asynchronies (SOAs) as a function of the stimulus-response (S-R) compatibility of the first reaction; the compatible arrow stimuli produced no refractoriness for the second reaction.



Adapted, by permission, from A.G. Greenwald and H.G. Schulman, 1973, "On doing two things at once: Elimination of the psychological refractory period effect," *Journal of Experimental Psychology* 101: 74. Copyright © 1973 by the American Psychological Association.

### *Implications of Refractoriness for Practical Situations*

We have seen that the second of two closely spaced reactions can suffer considerably in processing speed, and this fact can have important practical implications. For example, consider many fast-game situations, which often involve offensive and defensive players. Here, we often see the offensive player "fake" an opponent by displaying the initial parts of one action (e.g., a slight movement to the right) followed quickly by a different action (e.g., a movement to the left) that is actually carried to completion (such as what the hockey player is trying to do to the goalie in [figure 4.7](#)). If the defensive player responds to the first move, a full RT (about 150-220 ms) will be required, *plus* the added delay caused by refractoriness, before the defensive player can even *begin* to respond to the second move. Thus, RT to the second move could be as long as 500 ms (see Creamer, 1963; Karlin & Kestenbaum, 1968), which is a very long time in fast games, such as basketball and hockey, and daily activities, such as driving in high-speed traffic. But this is not the only problem. If the player has "taken the fake," (i.e., responded fully to  $S_1$ ), then he not only will suffer a delay in the RT to the "real" movement ( $S_2$ ) but also must overcome the momentum that the first movement has produced—plus make up any distance that he may have been traveled in the wrong direction.

Figure 4.7 Classic example of a psychological refractory period (PRP): The shooter is trying to draw the goalie out of position by faking the delivery of the shot.

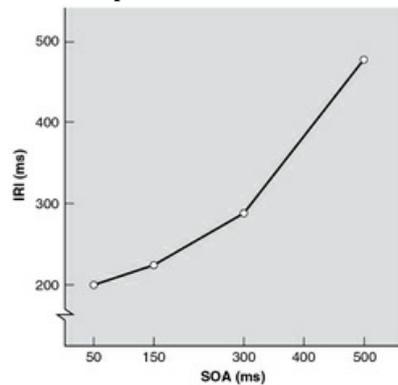


Based on findings from the PRP literature, a basic principle of faking is that the actual move should follow the fake by enough time that the second move is treated separately rather than grouped with the first one. Thus, the SOA should probably be around 50 ms or longer. Also, the second move must not follow the fake by so long that the refractory effects of responding to the fake have dissipated—probably not more than 250 ms (see [figure 4.5](#)). It would be interesting to study effective fakes in sport to discover whether the most effective SOAs correspond with estimates from experimentation. Such intervals may represent a part of natural defensive actions in other species. Watch a rabbit being chased by a dog. The rabbit runs with unpredictable directional changes, probably using intervals between directional changes that are highly effective in confusing the dog. Refractoriness might be an important survival mechanism in animals other than humans.

### *Separation Between Responses*

Evidence about psychological refractoriness suggests that the perceptual–motor system has difficulty responding to closely spaced stimuli, and that responses must therefore be separated considerably in time. How closely in time can two responses be produced, provided that they are not grouped and produced simultaneously? Kahneman (1973) examined this separation—called the *interresponse interval (IRI)* in [figure 4.3](#)—as it is affected by bringing the stimuli closer to each other in time. In [figure 4.8](#), we have plotted some of the data from Smith’s (1969) study, as Kahneman (1973) did. The SOAs were 50, 150, 300, and 500 ms, and the separations between responses (i.e., the IRIs) that resulted from these intervals are plotted.

Figure 4.8 The relation between the interresponse interval (IRI) and the stimulus onset asynchrony (SOA).



Data from Smith 1969; adapted from Kahneman 1973.

As the SOA decreased (moving leftward on the graph), the interval between the two responses decreased, but only to a certain point. It appears that no matter how small the interval between stimuli, provided they are not grouped so that their responses are emitted simultaneously, an approximately 200 ms separation occurs between sequential responses. This is a most important result and suggests that if a signal “gets into” the information-processing stages up to a certain point, a response to it is generated. If another stimulus is presented soon afterward, indicating that the system should do some *other* action, the second action must wait for at least 200 ms before it can be initiated.

Given this general principle, why is it that skilled piano players can produce many movements of the fingers in which the separation between movements is far less than 200 ms? Surely this observation contradicts the notion that a response can be emitted only every 200 ms. We will discuss this in detail in chapter 6, but for now, the issue mainly concerns the definition of a “response.” The system can prepare a “response” to a given stimulus that in itself is complex and involves many movements in rapid succession. The “response” that is planned in the response-programming stage is still just one response, but it may have many parts that are not called up separately. This can be thought of as *output chunking*, whereby many subelements are collected into a single unit, controlled by what is called a *motor program* (Keele, 1973; Schmidt, 1976a). Also, according to this general view, these programmed outputs occur in discrete “bursts” separated by at least 200 ms. These discrete elements are difficult to view directly, however, because the muscles and limbs smooth out the transitions between them, giving the impression that we respond continuously. In essence, then, many different *movements* can be separated by less than 200 ms if these movements are all contained in one “response.”

It is fortunate that  $S_2$  cannot get into the system to disrupt the preparation of a response to  $S_1$ . When preparing a response to a dangerous stimulus, participants will be successful only if they can process the information and produce the movement without interference from other conflicting signals. Consequently, rather than seeing refractoriness only as a “problem” to be overcome by the motor system in producing rapid-fire actions, we can also view refractoriness as protective. It tends to ensure that responses to important stimuli are appropriate and complete. This is consistent with Neumann’s (1987, 1996) view of attention as discussed earlier, according to which interference can be the result of an action having been selected.

### *Inhibition of Return*

Another finding in the literature that reveals an interference “after-effect” following the orienting of attention has been termed *inhibition of return* (Posner & Cohen, 1984). A trial begins with the presentation of an orienting cue—a type of warning cue that requires no overt response but simply alerts the participant that a stimulus will follow shortly, either at the same location or at a different location. An imperative signal occurs after a variable SOA either at the originally oriented cue location or at an uncued location. The participant’s goal is simply to make a response as fast as possible to the imperative signal. In comparison to the situation with the double-stimulation paradigm (see [figure 4.3](#)), no response is required to the orienting cue. But, similar to what we see with the PRP effect, the length of the SOA appears to be the critical determinant of how quickly the participant will respond to the

imperative signal.

The results from the original Posner and Cohen studies (1984), which have been replicated often. Two important effects emerge as a function of the SOA. First, if the imperative stimulus occurs at the same location as the orienting cue *and* with a short SOA (less than 200 ms), then RT is facilitated relative to an imperative stimulus location that is different than the orienting cue. This is the *beneficial effect* of orienting the participant's attention toward the location at which the imperative cue occurred, even though no overt response was required. More important, however, is what happens when the imperative signal occurs 300 ms or more after the orienting cue. In this case, completing the orienting response to the precue *delays* a response to the orienting (cued) location, compared to the RT in response to the cue that was not at the orienting location.

The “inhibition of return” seems to be a protective mechanism that prevents returning attention to a previous orienting cue that captured attention but did not require a response. Hypotheses differ regarding the mechanisms involved in producing the inhibition-of-return effect. Some suggest that inhibition of return is caused by an attention shift, whereby the previously attended-to cue loses salience (importance) after being fully processed (e.g., Fecteau & Munoz, 2003). Such a view would explain how one searches a map for a particular location, or searches a page for Waldo in a “Where's Waldo” scene. The start of the map search combines both top-down (directed search) and bottom-up (something that appears to “jump” off the map) features of orienting salience. Once that location has proven not to be the target of the search, its previous importance is inhibited, thereby allowing other potential locations to rise in salience. Another suggestion is that the inhibition has a motor basis—having made a saccadic eye movement to the precue makes a response to the same cue slower than to a new target location (Fischer, Pratt, & Neggers, 2003). Klein has provided reviews of this extensive literature (Klein, 2000, 2004; Taylor & Klein, 1998).

### *Revised Single-Channel View*

In sum, a single channel does seem to exist, contrary to the conclusion presented earlier in the section about the (original) single-channel hypothesis. But the single channel does not appear to apply to all stages of processing as Welford's (1952) version of the theory stated. Rather, it appears that parallel processing can occur during the early stages of information processing and that a single channel is properly placed during the stages in which decisions are made about the response. Pashler (1993, 1994) has presented persuasive evidence suggesting that the response-selection stage (which, for Pashler, includes response programming as we define it here) represents the bottleneck where single-channel processing occurs. The processing of a second stimulus in response selection and programming must wait until the first stimulus has cleared this stage. In other words, only one response at a time can be selected and programmed. Further processing of the second of two closely spaced stimuli is put on hold until the response selection and programming for the first stimulus are complete. This leads us to ask whether the response-selection stage or the response-programming stage (in our terms in chapter 3; different from Pashler's), or both of the stages, might be the precise location of the bottleneck in processing.

## Attention During Movement

To this point, we have examined attentional processes present during the RT period, which, of course, takes place prior to movement. But one can conceptualize a “stage” of processing, following response programming, in which the individual carries out the movement and keeps it under control. Strictly speaking, it is not a stage in the sense of the other stages, as it does not occur during RT (see chapter 3). Nevertheless, it is important to consider the attentional characteristics of these processes.

In thinking about our own skilled movements, we are left with the impression that skills require conscious awareness for their performance. We must be careful with these analyses, though, because we cannot be sure whether it is the movement itself that requires awareness or the programming and initiation of future movements (e.g., in a dive, when to “open up” to enter the water). We are in a weak position for determining the extent to which movements themselves require consciousness when we use only the methods of introspection.

On the other hand, sometimes it seems that a particular movement is performed without awareness (some consider such movements “automatic”), especially when it is a part of a well-learned sequence (e.g., part of a dance routine). People who routinely drive a car with a standard transmission sometimes find, when driving an automatic transmission car, that they attempt to depress the “clutch” at a stop sign even though the car has no clutch pedal. Do you typically realize that you have produced this movement only after having done so? Have you ever found, in buttoning your shirt and thinking sleepily about the upcoming day’s activities, that you are performing the motions even where a particular button is missing? Have you ever left the house and wondered if you turned off the burner on the stove? These examples, plus many others that come to mind, suggest that not all movements require attention for their performance while some seem to require considerable attention. Some of these “mindless” aspects of performance are described by Langer (1989).

When a movement requires a great deal of attention, what exactly is involved? As we mentioned earlier, attention could be devoted to the response-programming stage for future elements in a long sequence. Attention also could be devoted to other aspects of the environment. In driving, for example, the movements themselves might be carried out with minimal attention; instead, attention is directed to traffic patterns and other relevant features of the environment. Another possibility is that we pay attention to our movements to fine-tune their control—to carry out any necessary corrections, which can be thought of as “responses” as well. We consider some of these questions in the following sections.

### Secondary-Task Technique

An effective tool for evaluating the role of attention in simple movements involved *secondary* tasks, introduced in chapter 2. In the secondary-task technique, the participant performs a *primary* task for which the attention demand is of interest. But the participant is also occasionally presented with another task. These secondary tasks are of two types: *continuous* and *discrete*.

#### *Discrete Secondary Tasks*

In the discrete secondary task, a stimulus, called a *probe*, is presented at various times or places in the performance of the primary task, and a quick response to the probe is made with an effector not involved in the main task. The probes are often auditory, and the response may be either manual or vocal. This secondary-task method has been called the “probe technique” and is the participant of a large literature within the study of movement control (Abernethy, 1988, 2001). We discuss some details of this method later in the chapter.

#### *Continuous Secondary Tasks*

Continuous secondary tasks are those that are performed together with and throughout the duration of the primary task. Experiments reported by Welch (1898), for example, assessed maximum handgrip strength during the simultaneous performance of various tasks, such as reading, writing, arithmetic calculations, and various visual and auditory perception tasks. In all cases the maximum force output during the control trials (with no secondary task) was greater than when the task was performed simultaneously with another task. Importantly, Welch (1898) was the first to show that different dual-task situations created different “amounts” of interference. For instance, grip-strength performance was more proficient when participants added two numbers, compared with multiplying two numbers, leading to the conclusion that the multiplication task demanded more of the participant’s attention than did the addition task.

As an example, one research area that frequently uses continuous secondary tasks has to do with the attention demands of gait and posture. Beginning with the research of Kerr, Condon, and McDonald (1985), numerous researchers have assessed attention demands of standing balance under various conditions (see Woollacott & Shumway-Cook, 2002, for a review). Balance and gait control represent increasing challenges with advances in age, as falls often result in major health concerns. Although there are many contradictions in the findings of these studies, an important association exists between dual-task performance (and thus attention demand) and incidents of falling among the frail and elderly (Beauchet et al., 2009). Thus, the use of the secondary-task method may have important clinical implications for early detection of at-risk individuals.

In some experiments, the experimenter is interested in discovering how the participant coordinates the execution of two (or more) simultaneous movements. In this case, it is not the attention demands of one or the other that are of interest per se; rather, the primary concern is how the two tasks become regulated in space and time. You are probably well aware of the difficulty in rubbing your stomach with one hand while patting your head with the other. Of course, doing either of these tasks by itself is easy for most of us; but when we attempt them together, the two hands are particularly difficult to control, and a great deal of mental effort seems to be required. In another example (Klapp et al., 1985), it is particularly difficult to tap a regular rhythm with your left (nonpreferred) hand while tapping as quickly as you can with your right (preferred) hand. Such effects are not limited to these clever little demonstrations. In many piano performances, the two hands must perform with different rhythms for a short while, and most pianists claim that this is one of the most difficult tasks in these pieces. *Rubato* involves the gradual speeding or slowing of one hand with respect to the other, also considered a very advanced technique in piano playing (Peters, 1985).

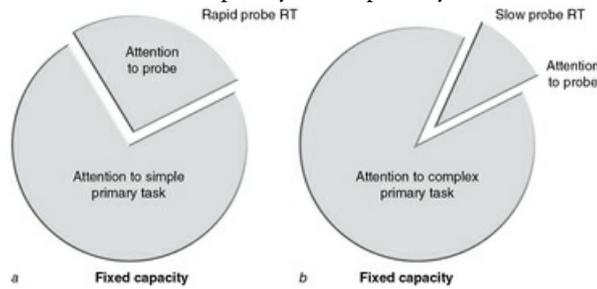
In these examples, the two tasks are internally generated and not “driven” by any obvious environmental signal. It would thus seem that not all of the interference we observe among tasks has to do with the processing of environmental stimuli leading to a response. Rather, an additional source of interference might have to do with the control of the limbs per se. Although it is tempting to attribute an attentional “overload” explanation to these and related effects, the issue is much more complex than this. In fact, later in the book we devote an entire chapter to the problems of simultaneously coordinating the actions of two or more effectors (see chapter 8).

### *Probe Technique*

This secondary-task method assumes a fixed (nonchanging) attentional capacity. The “pie chart,” illustrated in [figure 4.9](#), is an effective way to illustrate this fixed-capacity model. The “whole pie” represents the total attentional capacity available. If the capacity required for the primary task is low (about 75% of the fixed capacity, as illustrated in [figure 4.9a](#)), then the capacity remaining for processing the probe stimulus will be relatively large, which should lead to a probe RT that will be fast. However, if the primary task demands a much larger proportion of the fixed capacity (say, about 90%, as illustrated in [figure 4.9b](#)), then much less of the spare capacity remains for the probe stimulus, and its processing will be slower. Thus, the early work of this kind assumed that the duration of the probe RT could give an indication of the attention requirements of the main task.



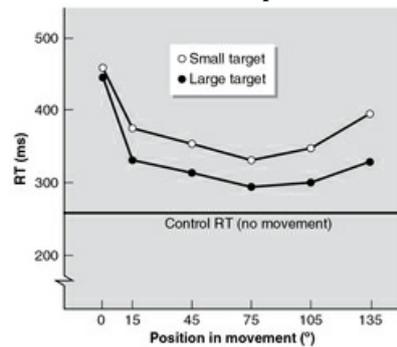
Figure 4.9 Assumptions of the probe reaction-time (RT) task: With fixed total capacity, attention to the probe decreases as the complexity of the primary task increases.



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In an early study by Posner and Keele (1969), participants made 700 ms wrist-twist movements of a handle through a range of 150°, attempting to move a pointer to either a large or a small target area. The experimenters presented probe signals at various points during the movement—at the start or at 15°, 45°, 75°, 105°, or 135° of handle movement. The probe RTs are plotted in [figure 4.10](#) as a function of their location within the movement. The horizontal line represents the no-movement, control probe RT (i.e., RT in the absence of a primary task). Several features of this figure are important to note. First, the finding that the probe RTs were always larger than the corresponding values of the control probe RT was taken as evidence that performing the primary task (making the pointing movements) generated interference—that is, they required attention. Next, probe RT for both tasks showed a U-shaped function; there was a marked slowing of the probe RT at the beginning of the movement, with somewhat less slowing at the end. This finding suggests that attention to the movement is strongest at the beginning, that a “relatively” attention-free portion occurs near the middle, and that attention is used near the end again, perhaps due to positioning the pointer accurately in the target zone. Finally, note that the probe RT increased as the target size decreased, especially near the end of the movement, suggesting that the movement became more attention demanding as end-point precision increased (see also Ells, 1973; Salmoni, Sullivan, & Starkes, 1976). In another of Posner and Keele’s (1969) experiments, blindfolded participants made a movement to a stop, which required essentially no target accuracy; the movement was analogous to pushing a door closed. In this example, there was no increased probe RT beginning at any of the later points during the movement, implying that this movement used no attention once it was initiated.

Figure 4.10 Probe reaction time (RT) elicited at various points in movements to large and small targets.



Reprinted from M.I. Posner and S.W. Keele, 1969, Attentional demands of movement. In *Proceedings of the 16th Congress of applied physiology* (Amsterdam, Amsterdam: Swets and Zeitlinger). By permission of M.I. Posner.

The probe technique has been used in a number of ways in attempts to assess the attentional demand involved in performing various jobs (Ogden, Levine, & Eisner, 1979); in the control of posture and gait (Abernethy, Hanna, & Plooy, 2002; Ojha, Kern, Lin, & Winstein, 2009; Woollacott & Shumway-Cook, 2002); and in various sport-related activities such as catching a ball (Populin, Rose, & Heath, 1990; Starkes, 1987), shooting a pistol (Rose & Christina, 1990), receiving tennis and volleyball serves (Castiello & Umiltà, 1988), and skating and stick-handling skills in hockey (Leavitt, 1979). A very important and recent addition to this literature involves the attention demands of time sharing during driving, which we consider in more detail later in this chapter.

### *Problems With Secondary Tasks*

A number of potential problems with the secondary-task paradigm require that interpretation of these experiments be made with caution. First, the method assumes a fixed, unitary capacity, which is, of course, contrary to Kahneman's (1973) views and contrary to the idea of *pools* of resources discussed earlier. Second, McLeod (1977, 1980) has identified a number of other difficulties. One of these was shown in his finding that a probe RT with a manual response interfered with a simultaneous tracking task, whereas a probe RT with a vocal response hardly interfered at all. If the probe RT actually measures some general, "spare," central capacity (attention), why was more of this capacity available when the only change was in the nature of the movement to be made in response to the probe?

Interpretation of results from continuous dual-task experiments involves a similar issue. A study by Yardley, Gardner, Leadbetter, and Lavie (1999) illustrates this point well. In this experiment, participants attempted to stand perfectly still on a platform while performing various secondary tasks. Of importance was the difference observed in balance when participants were asked to count backward by 7s from a three-digit number. When participants performed the counting task *silently*, the investigators observed no increase in postural sway compared to the single-task control condition. However, when participants counted backward out loud, postural sway increased dramatically, but no more so than when they simply repeated a three-digit number over and over. Yardley and colleagues concluded that it was not the attention demanded by the secondary task that interfered with performance; rather, increases in postural sway were more likely due to the extraneous postural movements caused by vocalizing aloud, or the attention demanded by the act of speaking, or both.

Whatever the exact nature of the interference might be, clear interference is found when various secondary tasks are paired with a variety of different primary tasks. These experiments seem to tell us that various movement tasks require many of the same processes that auditory-manual probe tasks do, and *not* that some undifferentiated capacity is or is not used. Conversely, findings that the secondary-task performance is not elevated by the primary task do not necessarily mean that the primary task is automatic; rather, they indicate that the particular processes needed in the secondary task are not also involved in *that* primary task. Of course, other secondary tasks could probably be found that *would* interfere with the primary task (Neumann, 1987); if so, this would force us to conclude that the primary task is not automatic after all.

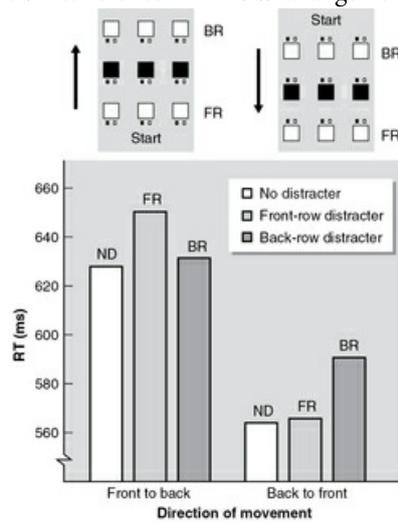
What has usually been meant by the conclusion that a task can be performed “automatically” is that it can be performed without interference from other mental tasks involving (conscious) information-processing activities. This fits with our subjective experiences about “automatic” movements that are performed without consciousness. But, as has been said previously (Neumann, 1987; Schmidt, 1987), it is probably best to think of automaticity *with respect to* some other simultaneous secondary task(s).

## Action-Centered Interference

A different way to examine interference effects during movement was introduced by Tipper, Lortie, and Baylis (1992). This experimental approach relates to the everyday problems of interference that one encounters when reaching for an object in a cluttered environment, such as reaching for a paper on a desk that has other papers scattered on it, or reaching for an apple in a basket containing various fruits (Castiello, 1996). The questions of interest relate to how potentially distracting objects in the environment produce interference effects in either the preparation or the execution of movement.

The task for participants in studies by Tipper and colleagues (1992) was to respond to the illumination of a light by pushing one of the buttons located on a table directly in front of them. As illustrated in [figure 4.11](#), the buttons were arranged in three rows of three buttons each; near each button were two lights—a red light indicated that the button should be pushed, and a yellow light indicated a distracter (nontarget) button that was simply there and was to be ignored. Response times to move from the home button to the target location were very fast in conditions in which none of the distracter lights were illuminated when a target light appeared. However, on some trials, a yellow light was illuminated at the same time that a red target light appeared. The critical issue addressed by Tipper and colleagues was whether the distracters (the yellow lights) would affect response time to reach the target button, and if so, which distracter locations would have the largest effects.

Figure 4.11 Action-centered interference in various arrangements of targets and distracters.



Adapted, by permission, from S.P Tipper, C. Lortie, and G.C. Baylis, 1992, "Selective reaching: Evidence for action-centered attention," *Journal of Experimental Psychology: Human Perception and Performance* 18: 893, 896. Copyright 1992 by the American Psychological Association.

Two sets of results are presented in [figure 4.11](#). On the left are the findings for a layout in which the participant's hand was moving away from the front of the table (which was the "start position") to contact a target in the middle row (i.e., one of the filled boxes). In this condition, only the distracters in the *front row* (FR) interfered with response time compared to a no-distracter (ND), control condition. When distracters appeared in the back row (BR), the response time was almost the same as in the no-distracter, control condition—hence, there was essentially no interference. Tipper and colleagues were able to reverse this pattern of findings by having movements start at the back of the table and move toward the participant (arrangement at upper right of [figure 4.11](#)). In this configuration, compared to no-distracter conditions, targets in the middle row were now unaffected by distracters in the front row but were severely interfered with by distracters in the back row (back and front as viewed from the participant's perspective). Therefore, in both spatial arrangements, the interference was largest when the distracter was located *between* the start and end points of the movement, but not when it was located "beyond" the target. The findings of Tipper and colleagues (1992) have been replicated and extended in a number of experiments showing that selective visual interference during movement is highly dependent on the nature of the action (e.g., Howard & Tipper, 1997; Meegan & Tipper, 1998; Pratt & Abrams, 1994). The "amount" of interference produced by a particular distracter appears to depend on its functional significance to the intentions of the main action (Weir et al., 2003; Welsh & Pratt, 2008). For example, when distracters are located close to a target, they tend to have the largest interference effect on the kinematics of the grasping hand (Jervis, Bennett, Thomas, Lim, & Castiello, 1999; Mon-Williams, Tresilian, Coppard, & Carson, 2001). In contrast, objects located along the path of the movement tend to have larger effects on the kinematics of the reaching action (Mon-Williams et al., 2001). This view suggests a rather radical departure from interference effects during movement as implied by various capacity views of attention. Rather, the findings support Neumann's (1996) view that the nature of the selected action drives attention and determines which potential factors will or will not cause interference.

## Distracted Driving

"Several years ago I observed what I believe to be the all-time record for distracted drivers. Driving north on I-95 into Baltimore, I was passed by a male driver who was holding a Styrofoam cup and a cigarette in one hand, and a cellular telephone in the other, and who had what appeared to have been a newspaper balanced on the steering wheel—all at approximately 70 miles per hour" (Ambrose, 1997).

With increasing frequency, one hears anecdotal reports of traffic accidents that occurred while a driver appeared to be using some type of handheld communication or entertainment device. The controversy was fueled by an analysis of accident reports and cell phone call records, which revealed a fourfold increase in accident risk when

the driver had been using a cell phone at the time of the incident (Redelmeier & Tibshirani, 1997). The researchers compared the elevated risks of distracted driving to the dangers of driving under the influence of intoxicants (see also Strayer, Drews, & Crouch, 2006).

Lawmakers in many countries around the world have debated how to deal with the issue of distracted driving, and researchers have responded with a wealth of data to inform them. Although this is a current “hot” topic, investigations on cell phone use were initiated by Brown, Tickner, and Simmons many years before, in 1969. Their participants made safety margin judgments (whether or not the car could fit through gaps) by either driving through or around markers on the road. On some trials the participants also performed a reasoning task via a hands-free telephone. Performing the reasoning task, while driving elevated, the frequency of gap judgment errors by almost 13%. (See “I.D. Brown on Distracted Driving.”)

## I.D. Brown on Distracted Driving

### Research Capsule

Research on talking on a cell phone during driving, though a topic of considerable recent research activity, was investigated many years ago by Brown and colleagues (1969). As evident in the following quotes, their theoretical orientation was clearly concerned with attention. Although single-channel theory (according to which switching between tasks is necessary in order to carry out more than one task) dominated their thinking, their hypotheses and findings remain as relevant today as they were in 1969. It is unfortunate that their plea for additional research on specific outstanding issues was not taken up in earnest for more than two decades.

“Having to use a hand microphone and having to manipulate push buttons to make or take a call will be inconvenient and may impair steering, gear changing, or other control skills. This is a problem which may be solved by engineering advances and is not the concern of the present paper. A more important and lasting problem arises from the hypothesis that man can be considered to act as a single communication channel of limited capacity. The prediction from this hypothesis is that the driver will often be able to telephone only by switching attention between the informational demands of the two tasks. Telephoning could thus interfere with driving by disrupting visual scanning, since visual and auditory information would have to be transmitted successively. It could also interfere by overloading short-term memory and impairing judgment of relative velocity. . . .” (p. 419)

“The general conclusion must be that some mutual interference between the concurrent tasks is inevitable under conditions of telephoning while driving on the road. The results suggest that, although more automatized control skills may be affected minimally by this division of attention, some perception and decision skills may be critically impaired. The extent to which this impairment is a function of the driving task, the informational content of the telephone message, and the individual characteristics of the driver must remain a subject for further research.” (pp. 423-424)

Sending and receiving text messages is an obvious source of structural interference during driving—one cannot fully scan the driving environment while looking at a communication device, and the texting hand is not available for other subtasks. But what are the dangers in simply *talking* on a cell phone during driving? Are handheld cell phones more dangerous than hands-free units, and is the whole issue of interference from cell phones related only to structural interference (i.e., looking at the screen, entering keystrokes)? Is talking on cell phone more dangerous than carrying on a conversation with a passenger in the car? We consider these and other issues in the next sections (see also Caird, Willness, Steel, & Scialfa, 2008; Collet, Guillot, & Petit, 2010a, 2010b; Haigney, & Westerman,

2001; Horrey & Wickens, 2006; McCartt, Hellinga, & Bratiman, 2006, for reviews).

### *Does Cell Phone Use Affect Driving?*

Researchers have no doubt that cell phone use, such as texting or talking, can compromise driving (e.g., Stavrinou, Jones, Garner, Griffin, Franklin, Ball, Sisiopiku, & Fine, 2013). The degree to which driving is impacted by cell phone conversation appears to depend on several factors, including the *driving environment*, the *characteristics of the driver*, and the *nature of the conversation* the driver is engaged in or listening to. The decrement in driving performance during cell phone use is shown to increase with increased traffic demand (Lee, Caven, Haake, & Brown, 2001; Strayer, Drews, & Johnston, 2003) and environmental complexity (Strayer & Johnston, 2001). Also, under dual-task driving conditions a greater performance decrement is observed for older drivers compared to younger drivers (Alm & Nilsson, 1995; Hancock, Lesch, & Simmons, 2003; McKnight & McKnight, 1993), although some discrepancy exists in the literature regarding the role of practice. Some studies suggest that practice lessens driving distraction (Brookhuis, de Vries, & de Waard, 1991; Chisholm, Caird, & Lockhart, 2008; Shinar, Tractinsky, & Compton, 2005), whereas others suggest that the distraction remains about the same (Cooper & Strayer, 2008). However, no evidence shows that practice *eliminates* the distraction from cell phones. In addition, conversations that require a larger number of reasoning operations impair performance more than tasks involving fewer operations (Briem & Hedman, 1995). Furthermore, even if drivers are not engaged in a conversation, listening to passengers' conversations can serve as a distraction. Overhearing a one-sided conversation (e.g., when a passenger is talking on a cell phone) is more distracting than overhearing a two-sided conversation and leads to performance decrements on a primary task (e.g., driving; Galván, Vessal, & Golley, 2013).

Conversations are not the only cell phone distraction; notifications informing the driver of an incoming message or e-mail can be distracting. For example, Stothart, Mitchum, and Yehnert (2015) found that performance of an attention-demanding task suffered as a consequence of receiving alerts. The detrimental effect is presumably the result of task-irrelevant thoughts (mind wandering) prompted by the notification.

In sum, the impact of the driving environment, driver experience, and the nature of the conversation is consistent with general attentional capacity limitations in performance discussed earlier in this chapter. However, more complex driving environments usually impose greater visual demands on the driver, and some have argued (e.g., Strayer et al., 2003) that secondary-task performance interferes with visual attention processes, causing an effect like *inattentive blindness* (see earlier discussion in this chapter; Yantis, 1993). Cell phone conversation reduces the capacity to perceive changes in the visual environment such as traffic patterns (Trbovich & Harbluk, 2003).

### *Cell Phone Use Versus Other Driver Distractions*

Cell phone use is only one of many potential distractions in driving (Cohen, 1997). Conversations with other passengers, listening to and adjusting audio equipment, and reading instrument panels and mirrors are just a few of the ways in which attention might be distracted. The research is not entirely clear, however, on how these other sources of distraction influence driving (Consiglio, Driscoll, Witte, & Berg, 2003; Irwin, Fitzgerald, & Berg, 2000; Strayer & Johnson, 2001). Tasks that require the driver to divert visual attention from the outside to the inside environment (e.g., tuning a radio) appear to be detrimental to performance (McKnight & McKnight, 1993), presumably because hazards to driving come mainly from the outside. The intensity and complexity of the cognitive and visual processes are important contributors to interference, and not simply the manual handling of the device as many have believed.

One of the arguments frequently raised against legislation on cell phone use during driving suggests that the distraction is no greater than talking with a passenger (which is both common and legal). In an epidemiological study, McEvoy, Stevenson, and Woodward (2007) found that the accident-risk odds rose by a factor of 1.6 when one passenger was in the vehicle and by a factor of 2.2 with two or more passengers. However, those increases were much less than the accident risk associated with cell phone use, which rose by a factor of 4.1. These findings are supported by experimental evidence (Drews, Pasupathi, & Strayer, 2008) suggesting that in-vehicle conversations among passengers tend to be considerably less hazardous for drivers than cell phone conversations.

Another argument is that the passenger can adjust the conversation (or stop it altogether) in demanding driving situations; obviously, this is not possible for the person on the other end of the cell phone conversations. Also, some argue that the passenger can provide comments that benefit safety (“Look out for the bicyclist!”), even during conversations with the driver.

### *Handheld Versus Hands-Free Cell Phones*

Despite the preponderance of legislation that bans handheld cell phone use during driving but permits the use of hands-free units, almost all experimental studies on the topic have shown that both are about equally detrimental to driving performance (Consiglio, Driscoll, Witte, & Berg, 2003; Lamble, Kauranen, Laakso, & Summala, 1999; Strayer & Johnston, 2001; Törnros & Bolling, 2005). In reviewing the evidence regarding distraction with the use of hands-free and handheld phones, Ishigami and Klein (2009) conclude simply that “the epidemiological and the experimental studies show a similar pattern: *talking* on the phone while driving impairs driving performance for both HH (handheld) and HF (hands-free) phones” (p. 163, emphasis added). Moreover, given the evidence that drivers tend to compensate more for the potential distraction of a handheld unit (e.g., by driving more slowly), Ishigami and Klein argued that driving and talking with a hands-free unit might even be *more* dangerous than with a handheld cell phone because of the driver’s mistaken belief that a conversation with a hands-free device is not attention demanding.

# Focus of Attention

What is the effect on movement when we specifically direct our attention to different aspects of the skill, such as body movements or the intended movement outcome? In other words, what is the effect when we vary the focus (object) of our attention?

## External Versus Internal Attentional Focus

Views about how one can direct attention optimally during action have been around since at least the late 19th century (e.g., Cattell, 1893). William James, the psychologist introduced at the beginning of the chapter, pointed out that a focus on the remote effects of one's actions is often more important than the action itself. Using the example of a reaching movement, James said, "Keep your eye at the place aimed at, and your hand will fetch [the target]; think of your hand, and you will likely miss your aim" (James, 1890, II, p. 520). Empirical studies on how different types of attentional focus affect motor performance and learning have surged in recent years. Two types to distinguish are internal and external focus of attention (for reviews, see Wulf, 2007, 2013).

An *internal focus of attention* is a concentration on body movements, such as the hand motion in dart throwing or the foot position when kicking a soccer ball. An *external focus of attention* is directed at the intended movement effect, such as the flight of a discus or the corner of a soccer goal where a player is aiming. Research since the late 1990s has clearly shown that adopting an external focus is more effective than adopting an internal focus, regardless of the type of skill, movement ability or disability, age, or skill level. These findings contradict the long-held view that novice learners need to focus on, and consciously control, their movements. Like skilled performers, beginners benefit from directing their attention externally to the planned movement effect or outcome. Instructions and feedback that promote such an external focus speed up the learning process. In a 2009 interview, Tiger Woods described an approach his father used when he first taught Tiger how to play golf—and how he continued to use the external-focus instruction his dad gave him in later years (see "Tiger Woods: Keep It Simple").

As noted in chapter 1, Guthrie (1952) described skilled performance as being characterized by a high level of movement effectiveness (i.e., accuracy, consistency) and efficiency, including the minimization of physical and mental energy (i.e., fluent, economical movements; automatic control). The following sections review some of the evidence supporting the notion that an external focus of attention facilitates learning so that motor skills are controlled automatically, and performed with greater effectiveness and efficiency, sooner. Several of these studies use within-participant designs in addition to traditional motor learning paradigms, with various groups practicing under different conditions and the use of retention or transfer tests (see chapter 9). The reason for this approach is that a participant can shift attentional focus relatively easily (when asked to do so), and the effect on performance is often seen immediately. Independent of the experimental design, the advantages seen when performers adopt an external relative to an internal focus are consistent.

### Tiger Woods: Keep It Simple

#### Research Capsule

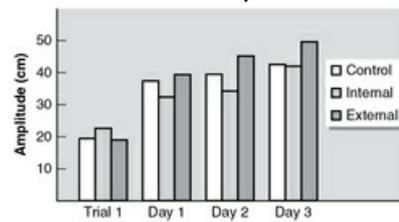
In an interview with Fortune.com in 2009 (Shambora, 2009), Tiger Woods talked about some of the early golf lessons he received from his father. When Tiger was about 6 years old, he recalled, his dad would ask him to pick a spot on the golf course to which he wanted to hit the ball. When Tiger identified his target, Mr. Woods would simply tell him to go ahead and hit the ball there (rather than adjust his stance or position his arms). Apparently, Mr. Woods knew quite well that detailed

instructions would not be beneficial, and that letting Tiger figure out how to hit the ball would be a more effective way of learning. Even as an adult, Tiger Woods went on to explain, he would often think of his dad's advice, particularly when he was struggling with his game, and simply focus on the spot he wanted to hit.

## External Focus Increases Movement Effectiveness

In the first experiments that demonstrated the learning benefits of adopting an external focus of attention, Wulf, Höß, and Prinz (1998) used two balance tasks. The use of balance tasks is perhaps not a coincidence, given that the first piece of anecdotal evidence for the attentional focus effect was related to windsurfing (Wulf, 2007). In the first experiment, using a ski simulator ([figure 4.12](#)), participants were asked to direct their attention to either the pressure they exerted on the wheels of the platform on which they were standing (external focus) or their feet that were exerting the force (internal focus). A third, control group, received no focus instructions. The external focus group produced significantly larger movement amplitudes compared on a retention test with both the internal focus and the control group; the two latter groups showed no difference. The learning benefit of adopting an external focus was replicated in a subsequent experiment that involved a *stabilometer*—a wooden balance platform that moves to the left and right like a teeter-totter. In this case, an external-focus group was asked to concentrate on keeping two markers horizontal that were attached to the platform directly in front of the participant's feet. An internal-focus group was asked to concentrate on keeping their feet horizontal. (Note that participants were instructed to look straight ahead, not at the markers or their feet, so that visual information would not be confounded with the attentional focus or concentration.) The group asked to direct their attention to the markers showed more effective balance performance, compared with the group that was instructed to focus on their feet. Thus, an external focus was again more effective.

Figure 4.12 Average amplitudes of the external focus, internal focus, and control groups performing the ski-simulator task (Wulf, Höß, & Prinz, 1998). The maximum amplitude was 55 cm. The figure shows performance on the first 90 s trial, at the end of each of 2 days of practice (trials 8 and 16, respectively), and at the end of the retention test on day 3 (trial 22).



Since those initial studies, numerous researchers have replicated the attentional focus effect with various tasks. Aside from other balance tasks, these studies have included tasks that required accuracy in hitting a target, such as kicking a soccer ball or serving a volleyball (Wulf, McConnel, Gärtner, & Schwarz, 2002), throwing darts (e.g., Marchant, Clough, & Crawshaw, 2007), hitting or putting golf balls (e.g., Land, Frank, & Schack, 2014; Wulf & Su, 2007), and shooting basketballs (Zachry, Wulf, Mercer, & Bezodis, 2005). When performing golf chip shots, both novice and expert golfers demonstrated greater accuracy in hitting a target when they were asked to focus on the club motion (external) rather than their arm motion (internal). In line with many other studies, performance in the control condition with no focus instruction was similar to that in the internal-focus condition and less effective than in the external-focus condition. Several other studies have used tasks that involved the production of a certain amount of force with the hand, tongue (Freedman, Maas, Caligiuri, Wulf, & Robin, 2007), or foot (e.g., Lohse, Sherwood, & Healy, 2011; see Marchant, 2011, for a review), as well as tracking (e.g., Porter & Anton, 2011) or musical tasks (e.g., Atkins & Duke, 2013; Duke, Cash, & Allen, 2011).

## External Focus Promotes Movement Efficiency

The efficiency of a motion can be measured in various ways. For example, if the same movement pattern is produced with less muscular (electromyographic, or EMG) activity, oxygen consumption, or a lower heart rate, it is considered more efficient or economical (Sparrow & Newell, 1998). More indirect measures of efficiency are those that signify effective coordination between muscles (i.e., minimal co-contraction) and within muscles (i.e., optimal motor unit recruitment; e.g., Farina, Fosci, & Merletti, 2002). Such measures include maximum force production, movement speed, or endurance. Studies have shown that adopting an external focus on the planned movement effect increases movement efficiency.

Focusing attention externally on the rim in basketball shooting (Zachry et al., 2005) or the trajectory of the dart in dart throwing (Lohse, Sherwood, & Healy, 2010), as opposed to the hand motion, has been found to increase throwing accuracy and is associated with reduced EMG activity. These findings suggest a link between muscular activity and movement accuracy. The superfluous recruitment of larger motor units when performers focus on body movements (Lohse, Healy, & Sherwood, 2011) can be viewed as noise in the motor system that interferes with the effective and efficient movement execution. Muscular activity has also been found to be lower when performers were asked to focus on the weight they were lifting as opposed to their arms or legs with which they were lifting the weight, or in control conditions (e.g., Marchant, Greig, & Scott, 2008; Vance, Wulf, Töllner, McNevin, & Mercer, 2004). Consequently, performers can perform more repetitions with the same weight (Marchant, Greig, Bullough, & Hitchen, 2011). Neumann and Brown (2012) found that participants were able to do more sit-ups with a focus on producing smooth movements relative to an internal focus on their abdominal muscles, and they did so with less EMG activity and lower heart rate.

Many tasks require the production of high speed or maximum forces. In those cases, intra- and intermuscular coordination are essential. Several studies have shown that an external focus is necessary for producing those forces. For example, faster running times were seen for an agility task (Porter, Nolan, Ostrowski, & Wulf, 2010) or sprint starts (Ille, Selin, Do, & Thon, 2013) when participants were asked to focus on clawing the floor with the shoes (external), compared with moving the legs and feet down and back as quickly as possible (internal).

Similarly, participants swam faster when they focused on pushing the water back as opposed to pulling their hands back (Freudenheim, Wulf, Madureira, & Corrêa, 2010). Even maximum vertical jump height (Wulf & Dufek, 2009; Wulf, Zachry, Granados, & Dufek, 2007; Wulf, Dufek, Lozano, & Pettigrew, 2010), standing long jump (Porter, Anton, & Wu, 2012; Porter, Ostrowski, Nolan, & Wu, 2010; Wu, Porter, & Brown, 2012), or discus throwing (Zarghami, Saemi, & Fathi, 2012) are enhanced when performers adopt an external focus (see Wulf, 2013, for a review).

## External Focus Improves Movement Form

External focus instructions not only result in greater movement effectiveness and efficiency but also elicit desired whole-body coordination patterns. Enhanced movement resulting from a single external focus cue was seen in a study by Abdollahipour, Wulf, Psotta, and Palomo Nieto (2015). Twelve-year old experienced gymnasts performed a 180-degree turn in the air. All gymnasts performed under three different conditions, in a counterbalanced order. In one condition, they were asked to focus on the direction in which their hands, which crossed in front of the chest, were pointing after the turn (internal focus). In another condition, they were instructed to focus on the direction in which a tape marker on their chest was pointing after the turn (external focus). In the control condition, they were not given any focus instructions. The authors measured both movement quality (i.e., number of deductions given by expert raters) and jump height. The external focus cue (tape marker) resulted in superior movement form as well as greater jump height, compared with the internal and control conditions.

Other studies using expert ratings of movement form (e.g., Wulf, Chiviacowsky, Schiller, & Ávila, 2010) or analyses of movement kinematics or kinetics (e.g., An, Wulf, & Kim, 2013; Christina & Alpenfels, 2014; Parr & Button, 2009) have shown similar benefits with an external focus. In one study with novice rowers, instructions directed at the blade (e.g., “Keep the blade level during the recovery”) rather than the hands (e.g., “Keep your hands level during the recovery”) led to greater improvements in the technique, as evidenced by various kinematic measures after a 7-week retention interval (Parr & Button, 2009). In another study with novice golfers (An et al., 2013), the learning of movement form was enhanced by a single external-focus instruction. In addition, the carry distance of the ball was increased relative to groups who received internal-focus or no-focus instructions. Finally, Christina and Alpenfels (2014) found that experienced golfers learned to make a change to their swing path more effectively with an external rather than internal focus instruction.

Based on the research evidence, adopting an external focus of attention on the intended movement effect provides multiple benefits relative to an internal focus on body movements. But how exactly does the control of movements change when we alter our focus of attention? The next section discusses how movements tend to be controlled more automatically if participants direct attention to the intended effect or outcome of the movements (external focus) instead of attempting to consciously control them (internal focus).

## Automaticity: The Constrained Action Hypothesis

Imagine you are using your cruise control while you are driving on a freeway. Assume you set it to 70 mph (about 112 kmh). If the traffic volume increases and you are unable to pass a slower-moving vehicle, you may have to reduce the desired speed to 69, 68, or perhaps 67 mph. To maintain a certain distance from the car in front of you, you may have to make some discreet adjustments. To do so, you repeatedly compare your car's speed to the speed of the car ahead of you and make decisions about whether to maintain, further decrease, or increase your speed. This process demands moderate attention. Now think about how you adjust your speed without using cruise control. Your foot on the gas pedal makes subtle and quick adjustments; it does so automatically, without you consciously controlling or even being aware of it. This difference in motor control is analogous to how an internal versus external focus of attention affects movement coordination.

Wulf, McNevin, and Shea (2001) explained the difference between the two types of attentional focus effects with the *constrained action hypothesis*. According to this idea, a focus on body movements promotes a conscious type of control. The result is that performers tend to constrain their motor system, thereby interfering with automatic control processes. In contrast, when performers concentrate on the intended movement effect, their motor system uses a more automatic control mode and takes advantage of unconscious, fast, and reflexive motor control processes. The result is a more effective, efficient, and fluid motion. Several converging lines of research support the notion that an external attentional focus promotes automaticity.

In the first study to examine this idea, Wulf et al. (2001) used a probe reaction time paradigm. As discussed in the section titled "Attention During Movement," a secondary task is often used to determine the degree of automaticity of a primary task (probe technique). In the study by Wulf et al. (2001), two groups of participants learning to balance on the stabilometer (primary task) were asked to focus on keeping their feet (internal focus) or markers in front of their feet (external focus) horizontal. During each 90-second trial, 8 tones occurred at random intervals. The participants' task was to press a handheld switch as quickly as possible in response to the tones (secondary task). The results supported the hypothesis that an external focus produces greater automaticity in balance control with faster reaction times in the external- versus the internal-focus group. These findings have been replicated in other studies. For example, Kal, van der Kamp, and Houdijk (2013) demonstrated reduced cognitive dual-task costs with an external relative to an internal focus using a cyclic leg extension–flexion task. Kal et al. also measured movement fluency (i.e., jerk) and movement regularity (i.e., sample entropy). Both fluency and regularity were enhanced with an external focus, providing further evidence for greater automaticity when an external focus is adopted.

Another way of assessing automaticity is to analyze the frequency characteristics of movement adjustments. In the study by Wulf, McNevin, and Shea (2001; see also Wulf, Shea, & Park, 2001), external-focus participants showed higher-frequency and lower-amplitude movement adjustments compared with internal-focus participants. These characteristics are seen as an indication of a more automatic, reflex-type mode of control (Gurfinkel, Ivanenko, Levik, & Babakova, 1995), suggesting that learners who were asked to focus externally used more, and faster, reflex loops operating at an automatic level, while those who focused internally on their feet used more conscious and slower feedback loops. The latter type of control is analogous to resetting the speed of your car by using cruise control, whereas the former type of control is displayed by your foot action when you simply focus your attention on maintaining a constant distance from the car in front of you.

## Attention and Anxiety

In this final section of the chapter we shift emphasis to some important aspects of human performance related to arousal and anxiety and their relationship to ideas about attention. Anxiety is common, as in an important game or match or when we are threatened with harm in some way. How do high-anxiety conditions affect the processing of information necessary for successful performance?

Consider this true story. An airline pilot with over 20,000 h of flying experience returned to San Francisco after an all-night flight from Hong Kong. He drove home to Oakland (20 mi away), slept for a few hours, and then drove to the local airport to check out his private plane for a flight. With his family of three aboard, he left for a destination a few hours away, watched an automobile race there, and late at night began the return flight. At about 2:00 a.m., he radioed that his heater was not working and that he was above a layer of clouds over the Oakland airport. A pilot with his experience would, in this situation, be expected to perform a relatively lengthy (20 to 30 min) instrument approach through the clouds to the airfield, but instead he radioed that he was looking for a “hole” in the clouds, presumably to avoid the instrument approach. The plane crashed a few minutes later, killing all aboard, after a wing broke off.

What happened? We might guess that the pilot was very fatigued from the overseas flight, from the two other flights that day, and from the car race; he was also cold and in a hurry to get home. The fatigue and cold led to a bad decision to find a “hole.” Also because of the fatigue, the pilot may have been handling the plane badly, perhaps becoming disoriented and diving too steeply through the “hole,” and the wing failed. Similar examples come from underwater diving, as pointed out by Norman (1976) and Bachrach (1970):

A woman enrolled in a diving course but lacking experience, was reported to have . . . drowned while diving for golf balls in a twelve-foot [pool]. When her body was recovered, she was wearing her weight belt, and, in addition, was still clutching a heavy bag of golf balls. (p. 122)

Again, something went wrong. Perhaps fatigue and cold led to panic. When the stress conditions become more severe, the responses of human performers can be severely disrupted. Many of these disrupted responses occur in true emergency situations, such as earthquakes, fires, battlefields, and other life-threatening situations. As such, they are difficult to study directly, and one must usually rely on various kinds of postevent measures to understand them.

Such situations often stem from what Janis, Defares, and Grossman (1983) call *hypervigilance* or what one might loosely term “panic.” The contributing conditions seem to be (a) a sudden and intense stimulus, (b) a potentially life-threatening outcome, and (c) a situation in which time to take an appropriate action is quickly running out. All of these seem to be present in most cases of a kind of vehicle accident termed “unintended acceleration” (Schmidt, 1989b, 1993; see chapter 6, “Pedal Misapplication Errors”), in which the driver panics when he or she mistakenly presses the accelerator rather than the brake, and the car accelerates unexpectedly (and with no intention on the driver’s part). The individual appears to freeze, perhaps because attention is so narrowed that no alternative actions are considered. It could also be that the driver considers many alternatives but, because of the increased distractibility, none long enough to initiate a solution; he or she “dithers” until it is too late. Also, the person tends to choose the action that is highest in the response hierarchy—the most common, “natural,” or highly practiced action (e.g., pressing the brake when the vehicle spins on ice). Moreover, the individual tends to persevere, producing the same response repeatedly, even though this action has not had the desired effect. These situations are not as rare as they might appear, as evidenced by analyses of numerous vehicle accidents (Perel, 1976). Further, they might also occur in highly stressful sport events, industrial tasks, theater or night club fires, and so forth, with outcomes that are much less dramatic or not so easily analyzed.

What effects do anxiety and panic have on information processing in these situations, causing people to abandon highly practiced techniques and resort to the skill level of an inexperienced beginner? There are many views of how anxiety or stress affect cognitive or motor performance. In a review of the literature, Nieuwenhuys and

Oudejans (2012) describe various influences of anxiety that can lead to degraded, and sometimes catastrophic, performance. These influences pertain to the perception of task-relevant information, the selection of action possibilities, and motor performance per se. For instance, a person's perception might be biased toward a threat rather than informational sources that are more important for task performance. Also, visual gaze and search behavior become less effective and less efficient, with frequent short-duration fixations, when people are anxious (see Janelle, 2002). Presumably not unrelated to changes in perception, the selection of actions is often not optimal in stressful situations. For example, in the crash of commuter plane Colgan Air Flight 3407 in February 2009, the pilot repeatedly performed the wrong action when he noticed that the plane was losing speed and began to stall while approaching Buffalo Niagara International Airport. Instead of pushing the control column in to increase the speed, he pulled it back to make the plane's nose go up, thereby decreasing the speed further, with fatal consequences. Finally, the impact of pressure on motor performance has been well documented. Several lines of research have identified self-focused attention as detrimental to performance (e.g., self-focus, Baumeister, 1984; explicit monitoring, Beilock & Carr, 2001; skill-focused attention, Gray, 2004; self-invoking trigger, McKay, Wulf, Lewthwaite, & Nordin, 2015; internal focus of attention, Wulf, 2013). The self-consciousness resulting from factors, such as the presence of an audience, causes performers to become overly cautious, thereby disrupting the fluidity of well-learned and typically automatic motions.

## Summary

Even though attention has had a long history of thought in psychology, we are still unclear about its nature and the principles of its operation—indeed, even its definition. Many theorists think of attention as a single, undifferentiated, limited capacity to process information; others argue that attention is really a number of pools of capacity, each specialized for separate kinds of processing. The successful performance of various tasks together is presumably limited by these capacities; therefore, attention demand is usually estimated indirectly by the extent to which tasks interfere with each other. Processing of sensory stimuli (or performing other processes early in the sequence) can apparently occur in parallel, with little interference from other tasks. But processes associated with response selection or with response programming or initiation interfere greatly with other activities.

Characteristics of attention play an important role in motor performance. Psychological refractoriness—the delay in responding to the second of two closely spaced stimuli—provides evidence that some single channel, or bottleneck, in processing exists in the response-selection or response-programming stage, before which processing is parallel and after which processing is serial. Other limitations in attention, such as the Stroop effect, inattention blindness, and inhibition of return, reveal that attending selectively to some information may have consequences that are not intentional. Other evidence, based on secondary-task techniques, suggests that attention demands are highest at both the initiation and termination stages of movements, particularly when the end of the action has an important precision component. The use of cell phones and other in-vehicle devices during driving provides an excellent example of attentional limits on daily activities. Some evidence suggests that directing one's attention to movement or environmental cues may differ according to one's skill level.

A person's focus of attention (concentration) has an important influence on both performance and learning. An external focus on the intended movement effect results in greater movement effectiveness and efficiency, compared with an internal focus on body movements. Directing attention to one's own movements disrupts automaticity. In contrast, an external focus promotes the use of the motor system's automatic control capabilities.

Arousal and anxiety influence performance. The mechanisms that appear to limit performance under stress are related to perceptual inefficiencies, the selection of inappropriate actions, and disruptions of movement automaticity and fluidity.

### Student Assignments

1. Prepare to answer the following questions in class discussion:
  - a. Using examples from a sport, illustrate three different aspects of the concept of attention.
  - b. Provide examples of inattention blindness in driving.
  - c. Find two other types of Stroop effects that have been studied in the research literature.
2. Find a research article not covered in the book on the effects of using a cellular device during driving.
3. Describe different ways in which automaticity (for example, resulting from an external focus of attention) can be measured.

### Notes

<sup>1</sup> Actually, the basic phenomena underlying the “Stroop effect” had been studied for about a half century before Stroop published his work in 1935, beginning with Cattell (1886; see MacLeod, 1991, for a historical review).

<sup>2</sup> In a way, this label is unfortunate. The original idea was that the delay in the participant's response to the second of two closely spaced stimuli is analogous to the delay when a single nerve fiber is stimulated electrically twice in rapid succession in physiological experiments. If the second stimulus is very close to the first (within about 5 ms), no response at all will result from the second stimulus. This effect has been termed the *absolute refractory period*, meaning that the nerve is insensitive to additional stimulation while it is refractory, and it “recovers” from the effects of the first stimulus. These neuronal processes probably have little to do with the psychological refractory

period, as the time course is much longer in the behavioral work (e.g., 200 ms).

## Part II

# Motor Control

- Chapter 5 Sensory Perceptual Contributions to Motor Control
- Chapter 6 Central Contributions to Motor Control
- Chapter 7 Principles of Speed and Accuracy
- Chapter 8 Coordination

Human motor control is a complex system with many interacting pieces, processes, and mechanisms. To attempt to understand the system as a whole would be extremely difficult, so scientists generally study various parts of the system in isolation. These parts are often studied as independent modes of control—fundamentally different ways in which the system's parts can work together. Chapter 5 focuses on the role of sensory information, considering the ways in which information from the environment influences, or even determines, movement behavior. Chapter 6 examines the central control and representation of action in situations in which sensory influences do not have a particularly strong role. Chapter 7 deals with various laws and models regarding the principles of speed and accuracy, especially as they pertain to the control of relatively simple movements. Chapter 8 considers more complex movement control, involving the coordination of more than one effector, often studied as a dynamic physical system.

# Chapter 5

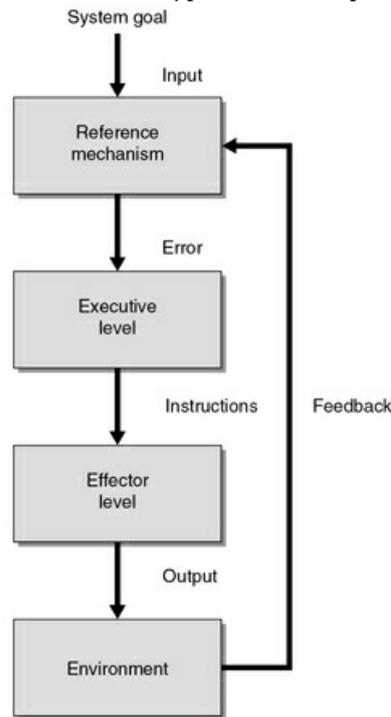
## Sensory and Perceptual Contributions to Motor Control

Sensation and perception complement each other to create meaning from our experiences, yet they are two completely different ways to interpret the world. *Sensation*, the physical stimulus, together with its physical properties, is registered by specialized sensory organs. The organs decode this sensory information, transforming it into neural impulses (signals) and sending them to the brain. *Perception* is mainly how the brain interprets a sensation. Perception occurs when the brain or spinal cord organizes the information and translates it into something meaningful that we can rationalize. Thus, sensation and perception complement each other to create meanings from what we experience. One of the ways in which motor control is achieved relies heavily on the concept that we use *sensory* (or *afferent*) *information* to regulate our movements. This can be information that tells us about the state of the environment, about the state of our own body, or about the state of our body with respect to the environment. A way to think about how sensory information is used in the control of action is to consider the moving human as a type of *closed-loop system*. A closed-loop system depends heavily on the involvement of particular types of sensory information as it interprets and executes its function. Such sensory information, when discussed in the context of closed-loop motor control, is often termed *movement-produced feedback*, or simply *feedback*, implying that the sensory information to be considered has arisen as the *result* of performed actions. In this chapter we discuss the various kinds of sensory and perceptual information that can be used in the control of movement.

## Closed-Loop Control Systems

One way of attempting to understand motor control has been to consider sensory contributions in ways analogous to mechanical systems' control. *Closed-loop* systems are important in many situations, especially those that require a system to “control itself” for long periods of time. (In contrast, see chapter 6 for a discussion of *open-loop* systems.) A diagram that illustrates how a simple closed-loop system works is shown in [figure 5.1](#). First, input about the system's goal is provided to a *reference mechanism*. In a home heating system, the overall goal might be to achieve and maintain a certain temperature in the house. The reference mechanism in this system is the specific temperature setting, say 68 °F—the temperature setting can be changed without affecting how the system operates. Next, the reference mechanism samples the environment that it is attempting to control to determine the current temperature. This information from the environment is usually termed *feedback*. The reference mechanism then compares the value of the goal (e.g., 68 °F) to that of the sample obtained from the environment (current temperature), and an *error* is computed, representing the difference between the actual and desired states. The error is information that is passed to an *executive level*, where decisions are made about how to reduce the error. If the error is large enough, instructions are sent from the executive level to the *effector level*, and a mechanism that has some effect on the environment is activated—in this case, the heater. The heater raises the temperature of the room, and this raised temperature will be sampled periodically. When the difference between the actual and desired temperatures is zero, the executive level shuts off the heater. In such a way, the heater cycles between being on and off as a function of the actual room temperature and thus maintains the system goal. Such systems are termed *closed loop* because the loop of control from the environment to decisions to action and back to the environment again is completed, or closed.

Figure 5.1 Elements of the typical closed-loop control system.



How does this model of the closed-loop system relate to the human motor control system? For now, think of the reference of correctness and the executive level as being contained in the stages of information processing, so that the system can receive and process feedback information following the stimulus-identification stage to determine movement error, and then program instructions to the musculature to reduce the error in the response-programming stage. Instructions are then given to the effector level, usually thought of as the muscles or as a program of action that actually controls the muscles. Then, the information obtained from the various muscle, joint, and tendon receptors, as well as from the eyes, ears, and so on, is sent back to the reference mechanisms for analysis, and decisions about future action are again made. Notice that, with this feedback loop (and the stages of processing), the implication is that *all* feedback is processed in this way—requiring attention (and consciousness). As we will learn later in this chapter, some (if not most) feedback for action is processed reflexively, “below” the level of consciousness (see Ghez & Krakauer, 2000; Pearson & Gordon, 2000b).

The various sources (or receptors) of sensory information that are available during movement are traditionally classified into three groups (after Sherrington, 1906). Perhaps the least important for our purposes is the class of receptors called *interoceptors*. They tell us about the states of our internal organs and have questionable relevance for motor behavior. However, sensory receptors that provide information about pain and how we perceive and adapt to that information has become an important area of study in the field of rehabilitation. The remaining two classes of receptors are divided according to whether they provide information about the movement of objects in the environment (*exteroceptors*) or information about our own movements (*proprioceptors*). The roots *extero* and *proprio* refer to events outside one’s body and events in one’s own body, respectively.

# Vision

Certainly the most critical receptor for supplying information about the movement of objects in the outside world is the eye. Therefore, we begin our discussion with the richest and most important feedback information used in the control of movement.

## How Vision Provides Information

Subjectively, we all know that darkness critically impairs the performance of many tasks, although we also know that vision is not essential for all motor performances. People who are blind learn to move in the environment with remarkable facility, although they are at a large disadvantage in many situations. In terms of human performance, vision provides information about the movements of objects in the environment, as well as about the movement of one's body in that environment, and much of motor control involves tailoring our motor behavior to meet these visually presented environmental demands.

### *Dorsal and Ventral Visual Streams*

Concerning vision as an exteroceptive system (for detecting events in the outside world), we have long known that central vision (involving visual acuity, contrast, object identification, and consciousness) is a major sensory component of many types of motor behavior. However, evidence and theorizing argue for the existence of two distinct streams of visual processing in the brain. The lines of evidence to support these different streams come from a wide range of levels of analysis, using various techniques and participants in the research. Indeed, even the names for the two visual streams differ markedly, with such proposed dichotomies as cognitive versus motor vision, explicit versus implicit vision, object versus spatial vision, overt versus covert vision (Bridgeman, 1996), and focal versus *ambient vision* (Trevarthen, 1968). We will refer to the two visual streams in terms of the anatomical distinction proposed by Ungerleider and Mishkin (1982)—the *dorsal* and *ventral* visual stream dichotomy (e.g., see the review and commentaries in Norman, 2002; Creem & Proffitt, 2001).

In one of these systems (the ventral system), the primary input is limited to central vision. This information requires contrast, focus, and sufficient light. This system is specialized for object identification and (conscious) perception of the environment. Thus, the ventral system is sensitive to what the person is looking at or focusing on (or both). In the other system (the dorsal system), the visual input is full field (nearly 180°), does not require focus, and seems to operate effectively even in very low-light situations. We can think of the retina of the eye as the recipient of rays of light from all parts of the field of vision. For any given position of the eye, a unique combination of these rays allows specification of the eye in space. More importantly, when the eye moves through space (as during walking), the angles of these rays change in predictable ways. These changes in the light rays—termed “optical flow” because the angles of these rays change continuously, or “flow”—specifying the nature of the eye's movement (and thus the person's movement) in space. We'll come back to optical flow and movement shortly.

Anatomically, both the dorsal and ventral streams are thought to project visual information from the environment by means of the retina to the primary visual cortex in the brain. From there, however, the *dorsal stream* sends information to the posterior parietal cortex, whereas the *ventral stream* projects to the inferotemporal cortex (Ungerleider & Mishkin, 1982). Of particular interest to researchers in motor behavior are the roles afforded by the two streams. Whereas ventral stream processing has been considered responsible for providing cognitive information about objects in the environment (e.g., object identification), processing by the dorsal stream is proposed to provide information specifically for the visual control of movement (Goodale & Milner, 1992; Goodale & Humphrey, 2001; Milner & Goodale, 1993, 1995). Thus, a generalization that has been the topic of hot debate is that ventral stream processing is *vision for perception* (identification) whereas dorsal stream processing is *vision for action* (Jeannerod, 1997; Jeannerod & Jacob, 2005; Milner & Goodale, 2008).

The nature of the information processed appears to be a key component of the distinction. For the ventral stream, information that is central to the identification and recognition of objects is crucial—this includes information picked up from the environment and information stored in memory. In contrast, the dorsal stream is particularly attuned to information about how we control our motor system to interact with an object. As Norman (2002) pointed out, however, it is important to keep in mind that a complementary relationship exists between visual processing in the two streams. For example, when looking for a hammer we use ventral stream information to recognize the hammer and dorsal stream information to pick it up (Norman, 2002). In the next sections, we review some of the evidence that supports the existence of two streams of visual information processing.<sup>1</sup>

### *Evidence for Two Visual Streams*

Classifying things is easy. Before a classification is accepted, however, scientists usually demand strong evidence that it facilitates understanding. One of the strongest kinds of evidence is a *dissociation*, in which the effect of some independent variable on one hypothesized construct (e.g., ventral stream) is different than the effect of the same variable on the other construct (e.g., dorsal stream). Support for the separation of hypothesized constructs is strong when clear dissociations are found. In the study of distinct streams of visual processing, dissociations have been found in two types of research investigations.

#### Perception–Action Dissociations in Brain-Injured Patients

Strong evidence that favors the dissociation between perception vision and action vision has been found in patients who have specific damage to parts of the brain involved in the processing of visual inputs. For example, patients who had a type of brain injury resulting in what is called *optic ataxia* were able to recognize an object but err but were unable to use this same visual information to guide their hand accurately to the object (Perenin & Vighetto, 1988). In contrast, patients with a type of disorder called *visual agnosia* were unable to recognize common objects, yet could use the visual information to grasp the objects accurately (Goodale & Milner, 1992; Goodale, Milner, Jakobson, & Carey, 1991). This dissociation in the ability of patients to use vision for one task but not the other represents a very important finding in support of visual stream separation. Researchers have also relied both on experiments with animals (e.g., Schneider, 1969; Trevarthen, 1968; Ungerleider & Mishkin, 1982) and on behavioral experiments involving healthy individuals to further study these visual streams.

#### Perception–Action Dissociations in Behavioral Studies

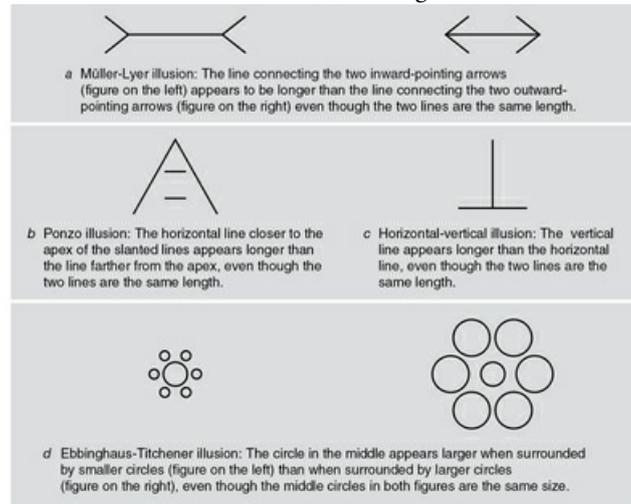
An important early study in the behavioral identification of the two visual streams was conducted by Bridgeman, Kirch, and Sperling (1981). They used an induced-motion paradigm, in which small movements of a surrounding background (a “frame”) in a given direction made it appear that a fixed target element within it moved in the opposite direction. Under these conditions, participants would say (i.e., they perceived, consciously) that the (actually stationary) target moved back and forth through about 2.5° of visual angle. This is a measure of the bias in the ventral processing system. Bridgeman and colleagues then suddenly extinguished the target and background, and the participant’s task was to move the hand to point to the last location of the target, providing a measure of the dorsal system’s accuracy. These pointing movements (to the *actual* position of the target) were largely unaffected by the movement of the background. In this way, Bridgeman and coworkers found that the movement of the background biased the visual information used for (conscious) perception of the target’s position but did not bias the visual information used for action. Another experiment used the reverse procedures: now, the target actually moved, and the background-frame moved in the opposite direction by such an amount that the person perceived (consciously but erroneously) that the target was stationary. When the target and background were extinguished, the pointing tended to be to the actual location of the target, not to the position that the performer perceived consciously.

This effect is actually a *double* dissociation: (1) The moving background (or frame) altered the conscious

perception of the fixed target position but not the pointing direction, and (2) the altered actual position of the target (whose location was perceived as fixed because of the moving background) did not bias the pointing direction. Similar double dissociations have also been shown for static images in which an off-centered frame biases the perceptual judgment of a particular stimulus target but does not bias a performer's reach toward the target (Bridgeman, Gemmer, Forsman, & Huemer, 2000).

These important findings, in which a participant-viewed stimulus resulted in a perception-vision bias but not an action-vision bias, have been the basis for a large number of empirical investigations involving visual *illusions*. Many of these studies used a similar experimental paradigm in which participants were asked to make perceptual judgments and actions involving various visual illusions as targets. [Figure 5.2](#) illustrates four of these visual illusions.

Figure 5.2 Various visual illusions used in aiming tasks: (a) Müller-Lyer illusion, (b) Ponzo illusion, (c) horizontal-vertical illusion, and (d) Ebbinghaus-Titchener illusion.



In investigations of the Ebbinghaus-Titchener illusion<sup>2</sup> (figure 5.2d), participants are asked to point to a circle in the center of surrounding circles (a two-dimensional version of the task), or to grasp a cylindrical disc that is located in the middle of surrounding discs (a three-dimensional version). In this illusion, the Ebbinghaus-Titchener display creates a bias to perceptual vision that makes the center circle surrounded by a ring of small circles appear larger than the center circle surrounded by a ring of large circles, even though the two center circles are identical in size. Most studies, however, have shown a dissociation of the effect of the illusion on perceptual versus action vision—the illusion has no influence on action vision, evaluated either as the movement time to point at the circles or as the size of the grasp used to pick up the center object; sometimes, the bias is much smaller than the effect on perceptual judgments of these circles (Aglioti, DeSouza, & Goodale, 1995; Haffenden & Goodale, 1998; Haffenden, Schiff, & Goodale, 2001). Similar perception vision and action vision dissociations have also been found for the Müller-Lyer illusion (figure 5.2a) (Otto-de Haart, Carey, & Milne, 1999), the Ponzo illusion (figure 5.2b) (Bartlett & Darling, 2002; Ellis, Flanagan, & Lederman, 1999; Ganel, Tanzer, & Goodale, 2008), and the horizontal-vertical illusion (figure 5.2c) (Servos, Carnahan, & Fedwick, 2000).

Note, however, that much controversy exists regarding the interpretation of visual illusion dissociations (e.g., Bruno, 2001; Carey, 2001). Some of the behavioral dissociations are found only under restricted and specialized experimental conditions (e.g., Fischer, 2001; Franz, Bühlhoff, & Fahle, 2003; van Donkelaar, 1999; Westwood, Dubrowski, Carnahan, & Roy, 2000; Wraga, Creem, & Proffitt, 2000), and sometimes the dissociations are not found at all (e.g., Meegan et al., 2004). Comprehensive reviews of this research area conclude that visual illusions appear to have a larger influence on perception than on action, although both appear to be influenced in similar ways by the visual information (Bruno, Bernardis, & Gentilucci, 2008; Bruno & Franz, 2009). Consequently, while some researchers feel that these behavioral data support the distinction between separate streams of visual processing, others are less convinced. For example, Glover (2002, 2004; Glover & Dixon, 2001) presented evidence that a perceptual tilt illusion affected action during the movement planning stage but not during the execution of the movement, leading to the view that differences in the use of action vision are dissociated between the planning and execution stages. In contrast, Smeets and Brenner (2001; Smeets, Brenner, de Grave, & Cuijpers, 2002) argue that object orientation in the environment affects visual processing *strategies* and does not imply separate streams of vision. An additional perspective pertaining to visual illusion dissociations comes from the action-specific perception account described in the following section.

### *Action-Specific Perception*

The *action-specific perception account* explains that people perceive the environment in terms of their ability to act in it (Witt, 2011). Mounting evidence supports this idea. For example, performers who throw a heavy ball to a

target perceive the target to be farther away compared with those who throw a light ball (Witt, Proffitt, & Epstein, 2004), softball players who are hitting better than another group of softball players see the ball as bigger (Witt & Proffitt, 2005), and people with narrow shoulders perceive doorways to be wider compared with people with wide shoulders (Stefanucci & Geuss, 2009). This research provides evidence about the ways in which the participant's ability or skill to act influences how the environment is perceived and used for not only the control of movement but also for motor learning (Chauvel, Wulf, & Maquestiaux, 2015).

### *Visual Information About Time to Contact*

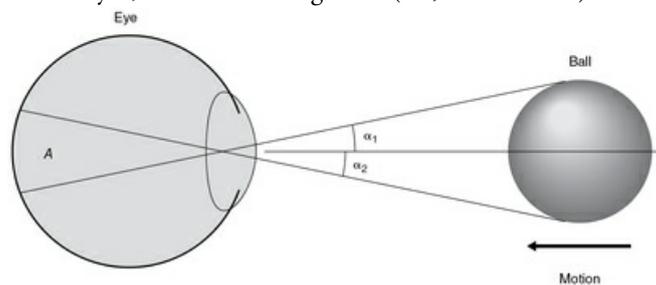
Another important issue related to the general topic of how visual information is provided has to do with the processing of dynamic information—visual information that changes over time, sometimes at a very rapid rate. For example, in passing another automobile, we are bombarded with various sources of visual inputs that change at different rates: the stationary environmental information that we drive past (such as road signs); the car that we are passing; the car that is coming rapidly toward us in the opposite lane; and the information within our own car, which is traveling at the same speed as ourselves. All these sources of information represent visual cues that a driver must perceive accurately in order to execute a safe pass.

Considerable research in motor behavior has been directed at a subset of skills involved in the perception of dynamic visual information. Many of these skills are used in ball games and require *interceptive* actions such as catching or striking. The moving object provides various types of information, such as its position in space and the way its position is changing over time (e.g., in the case of a pitched ball in baseball). However, probably the most important and frequently studied skill relates to the use of temporal information about *when* the object will arrive. This is called time-to-contact ( $T_c$ ) information.

An important view regarding how  $T_c$  is perceived was formulated by David Lee (1980, 1990; Lee & Young, 1985; see also Purdy, 1958) and relates quite closely to the work of James Gibson (1966, 1979; see “Visual Proprioception”). Consider an object, such as a ball, that is moving directly toward your eye, as shown in [figure 5.3](#). If the angles of the light rays from the edges of the ball (i.e.,  $\alpha_1$  and  $\alpha_2$ ) are increasing at the same rate (with respect to straight ahead), this information specifies that the ball is moving directly toward your eye. Such information, called *looming*, usually elicits strong avoidance reactions that appear to be nearly “automatic,” or at least difficult to inhibit, especially in infants. But in addition, Lee's work showed that these changes in visual information tell the viewer about the amount of time remaining until contact will be made (Lee, 1976, 1980, 1990, 2009; Lee & Young, 1985). In [figure 5.3](#), the edges of the ball cast a retinal image of size  $A$ , which increases in size as the ball comes closer; also, the more rapidly the ball approaches, the faster the image will be expanding. Let's abbreviate this rate of expansion occurring at some moment (or the derivative of  $A$  with respect to time) as  $\dot{A}$ , where the dot above the letter means the “rate of change of.” Lee defines “proportionate rate of expansion” as simply the rate of expansion  $\dot{A}$  divided by the size of the retinal image  $A$  (or  $\dot{A}/A$ ), which is a measure of the rate of change at some moment as a proportion of the size of the retinal image  $A$ . Lee (1976) showed mathematically that the reciprocal of this ratio, or  $A/\dot{A}$ , is directly proportional to  $T_c$ . This is true regardless of the size of the object, the velocity at which it travels, or its distance from the eye. That is, time to contact is defined as

$$T_c = \text{tau (or } \tau) = k A / \dot{A} \quad (5.1)$$

Figure 5.3 Diagram of a ball approaching an eye, showing the size of the image ( $A$ ) it projects on the retina; at any moment, the time until contact is proportional to tau, which is directly proportional to the retinal size  $A$  divided by  $\dot{A}$ , the rate of change of  $A$  (i.e.,  $\tau = k A / \dot{A}$ ).



where  $k$  is a proportionality (slope) constant. In other words,  $T_c$  is proportional to the reciprocal of the proportionate rate of expansion of the retinal image. This makes common sense. At a given distance, an object has a retinal size of  $A$ ; the rate of change in the object's retinal image ( $\dot{A}$ ) will be larger the faster it is traveling. This makes the denominator in equation 5.1 larger and hence tau smaller, indicating that there will be less time until the object contacts the eye.

Lee (1998) also formulated a general theory of how tau is used in the control of movement. In this view, all goal-directed actions require the closing of a *gap*. For example, running to catch a ball requires the closing of two gaps: (1) The gap between the ball's initial position and its point of interception, and (2) the gap between the catcher's initial position and the point of interception. Lee has suggested that *tau coupling* is one component of a general tau theory—that the closure of the two gaps occurs at the same relative rate (Lee, Georgopolous, Clark, Craig, & Port, 2001). This view follows closely the earlier theoretical formulations and retains the elegant concept that a relatively simple transformation of optical flow allows the specification of important temporal events in the environment. It is a relatively simple theory in the sense that perception does not depend on the “computation” of either distance or velocity cues per se. In a later section we will see how ideas regarding  $T_c$  have been used to explain various features of motor control.

## Time Required to Process Visual Feedback

Consider the following situation: Someone is working at night in a toolshed, striking the head of a nail with a hammer. Now imagine that the electrical power to the shed is lost and all the lights go out just as the hammer starts its downward swing to contact the nail. How does the sudden loss of vision affect the accuracy? Would accuracy have been affected any more or any less if the hammer had not yet started its downward swing, or if the size of the nail had been larger or smaller, if the swing had been faster or slower? Experimenters have studied research questions addressing situations such as these using various theoretical and experimental approaches, focusing much of that research on the amount of time available to process visual information.

### *Moving to Stationary Targets*

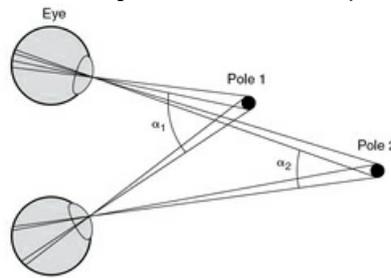
An initial estimate of the time required to process visual feedback was provided more than a century ago by Woodworth (1899). The research was motivated by his view that aiming movements consist of a two-component process. In the *initial-impulse* phase (also termed the *ballistic-* or *programmed-movement phase* by later researchers), Woodworth suggested that movements are initiated by an impulse that drives the limb toward the target. Once the movement is under way, the second phase provides an opportunity to correct any spatial error that may have occurred in the intended path of the limb. Woodworth called this second component the *current-control phase*, during which the participant uses visual feedback to *home in* on the target, making fine corrective adjustments as needed in order to land on the target. According to Woodworth, the successful completion of this second phase of the movement can occur only if there is sufficient time to process the error arising from the analysis of the visual feedback and to issue an efferent signal that will alter the spatial course of the movement. Thus, Woodworth

reasoned that aimed movements with vision should be more accurate than those made without vision *only if* there is sufficient time to use the visual feedback. Movements that are completed before visual feedback can be processed would be expected to result in target dispersions that are equally inaccurate for blind and sighted aims. The critical question, then, is, *What is the minimum amount of time required to process visual feedback?* A number of experiments using more or less the same experimental method as Woodworth's have addressed this question. Therefore, we will examine the Woodworth (1899) study in some detail (see also "R.S. Woodworth on Manual Aiming").

## Visual Proprioception

[Figure 5.4](#) illustrates one of James Gibson's concepts about how changes in head position contribute to changes in the angles of light rays entering the eye (Gibson, 1966, 1979). The pattern of rays experienced is called the *optical array*, and it provides a unique specification of the location of the eye in space. The changes in the optical array when the eye is moved from one place to another are called the *optical flow*, implying that the visual environment "flows past us" as we move around. An important point is that the particular patterns of flow specify distinct kinds of movements of the eyes with respect to the environment. For example, if the angle between the light rays from two sides of an object is constant over time, this specifies that you are not moving with respect to that object. If the angle between these rays is increasing, then you are moving toward the object; if it is decreasing, you are moving away from it. Also, if the angles from two sides of an object (with respect to straight ahead) are increasing at the same rate, the eye is moving toward the center of the object (e.g., your eye(s) are moving toward the center of a picture on the wall). In conditions in which the angles from both sides of an object are changing in the *same* direction, if the rate of increase in the angle of the rays from the right side of the object is greater than the rate of increase from the left side and continues in this way, you will pass the object so that it is on your right side.

Figure 5.4 The detection of distance: The angles of the light rays from the distant pole change less than those from the near pole as the head and eyes are moved.



The optical flow generated as you move in the environment also tells you about the *environment itself* in ways that could not be achieved if you were stationary. For example, imagine looking out the window at two telephone poles as illustrated in [figure 5.4](#). Which of them is closer? The question is difficult to answer if you remain still, because the poles appear to be nearly the same thickness and height. But if you move your head sideways, you can tell immediately. You will notice that one of the poles seems to “move more quickly” as you change head position. This, of course, is the same as saying that the angles of the rays received from one object changed more quickly ( $\alpha_1$  in the figure) than did those from the other ( $\alpha_2$ ), implying that pole 1 is closer than pole 2. Thus, the visual system, through movement of the entire head, body, or both, can provide rich information about the nature of the environment. In this view, vision is not merely an exteroceptive sense, passively providing information about the environment. It is also a proprioceptive sense telling us about our own movements. As well, vision is dependent on movement in some situations for informing us about the environment. In this way, vision and movement are very closely and reciprocally linked. Excellent discussions of this basic idea are found in Gibson (1966, 1979) and Lee (1980; Lee & Young, 1985), the latter showing relevance to many situations, such as sport-related motions and bird flight.

## R.S. Woodworth on Manual Aiming

### Research Capsule

R.S. Woodworth became one of the most noted American experimental psychologists of his time. The topic of his doctoral dissertation was motor control, and in 1899 he published the results of a large number of experiments on the topic of “accuracy of voluntary movement.” In this work, Woodworth touches on a wide array of topics related to the control of movement: the use of vision, handedness, biomechanical factors, fatigue, practice, and so on. One of his most lasting contributions has been the two-component model of movement aiming (i.e., initial adjustment vs. current control), and Woodworth’s ideas remain at the forefront of theorizing today (Elliott et al., 2010; Elliott, Helsen, & Chua, 2001; Newell & Vaillancourt, 2001b). In the following quote from Woodworth’s dissertation (Woodworth, 1899), note how effortlessly he moves between topics that would later become the center of much of our present understanding of these processes.

“If the reader desires a demonstration of the existence of the ‘later adjustments’ which constitute the most evident part of the ‘current control,’ let him watch the movements made in bringing the point of his pencil to rest on a certain dot. He will notice that after the bulk of the movement has brought the pencil near its goal, little extra movements are added, serving to bring the point to its mark with any required degree of accuracy. Probably the bulk of the movement is made by the arm as a whole,

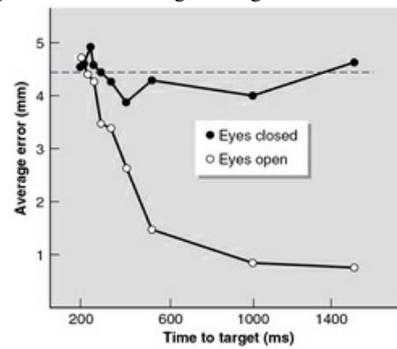
with little additions by the fingers. If now the reader will decrease the time allowed for the whole movement, he will find it more difficult, and finally impossible, to make the little additions. Rapid movements have to be made as wholes. If similar movements are made with eyes closed, it is soon found that the little additions are of no value. They may bring us further from the goal as likely as nearer.” (p. 54)

## Woodworth (1899)

To assess the minimal time required to process visual feedback, Woodworth asked his participants to make back-and-forth movements with a pen. The goal for each action was to produce a movement equal in length to the preceding one. A strip of paper moved beneath the performer’s pen at a constant velocity; thus a record of the previous movement could be used as the target for the next and served also as a permanent record that could be used later to calculate measures of error. Movements were performed with eyes open or closed, paced by a metronome at speeds of 200 to 20 cycles per minute (i.e., movement times [MTs] that ranged from 300 ms to 3 s per cycle, respectively). Aiming was done only in one direction—the return movement was made to a physically restricted stop. Thus, the values of available time to process visual feedback from the stop to the intended target were about half of the total cycle time, or between 150 ms and 1.5 s (Carlton, 1992).

The average errors (similar to absolute error [AE]; see chapter 2) in the eyes-open and eyes-closed conditions are illustrated by the open and filled circles in [figure 5.5](#). As seen on the far left side of the figure (short MTs), the eyes-open and eyes-closed conditions produced equivalent average error. As shown on the right side of the figure (long MTs), the availability of vision in the eyes-open condition resulted in much lower average error, relative to the eyes-closed condition and relative to short MTs with the eyes open. The critical point in the graph occurs when the eyes-closed and eyes-open conditions begin to depart in terms of average error. This departure point represents the time when vision of the target significantly reduces average error compared to the average performance of the eyes-closed condition (represented by the dotted line in [figure 5.5](#)). This point of departure occurs between movements of 215 ms duration and movements of 250 ms duration. That is, movements with durations of 250 ms or longer could benefit from the availability of vision (as seen by reduced error), but movements with durations of 215 ms or less did not benefit when vision was available. Notice that, for this task, the estimate of the time to process visual feedback seems to be about the same as in responding to a visual stimulus in a *choice reaction-time* (RT) task.

Figure 5.5 Aiming errors in moving to targets with the eyes open and closed.



Adapted from Woodworth 1899.

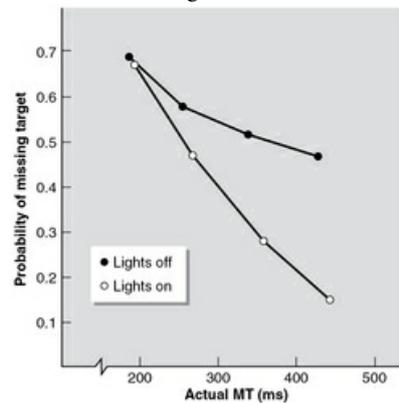
### Keele and Posner (1968)

Although Woodworth's empirical and theoretical contributions are considered landmarks in motor control research (Elliott et al., 2001; Newell & Vaillancourt, 2001b), there were some peculiarities. The repetitive, back-and-forth nature of the task meant that participants had to aim at the target and prepare to reverse the movement (to start it) at about the same time, making the role of vision more complex than in an aimed movement that simply terminates at the target, such as touching an object on a tablet or phone. As well, the nature of the task required participants to try to match the previous movement they had made; making the target more ambiguous than, for example, hitting a nail with a hammer or touching a keypad (Meyer, Smith, Kornblum, Abrams, & Wright, 1990, describe other peculiarities).

Keele and Posner (1968) overcame these problems by using a discrete-task version of Woodworth's research strategy. They trained their participants to move a stylus to a small target about 15 cm away. Knowledge of results about MT was provided, and participants were trained to move as closely as possible to assigned MT goals (150, 250, 350, and 450 ms). On certain randomly determined test trials, the experimenters turned off the room lights as soon as the stylus left the starting position, so that the entire movement was made in the dark.

Keele and Posner's results are illustrated in [figure 5.6](#), revealing the probability of missing this target as a function of the vision condition and the *actual* average MTs. In the 150 ms MT condition (the actual MT was 190 ms), about as many target misses were recorded when the lights were on (68%) as when the lights were off (69%). As the MTs increased, an advantage emerged when the room lights were on, consistent with the view that vision can be used when sufficient time is available for detecting and correcting errors.

Figure 5.6 Percentage of target misses with room lights on and off during movements of various durations.



From Keele and Posner 1968.

### Visual Feedback Uncertainty

Despite the changes in the design of their study, Keele and Posner's estimate of the time required to process visual feedback information (between 190 and 260 ms) was very similar to the estimate suggested by Woodworth (1899). But *uncertainty* about whether or not visual feedback would be available on a trial seems to have played an important role in the experiment of Keele and Posner (1968). In their methodology, the room lights went off unexpectedly on some trials in a randomly determined order. Perhaps if participants knew in advance that vision would or would not be available, their attention might have been focused more appropriately, and the estimate of the time to process visual feedback might be considerably less than in situations in which participants are "surprised" by the presence or absence of vision. If the participant could never fully expect to have vision available, then a strategy designed to employ vision might be avoided in favor of an alternative strategy. The unpredictability of vision in Keele and Posner's study may have prevented participants from using vision to its fullest when it was available. Thus, visual processing time in the study may have been overestimated.

To address this issue, Zelaznik, Hawkins, and Kisselburgh (1983) and Elliott and Allard (1985) performed experiments similar to Keele and Posner's except that in some conditions the participants knew in advance when vision would or would not be available. Elliott and Allard (experiment 1) used a series of trials in which the room lights were either left on or were turned off at *random* (as in Keele & Posner), and another series of trials in which room lights were manipulated in a *blocked* order (i.e., entire sets of trials were done either with or without vision). For movements made as fast as possible (225 ms), the availability of vision increased target aiming accuracy only when trials were blocked; no differences were found between vision and no-vision conditions when the trials were randomized (i.e., when visual feedback availability could not be anticipated). These findings raised the possibility that unpredictability and frequent switches between vision and no-vision conditions reduced processing efficiency (Cheng, Luis, & Tremblay, 2008).

Zelaznik and colleagues (1983) also found that visual feedback could be used more quickly in predictable trials than when it was presented randomly. In this study, all trials were conducted in a blocked (predictable) order. No advantage for the availability of visual feedback was found when MTs were about 75 ms; however, clear differences were present for MTs of about 150 ms and longer. These data suggest that vision, when its presence can be expected, can be used in far less time than the minimum suggested by Woodworth (1899) and by Keele and Posner (1968), perhaps with visual processing times as short as 100 ms. In other experiments, Zelaznik and colleagues showed that the advantage for the lights-on condition remained even if the procedures were reversed so that the lights were off initially but would come on suddenly.

Other studies support the contention that the visual processing values obtained by Woodworth (1899) and Keele and Posner (1968) were overestimates of the minimum time to process visual information. Carlton (1981a) prevented visual feedback during the initial 75% of the distance to the target; he found that vision could be used

in as little as 135 ms (see also Carlton, 1979, 1981b; Spijkers & Lochner, 1994). Smith and Bowen (1980) showed that distorted or delayed visual information caused disruptions in movement accuracy when the MTs were only 150 ms, also suggesting that visual processing time was far faster than had been previously measured. Similar results were reported by Elliott and Allard (1985, experiments 2 and 3). Suddenly perturbing the *location* of a visible target (immediately after the movement to the “old” target is begun) also resulted in very fast movement corrections, with latencies of about 100 ms (Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991; Pélisson, Prablanc, Goodale, & Jeannerod, 1986), although perturbing the target *size* necessitates considerably longer processing times (Paulignan, Jeannerod, MacKenzie, & Marteniuk, 1991).

When vision is available and MTs are sufficiently long to use that information, what is typically observed is a *correction* in the trajectory of an aimed movement to improve its end-point accuracy. Technological advances in movement analyses toward the end of the past century permitted researchers to examine the kinematics of these movements (see chapter 2) to make refined estimates of when participants were using visual information. Reviews of this research by Carlton (1992), Glencross and Barrett (1992), Elliott and colleagues (2001), and Khan and colleagues (2006) include discussions of a number of related methodologies used to investigate the time to process visual feedback. When all this evidence is taken together, it suggests that no single, *absolute* estimate of the time to process visual feedback is likely to be correct. The nature of the task, the type of visual information available, the predictability of this information, the expectations of the performer, and so on all affect the speed and effectiveness with which we use visual information in aiming (Elliott et al., 2017).

### *Intercepting Moving Targets*

Hitting a nail with a hammer is an example of just one type of action in which vision is used in motor control; the object is stationary, and the goal of the action is to make contact with the object (defined as a “closed” skill in chapter 2). Now consider another class of skills in the situation in which the environment is changing during the action (“open” skills). Is visual information about *moving objects* processed differently from that for stationary objects (Pélisson et al., 1986)?

An early study by Whiting, Gill, and Stephenson (1970) suggests that the answer might be yes. In this experiment, a ball was dropped from a 3 m height to an angled trampoline-like spring, which bounced the ball another 3 m toward the participant, who attempted to catch it. Trials were conducted in a completely darkened room, and a small bulb inside the ball could be lit for periods of 100, 150, 200, 250, or 300 ms after it hit the trampoline. Given a ball flight time of 400 ms (from the point when the ball left the trampoline until the catch was attempted), these viewing times left the participant without sight of the ball for periods of 300, 250, 200, 150, or 100 ms prior to hand contact, respectively. Although performance under the most favorable condition was not as accurate as in a control condition in which all the room lights were on<sup>3</sup> (approximately 93% of the attempted catches were successful), Whiting and colleagues found that catching performance improved as the viewing time became longer—even when the 150 and 100 ms conditions were compared! Thus, one conclusion is that visual information of the ball flight could be used in as little as 100 ms to improve catching performance (see Savelsbergh & Davids, 2002; Savelsbergh & Whiting, 1996; Savelsbergh, Whiting, & Pijpers, 1992, for discussion of related experiments).

One potentially confounding factor in the study by Whiting and colleagues (1970) was that the length of the viewing period covaried with the amount of time without vision; the greater the time with vision, the less time without it, and vice versa. An experimental approach that allows examination of the independent contribution of these factors uses *stroboscopic* conditions. The stroboscopic conditions are simulated with the use of goggles that can be alternately opened and closed during ball flight to provide periodic “snapshots” of visual information. Using this method, Elliott, Zuberec, and Milgram (1994) examined the independent contributions of the length of time that the goggles were open and the length of time that vision was not available (goggles closed). Interestingly, Elliott and colleagues found that the most important contribution to catching performance was *not* the amount of time vision was available, but rather the time *between* the visual snapshots of the ball (i.e., the length of time without vision). Participants could perform well with as few as 20 ms of available vision of the ball as long as no more than 80 ms intervened between “snapshots” (see also Assaiante, Marchand, & Amblard, 1989).

Apparently, longer periods without vision updating can support performance during aiming at stationary targets (Elliott, Chua, & Pollock, 1994). These findings do not constitute rejection of earlier estimates of the minimum time to process visual information. Rather, they serve to reject the idea that a minimum amount of *continuous* visual information is needed. These findings suggest that visual information can be processed *intermittently* (or quasi-continuously), using very short durations of information (see Elliott, Binsted, & Heath, 1999; Elliott et al., 2017, for reviews).

One can raise the argument that experimental occlusion of vision is not a natural approach to examining the speed of visual processing. In other words, in our example of the toolshed, the lights do not go out very often. Critics of this approach have used a number of alternative paradigms in which the use of visual feedback information is inferred from the adjustment (homing in) actions that occur during the preparation for object contact. For example, Bootsma and van Wieringen (1990) found that expert table tennis players could use visual information about the moving ball to adjust their forehand drive in the last 105 to 156 ms of ball flight (depending on the individual). Estimates ranging from 50 to 135 ms were reported by Lee, Young, Reddish, Lough, and Clayton (1983) in a task that required participants to jump to hit a falling ball. Longer estimates for responding to changes in the path of a ball after a perturbed bounce have also been obtained (about 190 ms in McLeod, 1987; 150-190 ms in Carlton, Carlton, & Kim, 1997). The longer delay times in these latter two studies, however, may be attributable to the unexpectedness of the change in flight path and the larger objects that were being manipulated (a cricket bat in McLeod, 1987; a tennis racket in Carlton et al., 1997).

### *Interpreting the Evidence*

It seems that vision, under various conditions, can be processed for motor control in considerably less time than our usual estimates of RT to a visual stimulus would suggest. One interpretation of these differences in visual processing time estimates is that the various experimental conditions appear to introduce *strategic* differences in the ways participants prepare for specific types of visual information. For example, Glencross and Barrett (1992) suggest that in some situations, participants may make *deliberate* errors (e.g., undershooting the target) in the initial movement phase, perhaps in order to reduce the uncertainty of the information specified by the visual feedback (see also Barrett & Glencross, 1989; Carlton, 1981a). With this strategy, the *amount of information* to be processed in the visual display is reduced because the direction of the corrective action is highly predictable.

Another interpretation is related to the hypothesis of two visual systems proposed by Trevarthen (1968) and Schneider (1969), discussed earlier in the chapter (see also Aschersleben & Müsseler, 1999). According to the dissociation (Goodale & Milner, 1992), much of the visual information for movement control is handled by the dorsal system, which is thought to be nonconscious and spatially oriented (Bridgeman et al., 1981; Pélissou et al., 1986). However, various experimental manipulations of visual feedback processing time may require use of the ventral visual system. Thus, it may be that the motor control studies using stationary stimuli have forced the participants to use the (slower) ventral system, which is not the system they would normally use in “real” environmental skill situations. What is clear is that the time to use visual information changes as a function of the characteristics of the target and the goals of the movement (Carlton, 1992). In the next sections we describe other evidence related to the role of vision in motor control.

## Vision and Anticipatory Actions

Situations in which the movement goal involves an interaction with a *changing* environment include cases in which the individual, the environment (or an object in the environment), or both are moving. For example, in ball sports, there are times when the performer must stand still and *intercept* a moving object (as in batting a ball) or must move to intercept a ball in flight (as in catching a forward pass in American football). Activities such as running or driving a car involve situations in which the motion of the individual results in a changing visual array. In all cases, information about the changing environment is used to prepare *anticipatory actions* that allow people to complete the task (such as catching a ball or avoiding objects in their path). The issue that we deal with next concerns how these actions become specified by the changing environment.

## *Interceptive Control*

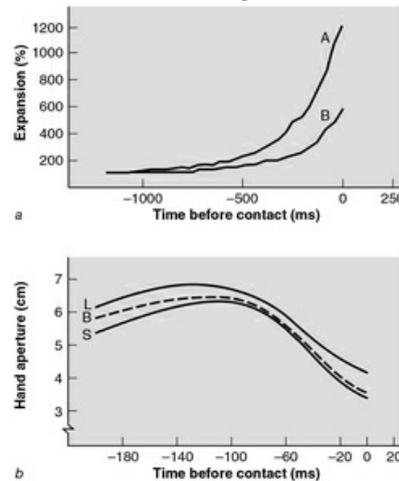
Most of the research on the role of vision during interceptive activities has involved a moving object, as in catching or striking a ball. According to Savelsbergh and colleagues (Savelsbergh & Whiting, 1996; Savelsbergh et al., 1992), the primary use of vision is to specify information about (1) *when* to intercept an object, in particular, temporal information about  $T_c$ ; and (2) *where* to go to intercept it, information about the spatial characteristics of the ball flight. Research suggests that the visual system specifies these types of information in different ways.

### Temporal Information

As mentioned previously in the chapter, there now appears to be considerable evidence that  $T_c$  can be specified by tau (Lee et al., 1983; see also Abernethy & Burgess-Limerick, 1992). An experiment by Savelsbergh, Whiting, and Bootsma (1991) illustrates how tau is used to specify *when* to carry out the hand actions required for grasping a moving ball. Participants were positioned with their elbow on a table and their wrist locked into a position such that a ball that swung on a pendulum would come directly into contact with the performer's palm. The only task was to time the catch of the ball with a grasping action; there was no spatial uncertainty. The experiment used 5.5 and 7.5 cm balls; a third ball was 5.5 cm but was covered with a balloon that could be inflated to appear to be the size of the 7.5 cm ball. Once the ball was released, the balloon *deflated* from 7.5 to 5.5 cm over the period of the ball flight (which was about 1.7 s).

A plot of the relative size of these objects is shown in [figure 5.7a](#) for a constant ball size (A) and with the deflating balloon (B). As the balls (A) approached the participant, the retinal image increased in size about 1,200%, but the retinal image of the deflating balloon (B) expanded only about 500%. Thus, the rate of expansion for the balls was considerably faster than for the balloon. The average apertures of the hand changed as participants prepared to catch the moving objects during the final 200 ms, as illustrated in [figure 5.7b](#). Throughout the final 200 ms of ball flight, the hand aperture was larger in anticipation of catching the large ball (L) compared to the small ball (S). But, for the deflating balloon (B), at 200 ms before contact, the hand had an aperture between the sizes of the large and the small ball; and as the balloon decreased to the size of the small ball, so did the hand aperture. Postexperiment interviews indicated that the participants were not aware of the deflating properties of the balloon; the scaling of hand aperture to the moment-to-moment size of the deflating balloon might have occurred without conscious awareness.

Figure 5.7 Temporal coordination of hand aperture with apparent ball size; zero point on horizontal axis indicates contact with ball. (a) Apparent rate of expansion during ball flight (A = constant ball size, B = deflating balloon); (b) hand aperture changes prior to contact (L = large ball, B = deflating balloon, S = small ball).



Adapted, by permission, from G.J. P. Savelsbergh, H.T.A. Whiting, and R.J. Bootsma, 1991, "Grasping tau," *Journal of Experimental Psychology: Human Perception and Performance* 17: 317 and 321. Copyright © 1991 by the American Psychological Association.

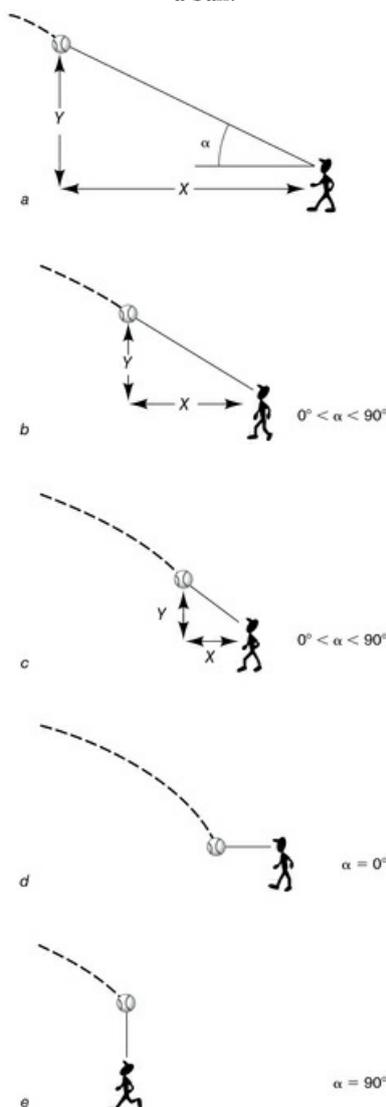
One interpretation is that  $T_c$  is used by the performer via the expansion of the optical flow, and that the catching actions were scaled in anticipation of intercepting the object with a temporally precise grasp. However, as cautioned by Abernethy and Burgess-Limerick (1992), the fact that this experiment and others (e.g., Lee, Lishman, & Thomson, 1982; Savelsbergh, Whiting, Pijpers, & van Santvoord, 1993) provide evidence *consistent* with the use of tau does not rule out the possibility that  $T_c$  can be specified in other ways as well (see also Cavallo & Laurent, 1988; Rock & Harris, 2006; Smeets, Brenner, Trébuchet, & Mestre, 1996; Stewart, Cudworth, & Lishman, 1993; Tresilian, 1995, 1997, 1999; Wann, 1996).

## Spatial Information

A difficult task faced by an outfielder in baseball is judging where to go to catch a batted ball, especially when the ball is hit directly at the outfielder. It is not uncommon, even among the most highly skilled players, for an outfielder to run forward to catch a ball, only to stop, reverse and run backward after realizing they made a mistake. What information is used to make these decisions about *where to go* to catch the ball?

McLeod and Dienes (1993, 1996), following earlier work by Chapman (1968; see also Michaels & Oudejans, 1992; Todd, 1981), suggested that the angle of elevation of gaze ( $\alpha$ ) between the fielder and the ball is used as the key information for making decisions about where to go to intercept the ball. The sequence of illustrations in [figure 5.8](#) describes McLeod and Dienes' (1996) analysis. [Figure 5.8a](#) shows how  $\alpha$  is computed in relation to a fielder in baseball or cricket. Given the path of the ball in [figure 5.8a](#), the fielder determines that movement toward the ball (to decrease  $x$ ) is required before the ball hits the ground (as  $y$  approaches 0). The fielder's forward movement is depicted in [figure 5.8, b](#) and *c* (further decreasing  $x$ ), as the ball falls toward the ground (further decreasing  $y$ ). In moving forward, the fielder must keep the angle of gaze ( $\alpha$ ) between  $0^\circ$  and  $90^\circ$ . If  $\alpha$  ever becomes  $0^\circ$  (i.e.,  $y = 0$  and  $x > 0$ ), then the ball will land in front of the fielder ([figure 5.8d](#)). Likewise, if  $\alpha$  ever equals  $90^\circ$  (i.e.,  $x = 0$  and  $y > 0$ ), then the ball will go over the fielder's head ([figure 5.8e](#)). But how does the fielder *use* this information to make the catch?

Figure 5.8 How a fielder uses the angle of elevation of gaze to decide whether to run forward or backward to catch a ball.

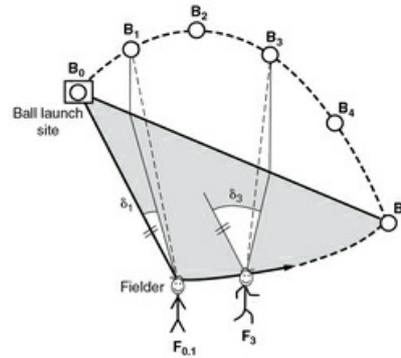


Reprinted, by permission, from P. McLeod and Z. Dienes, 1996, "Do fielders know where to go to catch the ball or only how to get there?" *Journal of Experimental Psychology: Human Perception and Performance* 22: 538. Copyright © 1996 by the American Psychological Association.

A considerable amount of research now suggests that the fielder will arrive at the correct place to catch the ball and that running speed is adjusted according to visual information (Lenoir, Musch, Thiery, & Savelsbergh, 2002; McLeod & Dienes, 1993, 1996; McLeod, Reed, & Dienes, 2001; Michaels & Oudejans, 1992; Oudejans, Michaels, Bakker, & Davids, 1999). According to McLeod and colleagues, fielders accelerate and decelerate their running speed based on successive samples of vertical gaze ( $\alpha$ , position of the height of the ball relative to eye level) and horizontal gaze ( $\delta$ , position of the ball relative to its origin  $M$ , home plate in the case of catching a hit baseball). Specifically, where fielders must run to the left or right (i.e., if the ball is not hit directly at the fielder), they adjust their running speed so that their horizontal gaze ( $\delta$ ) increases at a constant rate and the rate of increase in their vertical gaze ( $\alpha$ ) decreases steadily, as illustrated in [figure 5.9](#) (McLeod, Reed, & Dienes, 2003, 2006; Reed, McLeod, & Dienes, 2009). Of course, this strategy does not guarantee that the fielder will successfully make the catch, only that the fielder will be in the right position to try to do so.



Figure 5.9 Running to catch a fly ball. Running speed of the fielder is adjusted in order to maintain a constant rate of increase in the horizontal gaze ( $\delta$ ), the gaze angle relative to the origin of the hit, and to maintain a steadily decreasing rise in the rate of the vertical angle of gaze ( $\alpha$ , height of the ball).



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### Controlling Whole-Body Actions

The work by McLeod and others represents just a small part of a very large research field dealing with the control of the body as a whole, as in balance and in locomotion. Early thinking about postural control tended to focus on mechanisms that are seemingly obvious contributors to the skills, such as the *vestibular apparatus* in the inner ear. The receptors are sensitive to deviations from the vertical, to the orientation of the body in space, and to the accelerations applied to the head when the body is moved. All these aspects of balance possibly could be signaled by these receptors.

A second class of processes for the control of balance includes the various receptors associated with the joints and muscles. These processes are discussed in more detail later in this chapter; but, for now, consider that in posture, the system is organized to maintain particular angles (which implies muscle lengths) for the joints associated with a particular position of the body in space. When the body begins to lose this posture, the movement of the joints away from the goal position can be sensed by the joint receptors, or perhaps by the stretch of the muscles that control the joint, or by both. Also, there could be tactile sensation from the feet or toes indicating loss of balance. Each of these receptors, alone or in some combination, could conceivably provide the input necessary in order for the person to sense a loss of balance and could provide a basis for initiating a correction. Numerous chapters in the volume by Gandevia, Proske, and Stuart (2002) review this evidence in considerable detail (see also Rossignol, Dubuc, & Gossard, 2006; Shumway-Cook & Woollacott, 2007; Woollacott & Jensen, 1996).

### Vision and Balance

A third source of feedback about balance was emphasized by David Lee (see Lee, 1980, for a review). Earlier in this chapter we discussed the concept of visual proprioception, noting that it tells us where our eyes (and therefore our head and body) are in space and how they are moving (if they are) via analysis of the patterns of optical flow received from the surrounding surfaces and elements in the environment (see "Visual Proprioception"). Could vision be involved in the control of balance? One common finding, as pointed out by Lee (1980), is that people who are blind are generally less stable in posture than are sighted people; those without sight sway more when they stand. Also, sighted people sway more when they have their eyes closed versus open. This suggests that vision might have a role in balance (see also Shumway-Cook & Woollacott, 2007, chapter 9).

But more convincing evidence for this assertion comes from some of Lee's experiments (Lee & Aronson, 1974). Lee used a "moving room" apparatus whereby a person stood on a stationary floor in a three-sided "room" with walls (suspended from a ceiling) that could be moved backward and forward as a unit without movement of the floor. The experimenters studied the effect of this wall movement on the posture and sway of the participant

([figure 5.10](#) shows the general arrangement). With small children as participants, moving the wall a few centimeters toward them caused loss of balance, resulting in a rather ungraceful sitting response and great surprise on the part of the child. Moving the walls away from the child caused a drastic forward lean, which resulted in a stumble or a fall. When adult participants were studied, the effect was less dramatic; but increases in sway, in-phase with the direction of the wall movement, could be seen.

Figure 5.10 Experimental apparatus and paradigm for the “moving room.” David Lee is second from left.



Reprinted, by permission, from D.N. Lee and E. Aronson, 1974, “Visual proprioceptive control of standing in human infants,” *Perception and Psychophysics* 15: 530.

How can this be explained? Remember, the floor of the room was fixed, so that the movements of the walls could not have exerted *mechanical* influences on the position of the participants. The mechanisms associated with the joint angles and muscle lengths, as well as the vestibular apparatus, also were not directly affected. The most reasonable explanation is that moving the wall toward the child changed the optical flow and the optical array. If the child was using this information as a source of feedback, he or she could have interpreted the changed visual array as a loss of balance and consequently produced a compensation in the opposite direction. The walls appearing to move closer to the eye would, if the room were “normal,” provide an optic array signaling that the person was falling forward, and a compensation to move backward would be expected. This is just what Lee found: Moving the wall toward the participant caused them to fall backward. Nashner and Berthoz (1978) showed that responses to the changed optical flow could be generated in about 100 ms (from optical change to change in postural muscles’ electromyograms), which shows that these compensations are very fast and automatic and do not involve the stages of processing discussed in chapter 3.

## Vision and Locomotion

The role of vision during walking and running also seems to be greatly influenced by the optical flow of information (e.g., optical flow during split-belt locomotion can be used to enhance learning rate during adaptation; see Finley, Statton, & Bastian, 2013); much of the thinking about how we use this information continues to be influenced by Gibson (1958, 1966, 1979; see also Warren, 1998, for a review of Gibson’s perspective and Wann & Land, 2000, for a different perspective). We walk down busy streets and through crowded corridors and rarely bump into things or people. We walk on surfaces that have different textures and give them very little attention. But obviously we depend on vision to make our way through the environment. Is vision in this context used in the same way as discussed in the previous sections?

Consider jogging along an irregular path. In this case the placement of the feet with each step is much more critical than, say, on the smooth surface of a running track; to avoid injury, the jogger’s goal is to try to step on ground points that indicate good footing and to avoid unstable footings (such as tree roots and loose debris). If the jogger is running at a constant velocity, how is stride length altered in order to step selectively on good ground footings?

Warren, Young, and Lee (1986) had two experienced athletes run at a constant velocity on a treadmill. At various

times visual targets appeared on the treadmill, and the runner's task was to try to step on these targets by altering stride lengths as appropriate. The running kinematics revealed that almost all the variations in stride length were attributable to changes in the *vertical impulse* applied at takeoff. An increase in the vertical impulse propels the center of gravity farther upward and thus lengthens the time the lead leg spends in the air; thus, with forward velocity constant, the stride length will also increase. According to Warren and colleagues (1986), the vertical impulse necessary to achieve a specific distance is determined by the difference in  $T_c$  of the takeoff and target points, also called the tau gap ( $\Delta T$ ). Since the runner is moving at a constant velocity, the tau gap specifies the duration, and hence the length, of the stride required for the foot to go from the first to the second target (see also Hollands, Marple-Horvat, Henkes, & Rowan, 1995; Patla, 1989; Patla, Robinson, Samways, & Armstrong, 1989; Warren & Yaffe, 1989).

Of course, vision supplies much more than  $T_c$  information about how to walk without colliding with objects. Environmental cues provide information about *how* we must accommodate our actions. As mentioned earlier, from the action-specific perception account, relative body size such as shoulder width can influence our perception of door width (Stefanucci & Geuss, 2009). For example, in walking through *apertures*, such as doorways, there is a critical ratio between the aperture and shoulder width: For any aperture less than about 1.3 times the shoulder width, humans will generally rotate their upper body in order to increase the effective passage width (Warren & Whang, 1987). When we step over obstacles, a critical height value also appears to be evident. There is even evidence that the leading leg uses a greater clearance difference if the obstacle is fragile (Patla, Rietdyk, Martin, & Prentice, 1996). Many more examples have been investigated (e.g., Higuchi, Takada, Matsuura, & Imanaka, 2004). However, the main point here is that vision is used in complex ways in order to locomote through the environment safely and efficiently (Patla, 1997, 1998; Franchak & Adolph, 2010).

## Audition

Another of the senses traditionally classified as exteroceptive is hearing, or audition. Certainly, audition has a strongly exteroceptive role, informing us about the nature of movements in our environment—the direction of approach of a bicyclist in the dark, the sound of the starter’s gun, and so on. But at the same time, like vision, audition can tell us a great deal about our own movements.

As we all know, most of the movements we make in the environment produce sounds, such as the sound of footsteps when we are jogging or the sound of our own speech. The nature of these sounds, then, provides us with a great deal of information about our actions—for example, crunching sounds tell us about the kind of terrain we are jogging on, and beeps from our cell phone tell us about key taps or screen presses. Sounds serve an important role in sporting events as well. Judges use the sound of a diver entering the water as one indication of performance. The “crack of the bat” provides clues to the outfielder regarding how solidly a ball has been struck in baseball. Golfers can often tell what part of the club face has made contact with the ball on the basis of auditory cues. And yet, with all of this sensory feedback available to the performer, the role of audition and how it is used in motor performance remains a largely understudied research area (but see Gray, 2009b; Roberts, Jones, Mansfield, & Rothberg, 2005, for some exceptions).

To some extent, audition and vision are very similar, although there are obvious differences. In general, auditory information is processed faster than visual information, but vision seems to provide more useful information than audition. But there are some suggestions that the two types of information are used in similar ways. For example, while flying in a dark cave, bats use acoustic information to orient themselves; sounds from objects (exteroceptive feedback) and from their own movements (exproprioceptive feedback) provide information for orienting them within the cave. Lee (1990, 1998, 2009) suggested that animals (including humans) can determine  $T_c$  auditorily by using tau in exactly the same way as described earlier—except that tau is based on the acoustic-flow field rather than the visual-flow field (see also Ashmead, Davis, & Northington, 1995; Jenison, 1997).

# Proprioceptors

In the next section we review the set of sensors that provide proprioceptive information (or kinesthesia) about the movement of the body. Although they do not seem to be as salient for movement control as vision is, these sensors are fundamental in their importance for closed-loop control (Abbs & Winstein, 1990; Latash, 2008b). In the first section, we outline briefly their anatomy and function, and later we describe their role in motor control.

## Vestibular System

Sensors are located in the inner ear and provide information about movements of the head. One aspect of head movement that is critical for motor control is its orientation with respect to gravity; that is, whether the head is upside down, tilted, and so on. Such information is provided by the labyrinthine receptors such as the *otolith* organs—two small structures located in the inner ear (the *sacculle* and *utricle*) that signal information about the orientation of the head with respect to gravity. If the head is spinning (e.g., in a somersault), they provide information about the rate and direction of spin. Located near the otolith organs are three fluid-filled half circles, called the *semicircular canals*. Because the canals are oriented in each of the major planes of the body (frontal, sagittal, horizontal), these structures are in a position to sense particular directions of movement, as well as rotation. All of these vestibular structures contain thick fluid that moves when the head position changes. The movement of the liquid bends tiny hairs that send information to the central nervous system, informing about movements of the head. As one might imagine, these structures are important in balance, as well as in movements for which the person requires information about forces and accelerations applied to the head (e.g., in flying a plane, doing a somersault; see Kelly, 1991; Lackner & DiZio, 2000, for further discussion). Recent work in the growing field of space biology has focused on how the body's vestibular system adapts to conditions of zero or partial gravity (Jamon, 2014; Clément, Bukley, & Paloski, 2015).

## Muscle Receptors

Two main types of receptors provide complementary information about the state of the muscles. The *muscle spindle* is located in the fleshy part of the muscle body and is most active when the muscle is *stretched*. The *Golgi tendon organ* is located in the junction between the muscle and tendon and is most active when the muscle is producing *force* (Gordon & Ghez, 1991; Pearson & Gordon, 2000a).

### *Muscle Spindles*

Lying between the fibers of the main muscles of the body are small spindle-shaped (cigar-shaped) structures that are connected in parallel with the muscles such that they are stretched when the main muscle is stretched. The spindle consists of three main components: small muscle fibers called *intrafusals (muscle) fibers* (meaning *in the spindle*) that are innervated by *gamma ( $\gamma$ ) efferent (motor) neurons*. The spindles can activate *type Ia* and *type II afferent (sensory) neurons*.<sup>4</sup> The fibers in the main muscles are called *extrafusals fibers* (meaning *outside the spindle*). The intrafusals fibers are made up of two types, bag and chain fibers, whose polar ends provide a tension on the central region of the spindle, called the *equatorial region*. The sensory receptors located here are sensitive to the length of the equatorial region, mainly when the spindle is stretched (because the whole muscle is stretched, including the spindle). The major neurological connection to this sensory region is the *Ia afferent fiber*, whose output is related to the length of the equatorial region (thus signaling joint position information indirectly), as well as to the rate of change in length of this region (velocity information). The spindle connects to the alpha motor neurons for the same muscle, providing excitation to the muscle when it is stretched. This is the basis for the so-called “stretch reflex” discussed later in this chapter. Thus, the spindle appears to have a strong role in movement regulation (Vallbo, 1974; Pearson & Gordon, 2000b).

There has been a great deal of controversy about what the spindle actually signals to the central nervous system

(see Gandevia & Burke, 1992, and commentaries). A major conceptual problem in the past was that the output via the Ia afferent that presumably signals stretch or velocity is related to two separate factors. First, Ia afferent output is increased by the elongation of the overall muscle via elongation of the spindle as a whole. But, second, the Ia output is also related to the stretch placed on the equatorial region by the intrafusal fibers via the gamma motor neurons. Therefore, the central nervous system would have difficulty in interpreting changes in the Ia output as due to (a) changes in the overall muscle length with a constant gamma motor neuron activity, (b) changes in gamma motor neuron activity with a constant muscle length, or perhaps (c) changes in both (see “Muscle Spindles and the Gamma Loop”).

The system works to disentangle these factors by making use of the gamma motor system and the intrafusal muscle fibers. If the muscle should contract actively (and thus shorten), the stretch of the equatorial region of the spindles would be reduced, and the Ia afferents would decrease their activity. Under such conditions, the spindle would become insensitive to any additional, perhaps unexpected, muscle stretch. However, at the same time, the overall muscle is activated (via the alpha motor neurons), the gamma motor system activates the intrafusal fibers, which applies tension to the equatorial region of the spindles. This process has been termed *alpha-gamma coactivation*. This process acts to compensate for the (active) change in the overall muscle, so that the spindle can register changes in muscle length that are not caused by active shortening (e.g., from an unexpected external source).

Another problem was a lack of strong evidence that the Ia afferent fibers actually send information to the sensory cortex of the brain, where other sensory events were thought to be registered. This was suggested by Gelfand and Carter’s (1967) research on humans undergoing operations involving wrist tendon repair under local anesthetic only. When the tendons and connected muscles were passively stretched and the participants were asked what they felt when the tendon was pulled, they usually reported no sensations or sensations that were inconsistent with the direction of tendon pull. Primarily for these reasons, an older view held that the muscle spindles were not important for the conscious perception of movement or position.

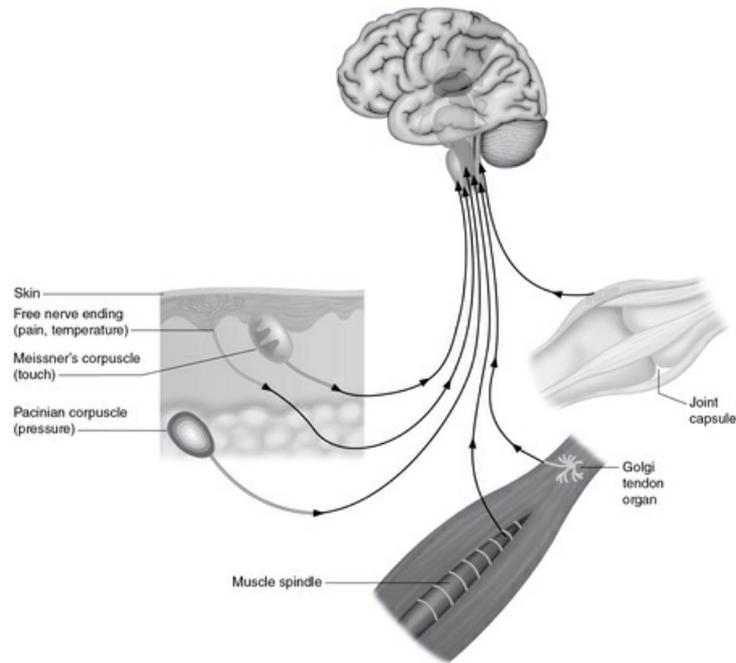
Data from Goodwin, McCloskey, and Matthews (1972) and others (Rogers, Bendrups, & Lewis, 1985; Sittig, Denier van der Gon, & Gielen, 1985a) have helped to change this point of view. In these studies, intact participants had a rapid vibration applied to the biceps tendon at the elbow. The blindfolded performer was asked to “track” the (experimenter-determined) passive movements of the vibrated arm with corresponding active movements of the other arm; thus, the individual had to perceive where the right arm was and match the (consciously felt) position with movements of the left arm. The vibration of the tendon produces a small, rapid, alternating stretch and release of the tendon, which affects the muscle spindle and distorts the output of the Ia afferents from the spindles located in the vibrated muscle. Goodwin and colleagues (1972) found as much as 40° misalignment of the vibrated arm with the nonvibrated arm. The interpretation was that the vibration distorted the Ia afferent information coming from the same muscle, which led to a misperception of that limb’s position and hence to improper (conscious) decisions about the positioning of the opposite limb. The argument, then, is that this information from the Ia afferent actually did reach consciousness and thus the Ia afferent was the basis for knowing the limb’s position. (To control for the possibility that the vibration merely influenced the structures in the joint capsule of the elbow, the authors placed the vibrator over the triceps tendon; now, the misalignment occurred in the opposite direction, as would be expected if the perception of the Ia afferent output from the triceps muscle were being disrupted.) Such evidence supports the idea that the muscle spindle provides information about limb position and velocity (Sittig, 1986; Sittig et al., 1985a, 1985b)—quite a different view from that held earlier. There is still some question as to whether or not the spindle is sufficiently sensitive to detect small positional changes, and thus, it may be only one of a number of sources for detecting position (see Kelso & Stelmach, 1976).

### *Golgi Tendon Organs*

The other receptor for muscle information is the Golgi tendon organ; these organs are tiny receptors located in the junction where the muscle “blends into” the tendon ([figure 5.11](#)). They seem to be ideally located to provide information about muscle tension because they lie in series with (i.e., between) the force-producing contractile

elements in the muscle and the tendon that attaches the muscle to the bone.

Figure 5.11 Muscle receptors: muscle spindle and Golgi tendon organ; skin receptors: free nerve ending, Meissner's corpuscle, and Pacinian corpuscle; and the joint capsule.



The Golgi tendon organs are highly sensitive detectors for active tension in localized portions of a muscle. In fact, they can respond to forces of less than 0.1 g (Houk & Henneman, 1967). Anatomical evidence revealed that each organ is attached (in series) to only a small group of 3 to 25 muscle fibers; it is not attached to the entire muscle as had previously been suspected. Thus, the various receptors sense forces produced in different parts of the muscle. Moreover, only a few (up to 15) different motor units<sup>5</sup> were represented in the muscle fibers attached to a single tendon organ, so the tendon organ appears to be in a good position to sense the tensions produced in a limited number of *individual* motor units—not from the whole muscle.

## Joint Receptors

Each of the joints of the various limbs is surrounded by a sheath called a joint capsule, which is primarily responsible for holding the lubricating fluid for the joint. Embedded within the joint capsules are different kinds of receptor cells known as the *joint receptors*. They are located primarily on the parts of the joint capsule that are stretched the most when the joint is moved, which originally led investigators to believe that these receptors were involved in the perception of joint position. Studying the cat hindlimb, Skoglund (1956) found individual receptors that were active at very specific locations in the range of limb movement (e.g., from 150° to 180° of joint angle for a particular cell). Another receptor would fire at a different set of joint angles, and so on. Presumably, the central nervous system could “know” the joint angles by detecting which of the joint receptors were active.

These conclusions have been seriously challenged, however (see Kelso & Stelmach, 1976, for a review). A number of investigators (e.g., Burgess & Clark, 1969) have found that only a small proportion of the joint receptors fire at specific angles; rather, most of the joint receptors tend to fire near the extremes of joint movement. Further, other researchers have found that the nature of the firing pattern is dependent on whether the movement is active or passive (Boyd & Roberts, 1953) and on the direction of motion of the joint (see Smith, 1977). The fact that the firing pattern of the joint receptors is dependent on factors other than the simple position of the limb has dimmed enthusiasm for the hypothesis that the joint receptors are the means by which the system senses joint position.

## Cutaneous Receptors

Other receptors related to movement perception are located in various places in the skin. Although such receptors can signal many separate states of the body, such as pain, pressure, heat, cold, or chemical stimuli, the important ones for movement control are those receptors that signal information about touch and, to some extent, deep pressure. In addition, pain sensations certainly constitute important information for specific kinds of movement behaviors and play a critically important role in movement rehabilitation, for example.

## Input to the Central Nervous System

Input from the various receptors comes together in the periphery into *spinal nerves*, collections of individual neurons (both sensory, or afferent, and motor, or efferent) that carry information toward and away from the spinal cord. These nerves branch into two roots near the cord, called the *dorsal roots* (posterior, or back) and *ventral roots* (anterior, or front), where they contact the spinal cord separately. At this point, there is almost complete division of the neurons into afferent (or sensory) neurons that enter via the dorsal roots and efferent (or motor) neurons that leave the cord via the ventral roots. Once inside the cord, the afferent neurons can either *synapse* (connect) with other neurons whose cell bodies are in the central gray matter or travel to higher or lower levels in the cord or to the brain in one of the many tracts that form the white matter adjacent to the gray matter.

The major pathways for transmitting signals from the periphery to the brain are the spinal tracts, located alongside the vertebrae that make up the spinal column. There are 8 cervical, 12 thoracic, 5 lumbar, and 5 sacral vertebrae, defining a number of *segments* of the spinal cord. Except for the input from the structures in the head and neck (for our purposes here, mainly from the eyes, ears, and vestibular apparatus, entering through one or more of the 12 cranial nerves), the input to the central nervous system is through the *dorsal roots*, which collect and guide the input to the spinal cord at each segment. Each segment serves a particular region of the body.

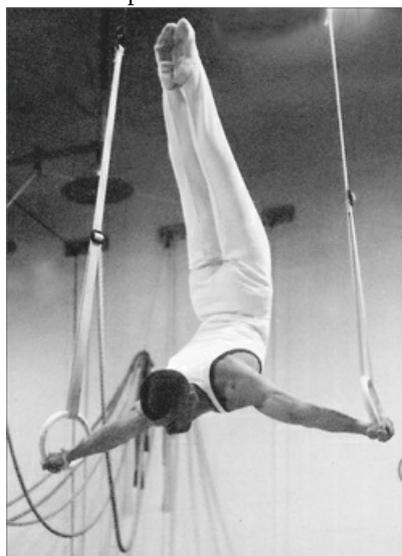
## Ensemble Characteristics

Proprioception enables us to tell with remarkable accuracy where our limbs are and how they are acting, but how do the various receptors mentioned in the previous sections contribute to our motor control capabilities? An important concept is that any one of the receptors in isolation from the others is generally ineffective in signaling information about the movements of the body. This is so because the various receptors are often sensitive to a variety of aspects of body motion at the same time. For example, the Golgi tendon organs probably cannot signal information about movement, because they cannot differentiate between the forces produced in a static contraction and the same forces produced when the limb is moving. The spindle is sensitive to muscle length, but it is also sensitive to the rate of change in length (velocity) and to the activity in the intrafusal fibers that are active during active contractions; so the spindle confounds information about position of the limb and the level of contraction of the muscles (force). And the joint receptors are sensitive to joint position, but their output can be affected by the tensions applied and by the direction of movement, or by whether the movement is active or passive (Paillard & Bruchon, 1968).

As a solution to this problem, many have suggested that the central nervous system combines and integrates information in some way to resolve the kind of ambiguity in the signals produced by any one of these receptors (e.g., Wetzell & Stuart, 1976). Producing an *ensemble* (meaning a grouping *together*) of information by combining the various separate sources could enable the generation of less ambiguous information about movement (Gandevia & Burke, 1992). How the central nervous system does this, and which sources of information are most strongly represented in which situations, are important questions for the future. It is easy to imagine how all or most of these sensory inputs would be involved in a skill such as that shown in [figure 5.12](#). We turn now to the ways in which these various sources of sensory information contribute to movement control (see the various chapters in the volume by Kandel, Schwartz, Jessell, Siegelbaum, & Hudspeth, 2013, for a good tutorial review).



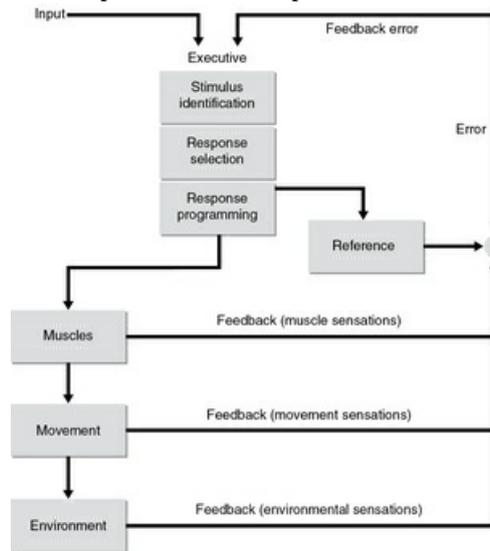
Figure 5.12 An inverted iron cross move on the still rings—where optical flow and other sources of feedback are almost certainly critical. The gymnast in the photo is Richard A. Schmidt, 1962 NCAA bronze medalist.



## Proprioception and Motor Control

The closed-loop ideas presented earlier regarding human performance have been considered in various ways (see Krakauer & Ghez, 2000), but one of the more common is to think of the closed-loop system as a system that contains the stages of information processing and conscious decision making discussed in chapter 3. (Of course, it is clear—to be discussed later in this chapter—that there are other embedded closed-loop systems that do not involve consciousness.) It is useful to consider the executive level of this system as consisting of the information-processing stages discussed in the previous two chapters. This idea is illustrated in [figure 5.13](#). An original command for action, such as an external stimulus or an internal self-generated “go” signal, starts the action by progressing through the stimulus-identification, response-selection, and response-programming stages, eventually leading to evocation of the movement commands to the muscles. This portion of the closed-loop model is similar to that involved in an open-loop system.

Figure 5.13 The expanded closed-loop model for movement control.



The difference becomes apparent, however, when one considers the actions just *subsequent* to this first aspect of the movement. First, a *reference of correctness* is generated that will serve as the standard against which the feedback from the performance is judged. This reference of correctness is also termed *feedforward*, or simply, *forward* information (see “When Can We Tickle Ourselves?”). We can think of this reference as a representation of the feedback qualities associated with moving as planned or as intended; it is analogous to the value to which you set your thermostat in your home heating system or to the compass heading for the automatic pilot of a ship. The reference of correctness represents the state of the feedback associated with the correct movements of the limbs during the intended action; it specifies the sensory qualities of *a goal*. According to the model presented in [figure 5.13](#), muscle contractions cause the muscles, limbs, and body to move, producing changes in the environment as a result. Each of these actions generates information. The contracting muscles and the movement of the body produce sensations from the various receptor systems described earlier. Then, via the reference of correctness, the system can compare the feedback it receives with the feedback it expects to receive. If feedback from the two sources is the same, the implication is that the movement is correct and that no adjustments are necessary. But if a difference exists between the feedback received and the reference, then an error is signaled and a correction is required.

## Influence of Movement Duration

Closed-loop models such as the one in [figure 5.13](#) are conceptualized in essentially two ways, depending on the nature of the motor skill. For rapid movements, feedback provides a basis for knowing (i.e., consciously) whether a movement produced was correct or not. For example, after a golf ball is hit, the sensations from the swing are available in memory for a brief period of time and can be analyzed. A professional golfer probably can tell a great deal about the direction and distance of the golf shot just from the feel and sound of it. A second way in which the closed-loop ideas in [figure 5.13](#) are used concerns the control of ongoing movements. These kinds of models have obvious relevance to continuous skills, such as steering a car down a highway. Think of the reference as evaluating the set of sensations associated with moving at a particular speed or with maintaining a certain distance behind another car. If one of these goals is not met, the feedback received and the reference do not match, and an error signal is fed back to the executive level to compute a correction. Thus, these closed-loop models view the control of a car on a highway as a series of corrections that keep the vehicle safely on the road.

### *Control of Long-Duration Movements*

The closed-loop model presented in [figure 5.13](#) has been very useful for describing certain kinds of movements.

The model seems to have the most relevance for tasks that require a great deal of time, because the processes involved in the analysis of the error information are relatively slow. Also, the model best relates to movements in which something is *regulated* at some constant value, such as keeping the car at a particular speed by monitoring the speedometer or keeping an airplane on the proper glide path when guiding it onto the runway. These are called *tracking* movements (see chapter 2), and they constitute an important class of motor behavior. Tracking tasks have received considerable study, much of this work having been directed to problems in vehicle control, gunnery, and the like. An excellent review of the research on tracking was provided by Poulton (1974); it has been updated by Hammerton (1989), Wickens and Hollands (2000), and Jagacinski and Flach (2003).

There are many different mathematical and physical models of tracking behavior; the major differences relate to how the system uses feedback information and how the system initiates a correction when errors are detected (see Jagacinski & Flach, 2003, for an excellent review). The most important generalization from this research is that if the models are used in computer or mechanical *simulations* of the human (in which the device is controlled in ways analogous to those in [figure 5.13](#)), these nonliving devices seem to “come alive” to behave in ways nearly indistinguishable from their human counterparts. For example, when we perform a laboratory tracking task, approximately 200 ms elapses between the appearance of an error and the initiation of a correction back toward the center of the track. Such lags and the character of the correction can be modeled very well, and the statistical agreement between the actual and simulated movements is quite good for this kind of task. This evidence does not prove that humans actually track this way, but the agreement between theoretical predictions and data is very strong, and alternative theories cannot boast of similar success. With advances in technology, lags in the system can be reduced to almost nothing, allowing corrections to be implemented sooner. The benefits of such advances show promise for avoiding accidents as self-driving or driverless cars become a reality in the not too distant future (Jiménez et al., 2016; Shaout, Colella, & Awad, 2011).

### *Changing the Reference of Correctness*

We can extend this idea somewhat (as Adams, 1971, 1976a, 1977, has done) to account for how the individual makes a limb movement such as would be involved in sawing a board or in reaching for a drink. Here, the reference of correctness is not a single state as in the earlier examples, but rather a *set of states* that changes at each moment in time. Because the reference is constantly changing, it can be matched against the feedback from the moving limb, which is also changing as the movement progresses, so that errors in the movement’s *trajectory* can be detected and corrected. This kind of mechanism is the basis for Adams’ (1971) theory of learning, according to which the performer learns a set of references of correctness that the closed-loop system is to “track” during the movement. We will have more to say about Adams’ ideas later in the book when we discuss learning theory (see chapter 12).

But these kinds of models have serious limitations. Engineers can design robots and other machines to behave in this way, using what they call *point-to-point computation* methods. The position of the limb at each point in space and at each time in the movement is represented by a reference of correctness, and the system can be made to track this set of positions across time to produce an action with a particular form. But the system must process information very rapidly, even for the simplest of movements. All these references of correctness must be stored somewhere, which creates difficulties when we realize that each point will be different if the movement begins from a slightly different place or if it is to take a slightly different pathway through space.

Engineers have generally found these methods very inefficient for machine (robot) control; such findings have led many motor behavior researchers (see Greene, 1972; Kelso, 1995; Turvey, 1977) away from these kinds of control processes to explain human skills. But there is still the possibility that the system might operate in this way at certain times or for certain skills that demand very high precision (e.g., threading a needle or slicing a loaf of bread). Also, such a mechanism might serve as the basis for *recognizing* errors at various places in the movement as it is carried out, without actually being the basis for controlling it. After a tennis stroke the performer could say that the elbow was bent too much on the backswing, and thus have the basis for making a correction in the movement on the next attempt. Finally, there is ample evidence that the system makes use of reflexive mechanisms (i.e., without using the information-processing stages), mechanical mechanisms (Bizzi, Accornero, Chapple, &

Hogan, 1982), or both to hold itself on the proper track; these possibilities are discussed later in the chapter.

A compromise view is that only *certain positions* in the movement are represented by references of correctness. One view is that feedback from the movement when it is at its end point is checked against a reference of correctness; then corrections are initiated to move the limb to the proper position if it is not already there. These views of motor control hold that the limb is more or less “thrown” in the direction of the end point by some kind of open-loop control, and that the limb then “homes in on” the target by closed-loop control (a view reminiscent of Woodworth, 1899; see “R.S. Woodworth on Manual Aiming”). Here, the actual trajectory of the limb is determined by how the limb is “thrown,” in combination with mechanical factors such as gravity, friction, and muscle forces. In this view, the trajectory is not determined by point-to-point computation as would be explained by a purely closed-loop system.

### *Control of Rapid Movements*

One of the most important points to have emerged from the evidence presented in chapters 3 and 4 was that the information-processing mechanisms, which lie at the very heart of the closed-loop system in [figure 5.13](#), require a great deal of *time* in order for stimuli to be processed to yield a response. So far we have assumed that each error signal the system receives must be processed in these stages and that the response (a correction) can follow only after all the stages of processing have been completed. Thus, a correction is seen in the same way as any other response to a stimulus. It requires a great deal of time and attention.

But there is a problem. In the closed-loop models such as that shown in [figure 5.13](#), rapid actions do not provide sufficient time for the system to (a) generate an error, (b) detect the error, (c) determine the correction, (d) initiate the correction, and (e) correct the movement before a rapid movement is completed. The left jab of the great boxer, Muhammad Ali, is a good example. The movement itself was about 40 ms; yet, according to our discussion earlier in this chapter, visually detecting an aiming error and correcting it during the same movement should require about 100 to 150 ms—the time necessary to complete the activities of the stages of information processing. The movement is finished before the correction can begin. For this reason, the closed-loop models of movement behavior do not seem well suited to explaining rapid movements.

Chapter 6 will raise this and other limitations to the closed-loop models again. For now, suffice it to say that the closed-loop mechanisms involving the stages of processing appear to have a very difficult time explaining rapid movements. Because these models have much credibility with respect to very slow movement and posture and have little with respect to rapid movement, it is possible that there are essentially two fundamentally different kinds of movements: fast and slow. We return to this distinction in chapter 6.

## Reflexive Closed-Loop Control

To this point we have considered only the kind of closed-loop model in which the determination of the correction was produced by conscious information-processing mechanisms, without considering the idea that the central nervous system contains closed-loop mechanisms that do not require any attention. Many examples are possible, such as the control of body temperature and the regulation of breathing during sleep. In this section we discuss evidence that these nonconscious mechanisms are involved in the control of voluntary movements as well.

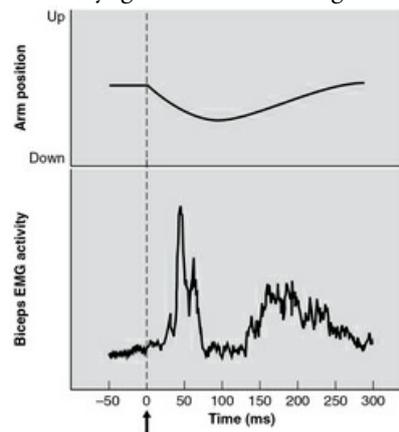
### *Latencies of Corrections*

An experiment by Dewhurst (1967) is representative of a number of studies on this problem. The participant was asked to hold the elbow at a right angle to support a light weight attached to the hand. The person could monitor the performance through vision of a display that signaled elbow angle. The experimenter recorded the position of the arm together with the rectified electromyographical (EMG) activity in the biceps muscle as the participant performed. Unexpectedly the weight attached to the hand was then increased, and naturally the hand began to move downward. After a brief period, the performer increased the EMG activity to the biceps muscle, which

increased its force output and brought the limb back to the right-angle position. Given that the lowered arm represents an error relative to the goal (of keeping the arm at a right angle), how much time will elapse before a correction is made, as would be seen by an increase in the elbow flexors' EMG? Note that if the person must process the visual or kinesthetic feedback (or both) from the arm through the information-processing stages, there should be no change in the biceps EMG for approximately 150 to 200 ms.

[Figure 5.14](#) shows the essential results. The weight was added at the point in time indicated by the arrow, and the limb began to move downward immediately. The records show a small burst of EMG about 35 to 40 ms after the weight was added and a larger irregular burst beginning about 50 ms afterward. Just after this second burst of EMG, the limb began to move back to the target position. This change in EMG represents a clear correction for the added weight, yet this correction was initiated far more quickly than can be explained by a closed-loop process that requires information processing as shown in [figure 5.13](#). Rather, the correction is thought to be due to the operation of reflexes in lower, probably spinal, levels in the central nervous system.

Figure 5.14 Movement and rectified electromyogram record showing the latencies of two reflex-based corrections.



Reprinted, by permission, from D.J. Dewhurst, 1967, "Neuromuscular control system," *IEEE Transactions on Biomedical Engineering* 14: 170, © 1967 IEEE.

### *Consciousness and Reflexive Corrections*

Another aspect of reflexive corrections for errors, aside from their apparent rapidity, is that they might not require attention as other corrections seem to. Evidence for this notion was provided in a study by Henry (1953), in which participants had to regulate the force they applied to a handle. The standing performer (blindfolded in the experiment) is pushing against a handle attached to a mechanical device that could alter the position of the handle continuously. The arrangement was such that if the performer was not pressing against the handle, the handle would move forward and backward unpredictably. But a spring had been placed between the machine and the handle, so that by modulating the force produced at each moment, the participant could maintain the handle in a constant position.

Henry used three conditions. In one condition, the participant's task was to keep the *pressure* against the handle fixed by varying the position of the handle. When the handle pushed against the participant, the correct response was to "ease up," so that the pressure between the handle and the person's hand was held constant. In the second condition, the participant was to compensate for the changing pressures exerted by the handle so that a constant *position* of the handle was maintained but with the exertion of constantly changing pressure. A third condition was used to assess the conscious *perception* of change; the performer attempted to hold the arm immobile, reporting through a left-finger movement when a change in the pressure exerted by the apparatus was sensed. The pressure changes were different for different segments in the testing period, and Henry could obtain an estimate of the amount of change that was required for conscious perception of change.

Henry (1953) found that the "threshold" force needed for an appropriate adjustment depended strongly on *what* the participant was asked to control. When the performer was asked to report a conscious change, a force of 0.56 dynes was required for detection. But when the person was asked to hold the *position* constant, a force change of only 0.30 dynes was successfully detected and responded to; apparently, in this constant-position condition, participants were responding to forces too small to be detected consciously. Even more striking was the finding that position changes associated with a force change of only 0.03 dynes produced successful modifications in movement control. Thus, the motor system, in holding a constant *position* against the apparatus, could respond to a change that was considerably less than the change necessary for conscious awareness (i.e., 0.03 vs. 0.56 dynes). In the constant-pressure condition—and particularly in the constant-position condition—the motor system was responding to stimuli that were too small to be detected consciously. As compared to the change required to adjust to a change in position, the change had to be 19 times larger for conscious detection. These small adjustments were apparently made without the person's awareness.

Experiments like the ones just described show two important things about movement control. First, studies like Dewhurst's (1967; see also Houk & Rymer, 1981; see Lee, Murphy, & Tatton, 1983, for a review) demonstrate that the corrections for suddenly presented changes in position can be initiated with correction latencies of 30 to

80 ms—far more rapidly than would be expected based on conscious-processing estimates. This kind of result suggests that the information-processing stages, at least as shown in [figure 5.13](#), are not involved in these actions. Second, the data from Henry (1953) and others show that people can make adjustments for changes in position—and perhaps for changes in tension—so small that they cannot even perceive them consciously. These data also indicate that the stages of information processing are not involved, because at least some of these stages are thought to entail conscious processing and attention in the sense discussed in chapter 4. Both of these lines of evidence suggest that these kinds of corrections are produced via reflexive mechanisms that do not concern the stages of processing.

### *Muscle Spindles and the Gamma Loop*

The mechanisms responsible for the effects just described probably involve the muscle spindle, the small, cigar-shaped structure located between and in parallel to the main fibers of the skeletal muscles (see [figure 5.11](#)). Recall from [figure 5.11](#) and associated text that the muscle spindles are specialized to detect changes in muscle length. The tension on the equatorial (sensory) region, and thus the output of the Ia afferent neurons, is adjusted via the gamma motor system (and intrafusal muscle fibers) for contractions of the main muscle. Thus, at essentially any point in the action's trajectory, the muscle spindles are set to respond to a muscle length that is different from that anticipated (or intended). Such changes in the muscle length could be caused by unexpected loads applied to (or removed from) the limb's movement, or by the inherent variability of the main muscle's contractions (see the discussion of force variability in chapter 7), or both. Thus, it appears that the muscle spindles and the gamma system provide a means for correcting small changes in the external loads—and that such changes are fast, are not mediated by the stages of processing in [figure 5.13](#), and are automatic in the sense that they do not require conscious attention.

The information from the Ia afferent is sent to several places; the Ia afferent signals synapse with the alpha motor neurons in the same muscle to generate greater (or lesser) muscle force to compensate for small changes in load. These signals are also sent upward to various sensory regions in the brain that could mediate more elaborate and complex corrections (e.g., the cortex, cerebellum, or both; Ghez & Thach, 2000). These compensations are effective mainly for small changes in loads; we all know that if we attempt to lift an “empty” box that is actually full of bricks, we stop lifting almost immediately and attempt the action again with a completely new pattern of action.

This process is the basis of what has been called the *monosynaptic stretch reflex*. You experience an example of this reflex when a neurologist lightly strikes your patellar tendon with a small rubber “hammer” just below the kneecap with the knee flexed. The resulting “knee-jerk reflex” is caused by the rapid stretch of the quadriceps muscle, which stretches the spindles in the muscle. This increases the firing of the Ia afferent transmitted to the cord, increasing the alpha motor neuron firing rate, which causes the muscle to contract. This is an *autogenetic reflex*, because it causes an action in the same muscle that was stimulated. The loop time, or the time from the initial stretch until the extrafusal fibers are increased in their activation, is about 30 to 40 ms in humans. Because this 30 to 40 ms value corresponds with the latency for the first burst of EMG shown in the Dewhurst (1967) experiment (see [figure 5.14](#)), this monosynaptic mechanism is probably responsible for this first compensation for the added weight. This information may explain how Dewhurst's (1967) participants responded so quickly to the added weight. It also helps to explain why Henry's (1953) participants were able to make corrections for position that they could not even perceive; some of the corrections for changes in position occur in the spinal cord, without the conscious involvement of the information-processing stages.

Notice also that the reflex activity is more complicated than simply activating the one muscle that was stretched. When the neurologist's hammer strikes the tendon, that muscle is stretched, leading to increased firing in the Ia afferent fibers from its spindles. These Ia afferents transmit their signal into the dorsal roots, where the Ia synapses with several other neurons. First, it synapses with the alpha motor neurons that activate that muscle via the monosynaptic stretch reflex. Second, the Ia synapses with other alpha motor neurons (not shown) for muscles acting as synergists for this action (muscles oriented to aid in the action). Third, the Ia synapses with Ia inhibitory interneurons, which in turn synapses with the alpha motor neuron for the antagonist muscle (here, the triceps)

and inhibits its action. This reflex-based inhibition of the muscle acting in opposition to the muscle stimulated is called *reciprocal inhibition*. Thus, the stretch from striking the tendon with a rubber hammer has (a) increased activation in the muscle that was stretched (the agonist), (b) increased activation in synergistic muscle(s), and (c) inhibited activity in the muscle acting as an antagonist—all rapidly, automatically, and without consciousness. Also, if this had occurred in the legs, the stretch reflex (say, for right-knee flexion) would have produced increased activities in the *left*-knee extensors, and, via reciprocal inhibition, decreased activity in the left-knee flexors (see Pearson & Gordon, 2013b, for more details), presumably to allow the individual to provide postural support when the right knee was flexed reflexively.

This kind of reflexive adjustment is applicable to situations other than those in which the limbs are being held in a static position. Numerous investigations have shown that these processes seem to keep an ongoing movement on course. For example, Marsden, Merton, and Morton (1972) had participants move the last joint of the thumb back and forth in time to a metronome. At an unpredictable time, the movement of the thumb was resisted. The result was an additional burst of EMG within 30 ms of the perturbation. It is impressive that this occurred when the perturbation occurred at *any* location or time in the thumb's cycle. Similar findings have been shown in the breathing cycle by Sears and Newsom-Davis (1968); when the resistance to airflow was suddenly changed at various places in the cycle, the EMG in the intercostal muscles (which control the rib cage volume) increased in activity with a latency of 30 ms, regardless of when in the cycle the resistance to airflow was changed. Nashner and Woollacott (1979) have presented similar findings for the situation in which the ankle joint is unexpectedly perturbed during normal walking. One interpretation of these findings is that there is a reference of correctness that “moves with” the overall movement so that, at any time in the movement, the limb's desired or planned location can be specified (Schmidt, 1976a). Thus, it appears that the muscle spindles—because they work in concert with the alpha and gamma systems as described earlier—are able to provide information about whether the limb is in a position different from that specified, even during the execution of an action, and can induce rapid, automatic, reflex-based corrections if it is not.

More recent research has added considerably to our understanding of these reflexive processes in movement control. There is considerable evidence that the reflexive response is not always autogenetic, in that the effects of a stimulus (such as a sudden stretch) can be seen in many of the participating muscles—not just in the one(s) stimulated (Pearson & Gordon, 2013b). Thus, these reflexive activities can be viewed as rapid, automatic, involuntary, and *coordinated* responses to disruptive stimuli.

We can conceptualize the function of these reflexes as directed at ensuring that the original *goal* of the action is achieved in the event of a perturbation to it during execution. Consider a task in which you are to repeatedly touch the tip of your right thumb to the tip of your right index finger. That is, both digit tips are moving toward the goal of touching each other. Now, imagine the application of a perturbing force that resists (only) the thumb's movement somewhat. We would expect automatic, rapid changes in the thumb musculature—and this is what you see. But, in addition, we will observe changes in the *index finger* musculature that are coordinated with the changes in the thumb musculature; this happens even though the index finger was not perturbed at all. One way to explain such findings is that the motor system has set up the goal of touching the two digit tips; the thumb's progress toward that goal is slowed by the perturbation. So, the index finger's action is also adjusted (sped up), presumably so that the goal of digit touching is achieved (see Pearson & Gordon, 2013b, for a more complete discussion).

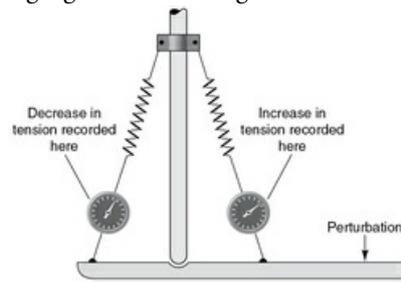
## Control of Muscle Stiffness

We have seen how the muscle spindles are involved not only in the maintenance of static positions (e.g., posture) but also in maintaining the trajectories of various limbs involved in a goal-directed action. But the spindle seems also to be related to the control of muscle *stiffness*, which is probably very important in the control of posture and other movements. Stiffness, one of the measures used by engineers (and others) to describe the characteristics of elastic materials (e.g., springs), is defined in terms of the amount of tension increase that is required to increase the length of the object by a certain amount (one unit). Engineers define stiffness more precisely as the change in

tension divided by the resulting change in length, or the slope of the length–tension relationship. If a spring is very stiff, a great deal of tension is needed to increase its length by a given amount; for a less stiff spring, less tension is required. This is important in our context because the muscle seems to provide a compliant (springy) interface between the performer and the environment.

When we maintain posture, the muscles supporting the skeleton are contracting under the influence of the gamma loop just described. This is conceptualized in [figure 5.15](#), which shows a bone in equilibrium being supported by two opposing muscles producing force (equal and opposite joint torques). If the system is perturbed, causing the bone to move downward, the muscle on the right side of the diagram is lengthened slightly, causing the stretch reflex described earlier. Perhaps even more important, because the contracting muscle is a “springy” substance, more tension is produced in it by purely *mechanical* means as its length increases. Furthermore, this mechanical change in tension is *instantaneous*, just as the change in tension in a metal spring would be if it were stretched. Such increases in tension have the effect of opposing the perturbation, bringing the system back to the original position. Nichols and Houk (1976) have provided evidence that the muscle spindle is responsible for the maintenance of muscle stiffness when the muscle is stretched, so that the muscle can continue to act as a spring in the control of posture and similar movements (see also Houk, 1979; Houk & Rymer, 1981).

Figure 5.15 Muscle spring model with gauges for measuring tension in the “tendons” as a perturbation is applied.



## Long-Loop Reflexes

In addition to the monosynaptic reflex activity (the EMG activity that began with a latency of about 30 ms), there is another kind of activity responsible for the more sustained burst that occurred about 50 ms after the weight was added, and yet more starting at about 130 ms. This second burst at about 50 to 70 ms occurs too rapidly to be explained by the stages of information processing, yet it is apparently too slow to be accounted for by the monosynaptic stretch reflex. The early burst at 30 ms was very brief and did not result in much actual increase in force, whereas the burst at 50 to 80 ms was larger, was more sustained, and probably resulted in the force changes necessary to move the limb back toward the horizontal position. The response at 130 ms is probably the RT response, mediated by the stages of processing. The response to muscle stretch with a latency of 50 to 70 ms has been termed the *long-loop reflex* (also called the *functional stretch reflex*).

The long-loop reflex fits neatly into the overall picture of segmental limb control. When the spindle is stretched and the Ia afferent is increased in its activation, the information is fed back to the spinal cord where it activates the alpha motor neuron and the same (and functionally related) muscle. This signal is also sent to higher segmental levels in the cord, to the brain, or both. Information from the Ia afferent is integrated with other information in sensory and motor centers in the brain that can initiate a more complete or more complex response to the imposed stretch. Because the information travels to a higher center to be organized, and because more information needs to be considered and more synapses are involved, the reflex requires more time—50 to 70 ms rather than 30 to 40 ms for the monosynaptic reflex.

Something appears to be regained, however, with the loss in time. First, the EMG activity from the long-loop reflex is far stronger (producing more force change) than that involved in the monosynaptic stretch reflex. Second, because the reflex is organized in a higher center, it is more *flexible* than the monosynaptic reflex. For example, Evarts (1973) has shown that, if the participant in a task similar to Dewhurst's (1967) is told to “resist” the stretch, a burst pattern like that in [figure 5.14](#) occurs. If the participant is told to “let go,” so that when the weight is added the performer simply lets his or her arm be moved by it, the second burst (presumably due to the long-loop reflex) nearly disappears but the first burst remains, unaffected. It appears that *prior instructions* can change the reflexive response to a given stimulus (the added weight) so that the reaction is appropriate for the particular situation. The monosynaptic reflex, residing at a very low level in the spinal cord, can probably not be modulated by prior instructions (at least to any great degree). However, it has been shown that spinal cord reflexes can be conditioned, using operant conditioning techniques (Wolpaw et al., 1987). It is fortunate that we are constructed in this fashion, as there are situations in which we must resist very strongly when perturbations occur. Other situations arise in which a very strong resistance would mean a serious accident; in skiing over bumps, for example, failing to “let go” would result in a very stiff leg musculature when a very compliant (springy and supple) one would be more desirable.

## Triggered Reactions

So far, we have seen three distinct processes leading to increased EMG in response to perturbations such as an added weight. These are the monosynaptic stretch reflex (30 to 50 ms latency), the long-loop reflex (or functional

stretch reflex, 50-70 ms), and of course the voluntary RT response discussed in chapter 4 that begins at about 130 ms in Dewhurst's (see [figure 5.14](#)) study.<sup>6</sup> Crago, Houk, and Hasan (1976) argue, however, that there is yet a fourth kind of response that falls between the 50 to 70 ms long-loop response and the voluntary RT latency. They call these responses *triggered reactions*: prestructured, coordinated reactions in the same or in closely related musculature that are "triggered" into action by various receptors. Such reactions have latencies from 80 to perhaps 200 ms, and the latencies are far more variable than are those of the faster reflexes. Presumably the triggered reaction is like a "very fast RT," perhaps bypassing some of the stages of information processing because the reaction to the stretch is stereotyped, predictable, and well-practiced. The performer does not have to spend much time in processes like response selection and programming, and the reaction is just "triggered off" almost as if it were automatic (see Schmidt, 1987).

What evidence is there for this kind of control? Crago and colleagues (1976) have shown not only that portions of the response to an unexpected stretch perturbation were faster than RT (as we have seen before), but also that the latencies increased as the number of stimulus–response alternatives increased from one to two; here, the perturbation was (a) always a flexion (i.e., a one-choice task) or (b) either a flexion or an extension (i.e., a two-choice task). We usually think of processes involved in resolving choice as being "located" in a response-selection stage (Hick's law, see chapter 3); these results suggest that, unlike the monosynaptic stretch reflexes, the responses might be mediated in some way by the stages of information processing. Perhaps some of the processes are bypassed, leading to latencies shorter than "normal" RT latencies. [Table 5.1](#) summarizes these several processes. More research is clearly needed to clarify these issues.

**Table 5.1 Four Kinds of Responses to Environmental Stimuli During Movement, and Some of Their Differing Characteristics**

Response type	Loop time (ms)	CATEGORY ANALYSIS		
		Structures involved	Modified by instructions	Affected by number of choices
Myotatic reflexes (autogenetic)	30-50	Spindles, gamma loop, same muscles	No	No
Long-loop reflexes (autogenetic)	50-80	Spindles, cortex or cerebellum, same muscles	Yes	No
Triggered reactions (not autogenetic)	80-120	Various receptors, higher centers, and associated musculature	Yes	Yes
Reaction time (not autogenetic)	120-180	Various receptors, higher centers, any musculature	Yes	Yes

### Tactile Feedback

Recently, we have seen evidence of the initiation of reflex-like control by the *cutaneous receptors* in the skin. We have long known that the cutaneous receptors can be the trigger for withdrawal responses—as in jerking your hand from a hot surface (Johansson & Westling, 1991; Johansson & Flanagan, 2009).

### Wineglass Effect

Suppose you are washing dishes and raise an object to check its cleanliness—for example, holding the stem of an expensive wineglass between your fingertips. If the glass begins to tip or slip (because of the wet surface), a common reaction is to increase the grip of force with your fingers to stop it. Using a laboratory analog of this basic idea, Johansson and Westling (1984, 1988, 1990; Westling & Johansson, 1984; see also Ghez & Krakauer, 2000, and Johansson & Westling, 1991) have studied the motor reactions to stimuli indicating loss of grip. They asked participants to lift small objects (having various degrees of surface friction) between the thumb and index finger and hoist them with an elbow flexion action. The stimuli indicating that the object is slipping are a set of tiny vibrations in the skin of the fingers, which we detect through the cutaneous receptors. After the onset of a slip (which can be measured by vibration sensors in apparatus), participants showed an increase in the EMG in muscles responsible for finger gripping force and with a latency of only about 80 ms (see also Cole & Abbs, 1988). These reflexes were fast enough to prevent a noticeable movement of the object, and often the participant did not even know that a slip had occurred. Sometimes, several of these slips and catches were seen in a single lift of the object, each with very short latencies. In addition to the increase in gripping forces, there was at the same time a corresponding *decrease* in the EMG in the elbow flexors, as if the system were reducing the slippage by decreasing the hand’s upward acceleration. All this resulted in a beautifully coordinated response to the slipping, which was evidenced in a number of joints—not just in the structures directly affected by the stimulus. The reaction was very fast and probably nonconscious, and seemed to have the overall “goal” of reorganizing the system slightly to complete the action successfully (i.e., lifting without dropping). Thus, in this example, as well as in others mentioned here, the stimulus does not (only) *directly* affect the muscles that make the response as in the example from Dewhurst (1967); that is, the response to the stimulation is not (simply) autogenetic, but rather is coordinated across several muscles and joints.

### Object Manipulation

In addition, it appears that cutaneous receptors can provide sensitive feedback about the fingers’ contact with objects being manipulated. One example involves anesthetizing (via needle injections) the tips of the thumb, index, and middle finger. Before the injection, the participant could remove a wooden match from a matchbox and light it by striking it against the side of the matchbox—a very common, unremarkable action requiring about 8 s. However, after the anesthetic was injected, which eliminated cutaneous feedback from the fingertips temporarily, this task became very difficult; the participant dropped matches several times and produced very clumsy and “labored” actions, eventually succeeding in lighting the match in about 29 s. In addition, it appeared that the individual made extensive use of visual feedback after the injections, but this apparently did not make up

for the loss of tactile sensation, perhaps because the visual feedback was far slower than the reflex-like feedback from the cutaneous receptors (Johansson & Flanagan, 2009).

### *Speech Perturbations*

Another example of triggered reactions was provided by Abbs and Gracco (1983; Abbs, Gracco, & Cole, 1984) and by Kelso, Tuller, Vatikiotis-Bateson, and Fowler (1984). In Abbs' work, the performers were asked to utter nonsense syllables such as /afa/ and /aba/. Try /aba/, for example; the lips must be open to make the initial vowel sound, and then they must come together briefly to make the stop consonant /b/. In their experiments, Abbs and colleagues (1984) would occasionally perturb the lower jaw (during the utterance of /aba/) with a small downward force pulse that prevented the lower lip from rising to make contact with the upper lip in its normal position, and the EMG from the musculature in the *upper* lip and its position were measured. When the perturbation was applied, EMG increased in the *upper* lip musculature, which moved the upper lip downward, all with a latency of about 25 to 70 ms. Notice that, as in the wineglass example, this is not an autogenetic response, because the response to the stimulation does not occur (only) in the stimulated muscle and seems to be organized with the "purpose" of completing the *action* of making the proper sound (which required lip closure for success). Furthermore, the reaction seems to be dependent on practice, as it is difficult to argue that making the particular sound /aba/ is genetically determined; this feature of susceptibility to practice might be yet another distinguishing characteristic of triggered reactions. However, this effect is analogous to the so-called *reflex-reversal phenomenon* in the study of locomotion; in locomotion, it is difficult to argue that learning plays a large role. In this situation, the same stimulus elicits one reflex when the leg is in the swing phase, and a different reflex when the leg is in the stance phase. See chapter 6 for a fuller discussion.

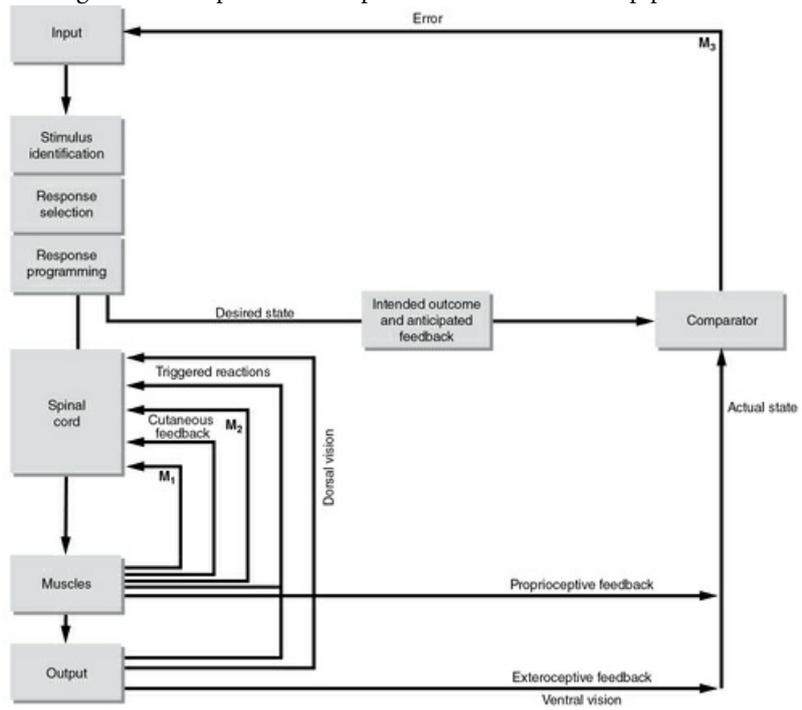
### *Role of Reflexes in Skilled Actions*

It is interesting to think about the possible role of the various reflexes in the control of movement, and the evidence for such contributions is mounting steadily. At this point, there is considerable evidence for the involvement of reflex-like processes in voluntary motor behavior. We have seen stretch reflexes, reflex reversals, cutaneous feedback effects, triggered reactions, and dorsal vision effects. All of these have the property of providing stereotyped (if sometimes somewhat complex) responses to stimuli, and all with latencies far shorter than our usual estimates of reaction time. Thus, it is difficult to argue that the stages of processing (identification, selection, programming; see chapter 3) have any role in these reactions. This evidence, taken together, suggests that these reactions are automatic (nonconscious) responses, which seem to have the property of ensuring that the original action is carried out faithfully even in the face of small perturbations.

This idea can be summarized from the flowchart in [figure 5.16](#). Here, we attempt to show that many simultaneous feedback loops appear to be involved in one way or another in movement control. One of these—the outermost loop, shown as a heavy line in [figure 5.16](#)—involves the stages of processing, reaction time ( $M_3$  response), and attention as we argued in chapter 3. However, in the present chapter we have provided evidence for various reflex-like processes that appear not to involve the stages of processing. The innermost loop is the  $M_1$  response, probably the most rapid of all, traversing from an involved muscle to the spinal cord and back to that muscle. Feedback from cutaneous receptors in the fingertips is involved in nonconscious control, and this feedback can also be conceptualized as operating mainly nonconsciously, as we have discussed (Johansson & Flanagan, 2009). The  $M_2$  response also travels to the spinal cord, but extends as well to somewhat higher levels than the  $M_1$  response. Triggered reactions arising from receptors in various muscles or from the environment can also be thought of as providing input to some level of the spinal cord. Finally, dorsal vision can influence (at least) balance nonconsciously, certainly not involving the stages of processing.<sup>7</sup> For a full discussion of these reflex-like responses as they pertain to the central contributions to motor control, see chapter 6.



Figure 5.16 Expanded conceptual model of closed-loop processes.



## Feedforward Influences on Motor Control

In this section we consider evidence that the motor system operates with a *feedforward* control mode. This term—coined to contrast with the concept of *feedback*—is usually defined as the sending of a signal that (a) readies the system for the upcoming motor command or (b) readies the system for the receipt of some particular kind of feedback information (or does both). Such processes appear to occur frequently, and we will consider a few examples. Notice that the reference mechanisms illustrated in [figures 5.13](#) and [5.16](#) are examples of a feedforward process.

### Saccadic Eye Movements

Numerous situations exist in which the idea of feedforward control appears to be involved in the production and evaluation of human behavior. One of the earliest notions of feedforward control concerned the mechanisms of visual perception after the eye made a *saccade*—a very rapid, jerky movement of the eyes from one position to a new position. Of course, the light patterns falling on the retina are different before, during, and after the saccade. But how does the person know whether the eye moved in a stable world or whether the world moved, with the eye remaining stationary? The pattern of stimulation (optical flow pattern) on the retina could be exactly the same in both cases.

The answer suggested by von Holst (1954; von Holst & Mittelstaedt, 1950), Sperry (1950), and others (e.g., Gallistel, 1980) was that the visual perceptual system was informed about the upcoming movement of the eye ahead of time, so that the pattern of changed visual input could be evaluated properly. This advance (feedforward) information was termed *corollary discharge*, or *effeence copy*, by these authors (see also Evarts, 1973, and Kelso, 1982, for reviews).

The idea is that a “copy” of the motor (efferent) command to the eye muscles is also sent to some other location in the brain, where it is used to evaluate the incoming visual feedback signals and to “correct for” the fact that the image on the retina is about to move. Thus, the individual perceives the environment as stable because he or she “knows” that the eye has moved via a saccade. How such a system works is the subject of much debate, but many scientists have argued that some such mechanism must exist in order for the individual to interpret incoming visual signals correctly.

### Efference Copy in Limb Control

The efference copy mechanism appears to have a parallel in the control or evaluation of limb movements. First, as pointed out by Evarts (1973), there is neurological evidence that information destined for the muscles is also sent to places in the brain that are primarily sensory in nature. Perhaps the purpose of such activities is to “tell” the sensory system what was ordered by the motor system and to ready it for receipt of the feedback. Thus, the idea of efference copy is much like the establishment of the reference of correctness against which the feedback signals will be compared. One component of this feedforward must simply be the knowledge *that* the person moved voluntarily (as opposed to passively), so that the person can distinguish feedback from movement as due to active motion versus passive motion.

Related to this example is the well-known heightened kinesthetic sensitivity when the person is moving *actively* versus passively (Brodie & Ross, 1985). Do this experiment. Take a few different grades of sandpaper, and rank them in terms of roughness by rubbing them with your index finger (eyes closed). First, move your finger actively over the surfaces. Then have someone hold your finger and move it over the surface in the same way but without your active muscular involvement. You will likely find that your perception of roughness is much impaired when you are moved passively. Why? One answer is that when the motor system sends the commands to move actively, it also sends an efference copy of the commands to sensory areas in the brain to enable proper evaluation of the feedback. But when the finger is moved passively, no motor commands are issued to the muscles; hence there is no

fference copy, and the “same” feedback signals from the finger are not perceived as accurately (see Lederman & Klatzky, 1997, 2009, for further evidence and discussion).

## Preparatory Postural Reactions

Consider a situation in which a standing participant awaits a signal to raise the arm (with a weight in the hand) quickly from a relaxed position at the side to a position in front of the body, as if to point straight ahead. According to earlier discussions about such actions, the commands for the shoulder muscles are generated after an RT of about 150 to 200 ms or so following an external “go” signal. But if the person is in a balanced stance, a sudden movement of the (loaded) arm forward and upward will cause a shift in the person’s center of gravity, and he or she will lose balance unless some compensation is provided prior to or along with the movement itself. When is such compensation produced—before, during, or after the action?

Belen’kii, Gurfinkel, and Pal’tsev (1967; see also Cordo & Nashner, 1982) recorded the EMG activity from the support muscles of the legs as well as the prime-moving shoulder muscles in this rapid arm-raise task (performed as a reaction to a stimulus). After the stimulus came on, the first signs of EMG activity occurred in the large muscles in the back of the leg (biceps femoris) on the opposite side of the body from the intended action—and these changes occurred about 60 ms *before* any EMG was seen in the shoulder muscles. The actions of the EMGs in the legs could not have been caused by an imbalance resulting from the movement of the arm, because these changes occurred before the first EMG changes in the shoulder did and even longer before any movement in the shoulder occurred. It is possible to consider these changes as an example of feedforward control, in which the motor system sends commands to the spinal levels associated with the leg musculature prior to the arm action; the purpose is to “prepare” the legs so that the body does not lose balance when the arm finally moves, or to ready the motor unit pools in the spinal cord for the upcoming signal to contract (called *spinal tuning*), or both.

Another, related view is that the changes in the patterns of EMGs in the legs prior to action could be considered a part of the coordination of the entire action, beginning with change in the legs. W. Lee (1980), using this same task, found that the temporal aspects of the EMGs are quite closely linked, with the various muscles acting in the same order and with a nearly constant pattern of action for various trials. (See chapter 8 for more evidence related to the processes involved in coordination.) This supports the idea that the feedforward information is an integral part of the overall control system (discussed later in this chapter), or part of the motor program for action as we discuss in the next chapter.

## Detection and Correction of Errors

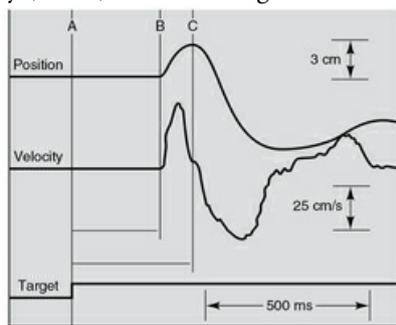
What role does feedforward information play in the detection and correction of errors? It is thought that this feedforward information is, first of all, information *that* a movement was ordered. Also, this feedforward information presumably contains the expected sensory consequences of the movement just ordered. As an example, if you ask a friend to text your neighbor while you look on, then in some way you “know” that the neighbor’s cell is pinging with a new text message even though you cannot hear it directly. Knowing that your friend has sent a text is almost as reliable as hearing the ping on your neighbor’s cell phone. In this way, feedforward information can be thought of as a variant of feedback.

If feedforward (or efference copy) could, in this general way, be evaluated as a kind of sensory information, then the idea is that it can be evaluated against a reference of correctness just as feedback can be evaluated. If the subsequent analysis of the efference copy in relation to this reference indicated that there was *going to be* an error, a correction could be initiated and a new movement command could be sent. This has the advantage of initiating the correction much more quickly than would be the case if feedback from the (errant) movement was evaluated; and the correction could even be given before the errant movement was initiated, or at least before the movement could “do much damage” in the environment.

Various experiments appear to provide evidence for such processes. For example, Angel and Higgins (1969) used a

step tracking task in which the target would move suddenly in discrete steps to the left or right; the participant's task was to follow the target movement with appropriate limb movements. When the performer is highly motivated to minimize RT, he or she will move in the wrong direction occasionally, reverse the move, and then move rapidly to the correct target. [Figure 5.17](#) is a diagram of a typical corrected trial, showing the incorrect initial movement (beginning at point B) and the subsequent correction (beginning at point C). Interestingly, the correction times, measured as the interval from the beginning of the incorrect movement until the beginning of the correction, from B to C in the figure, were as short as 90 ms. The performers could not have been processing movement feedback from proprioception or vision in the stages of processing, because the correction for the false move was made more rapidly than could be accounted for by the usual feedback-processing mechanisms. Perhaps the participants were using a central feedback loop based on efference copy as a basis for initiating these corrections.

Figure 5.17 Position (top) and velocity (center) traces showing an error with “rapid” correction toward the target.



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We discussed these so-called “rapid error corrections” earlier (in chapter 3). But, the hypothesis of efference copy–based “rapid” corrections just mentioned can also be explained in other ways. For example, when the participant moves, he or she feeds forward a prediction of the expected sensory consequences of the display. That is, if the participant guesses “left,” he or she will feed forward the expected sensory (visual) consequences of the left signal coming on, and then trigger off the (incorrect) action with a very fast RT (152 ms). However, if the proper response is “right” on that trial, then what the participant expects to see (the left signal being on) is not matched by the signal that actually appeared (the right signal). This mismatch is the “stimulus” indicating that the response will surely be an error, and corrective actions to move left are initiated then, using the stages of processing in the “usual” way. If so, the latency of the onset of the correction is not really very “rapid.” In Schmidt-Gordon (1977), this correction had a latency of 276 ms (from signal onset to reversal in direction, or from A to C in [figure 5.17](#)). Thus, in this interpretation, these “rapid” corrections are not rapid at all, and we need not invoke efference copy explanations to explain them.

The notion of efference copy also has the difficulty of explaining how efferent (or motor) information can be compared against sensory information (see Schmidt & Gordon, 1977). The problem is that the “language” of the motor information is in terms of which muscles to contract, when, in what order and timing, and with what force (see chapter 6). The sensory information arising from the action is in the form of limb movement, joint positions, and muscle forces. So, how can the system compare the information about motor commands with the information about movement feedback if these signals are in different codes? For several authors, this problem requires that the feedforward information be in the same code as the sensory information, which is the basis for the reference of correctness seen in [figure 5.13](#) (see Schmidt, 1975b) and a class of models discussed next.

## Forward Models of Motor Control

Consider the simple example of being tickled. Most of us have body parts that are responsive to touch and that result in mild to extreme sensations when brushed lightly. With only a few exceptions (see “When Can We Tickle Ourselves?”), those responses are completely avoided when the same tickling movements are produced by our own actions. Why? A class of theories of motor control known as *forward models* provides a fairly simple explanation of why we are unable to tickle ourselves (see Desmurget & Grafton, 2000; Shadmehr & Krakauer, 2008; Wolpert, Ghahramani, & Flanagan, 2001; Wolpert, Miall, & Kawato, 1998, for overviews). Flanagan and colleagues elaborated further on this idea by saying that “prediction turns motor commands into expected sensory consequences, whereas control turns desired consequences into motor commands” (Flanagan, Vetter, Johansson, & Wolpert, 2003, p. 146). The basic idea is that when a limb movement is initiated, a “model” of the *predicted* consequences of the action is also generated. This is called a “forward” model because it is a prediction of the movement’s sensory consequences before the actual sensory consequences have been generated. If the actual sensory consequences match the expected consequences (as they would if we try to tickle ourselves), this evokes no tickling response. But, when someone else tickles us, the actual sensory consequences do not match the expected consequences, because the expected consequences of the (other person’s movement) do not exist for comparison, and the result is the tickling sensation.

In other kinds of actions, once the movement is begun, the predicted and actual consequences are compared and corrections for discrepancies between them can be initiated with minimal time delays. Thus, forward models of motor control avoid many of the processing delays that are implicit in traditional feedback-based theories of control. And, unlike feedforward-based theories, forward models have the advantage of using actual feedback in error correction processes to avoid the problem of motor and sensory coding states as mentioned in the previous section.

### When Can We Tickle Ourselves?

Most of us have certain areas of our bodies that are particularly susceptible to tickling. Stimulation of these areas results in a mixture of feelings that often includes both excitement and discomfort. Perhaps somewhat surprisingly, the act of tickling has become a study of interest to motor control scientists. The reason is simple: Although we respond to tickling by someone else, we do not respond when we attempt to tickle ourselves (Claxton, 1975; Weiskrantz, Elliott, & Darlington, 1971), unless this is done under special circumstances. Why is this so?

Some researchers suggest that the inability to tickle ourselves is related to predictive processes involved in motor control. According to Blakemore, Wolpert, and Frith (1998, 2000), the act of producing a movement that would normally stimulate a ticklish part of the body produces an *expectation* of the sensory consequences of the action. This expectation has the effect of *canceling* the sensations that would normally arise if the area is stimulated by the person but cannot cancel those sensations that arise when the person is stimulated by another agent. Support for this comes from studies using functional magnetic resonance imaging (fMRI); brain activity during tickles shows less activation under self-generated than externally generated tickles (Blakemore et al., 2000).

In another study, however, Blakemore, Frith, and Wolpert (1999) employed a robotic device that could be used to generate a tickling sensation externally or could be manipulated by the individual. As expected, higher ratings of “tickliness” were found on external than on self-generated tickle trials, even when the machine provided the tickles. However, in some trials the robot did not execute the movement until a brief period of time (100, 200 or 300 ms) had elapsed after the participant had commanded the tickle. The 100 ms lag resulted in a greater feeling of tickliness compared to immediately experienced self-tickles. Moreover, lags of 200 and 300 ms produced as much sensation of tickliness as externally produced tickles. One explanation for this finding was that the predictive information fed forward in expectation of certain sensory consequences had a rather short “shelf life,” essentially as short-term (visual) sensory store (STSS) does, as discussed in chapter 3. Perhaps this rapid decay in memory quality is characteristic of feedforward information generally. Other explanations are equally plausible, however, and further research is warranted to sort out this interesting phenomenon.

## Summary

Closed-loop systems involve the comparison of feedback against a reference of correctness, the determination of an error, and a subsequent correction. The receptors for the feedback supplied to closed-loop systems are the eyes, ears, and vestibular apparatus, as well as the Golgi tendon organs, the muscle spindles, the joint receptors, and touch receptors in various places in the skin. All these sources provide input to the central nervous system, and then the information is presumably combined for the purpose of analysis of movement.

Vision provides the richest source of information for closed-loop control. Vision can be used in a variety of ways, providing information about errors in movement as well as predictive information so that potential errors can be anticipated and avoided. The action-specific perception account explains that people perceive the environment in terms of their ability to act in it. Closed-loop control models seem to have their greatest strength in explaining movements that are slow in time or that have very high accuracy requirements (or both). Tracking tasks are most obviously related to closed-loop processes. These closed-loop models have difficulty explaining the kinds of corrections seen in very rapid movements, however, and this fact leads to the suggestion that two fundamentally different kinds of movements exist: slow and fast. However, strong evidence exists for closed-loop reflexive control in limb movements. Most of this work suggests involvement of the muscle spindle and the gamma loop, but other receptors are involved as well. Such reflexive corrections can be classified as (a) the monosynaptic stretch reflex (latency = 30-50 ms), (b) the long-loop or transcortical (or functional) stretch reflex (latency = 50-80 ms), (c) the triggered reaction (latency = 80-120 ms), and (d) RT (latency = 120-180 ms or longer).

Feedforward control models involve the delivery of information to some other part of the system to “prepare it” for incoming sensory information or for an upcoming motor command (as in spinal tuning). Thus, feedforward information serves an important role in error detection and correction, often occurring in anticipation of the error and more importantly, avoid many of the processing delays that are implicit in traditional feedback-based theories of control.

### Student Assignments

1. Prepare to answer the following questions during class discussion:
  - a. Describe the closed-loop operation of any human-made device of daily living (e.g., a furnace).
  - b. Describe the anatomical parts and what each contributes to the stretch reflex.
  - c. What are the psychophysiological cues that humans use for depth perception?
2. Find a recent research article (within the past five years) that compares the effect of a visual illusion on perception and motor control.

### Notes

<sup>1</sup> Anatomical and neurophysiological evidence that supports the two visual stream proposal is reviewed by Norman (2002) and Bear, Connors, and Paradiso (2001, chapter 10).

<sup>2</sup> Some authors refer to this illusion as the Ebbinghaus illusion while others refer to it as the Titchener illusion (see also footnote 1 in Fischer, 2001).

<sup>3</sup> Performance in the various vision conditions may have reached a ceiling level. Thus, direct comparison to performance in the control condition with full room lighting is problematic because of the richer sources of contextual cues provided, which appear to be particularly important for reducing spatial errors (Montagne & Laurent, 1994). Whiting and colleagues (1970) also noted that participants used a different catching strategy in the full room lighting condition whereby they would move with the ball and delay their attempts to make the catch, thereby gaining themselves an additional 100 ms or so of ball flight information.

<sup>4</sup> The root *fusal* means fusiform or spindle-shaped; so intrafusal fibers are muscle fibers within the spindle, and the

extrafusal fibers are those outside the spindle—that is, the fibers of the muscle in which the spindle is embedded. The Greek letter gamma ( $\gamma$ ) refers to the spindle system (the intrafusal fibers are thus innervated by the gamma motor neurons; the alpha motor neurons innervate the extrafusal fibers). The term Ia refers to the fact that the sensory (afferent) fiber emerging from the spindle is a large type I afferent; the a refers to the fact that this fiber comes from the spindle (type Ib fibers come from the Golgi tendon organs). Type II afferents are smaller in diameter and conduct impulses more slowly than the type I afferents.

<sup>5</sup> A motor unit is defined as an alpha motor neuron and all of the muscle fibers that it innervates. In humans, the number of fibers supplied by one alpha motor neuron might vary from a few (in muscles requiring fine control—in the hand, larynx, eyes) up to several thousand (in muscles requiring only gross control—in the trunk). There could be from a few to several hundred motor units in any one muscle (see Leob & Ghez, 2000).

<sup>6</sup> This 120 ms value in [figure 5.14](#) is considerably shorter than the typical RT latency discussed in chapters 3 and 4. But in [figure 5.14](#), the latency is measured by the EMG change, whereas in chapters 3 and 4 the RT is measured with respect to the movement, which usually occurs with an additional delay of at least 50 ms.

<sup>7</sup> This diagram is not meant to be correct anatomically. For example, visual information probably travels to high levels in the central nervous system (visual cortex) and is certainly not “housed” in the spinal cord, *per se*. Rather, this diagram should be taken as a set of functional pathways—some of which involve the stages of processing and some of which do not.

## Chapter 6

# Central Contributions to Motor Control

The focus in the last chapter was primarily on the role of sensory mechanisms. Motor control was considered as a closed-loop system, dependent on feedback either (a) for online corrections mediated by the stages of processing, or (b) for corrections or compensations in the action that are reflex based and not mediated by the stages of processing. In contrast to this closed-loop viewpoint is an open-loop system, in which the instructions for movement are structured in advance and are executed without regard to the effects they may have on the environment. That is, the behavior of the open-loop system is not sensitive to feedback that requires a change in goal.

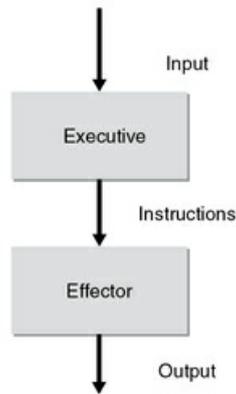
A good example of an open-loop system is the traffic signal at a major intersection. The timing pattern of green, yellow, and red is controlled from a program that handles this sequence without regard to moment-to-moment variations in traffic patterns. Because there is no feedback from the traffic conditions back to the executive, there can be no immediate modification in the pattern if an accident occurs or if traffic is particularly heavy. However, even though the program for the traffic lights is inflexible, we should not get the idea that it must be simple. The program can be structured so that the north–south street has a 20% longer green light duration than the east–west street during rush hours, with this relation being altered in midday when the traffic pattern is often different. But the only way modifications in timing can occur is for the programmer to structure them into the program in advance. More modern traffic intersections use video cameras to recognize the flow of traffic and then use an algorithm to alter the timing pattern so that traffic flows efficiently (and the cameras can catch drivers who disobey the traffic lights).

This chapter presents traditional evidence (from the information-processing perspective) that has been used to support a construct called a motor program. The idea is that the central nervous system has a representation of the skill to be performed, and this representation guides the motor control commands. Some of the criticisms and concerns about this idea are described, albeit briefly. Scientists who do not believe in the motor program construct have a fundamental difference of opinion with those scientists from an information-processing perspective who believe in such representations (also called internal models by neuroscientists; Wolpert, Ghahramani, & Jordan, 1995). This philosophical difference does not have an easy resolution. The dynamical-systems account strongly promotes the idea that self-organized biophysical systems can be used to describe motor control and coordination. These principles work across various time scales and are not privileged to an organism that has a very smart brain. Proponents of the dynamical-systems account ask different questions for their research agenda than for a more traditional *information-processing approach*. Although we will not thoroughly explain the dynamical account, readers are encouraged to read Kugler, Kelso, and Turvey (1982), Kelso (1995), and the writing of Newell (1985, 1986) to develop an appreciation of this important perspective on motor coordination and control.

## Open-Loop Processes

A diagram of a typical open-loop system is shown in [figure 6.1](#). The executive and effector mechanisms can be thought of in the same way as for the closed-loop system in [figure 5.1](#), but the feedback loop and the reference of correctness are missing (the feedback pathway is “cut” or “open,” as when a switch is open—hence the label “open loop”). The executive has a package of instructions, called a ‘program’ to send to the effector, and the effector carries them out without the possibility of modification if something goes wrong. In this chapter, we emphasize the open-loop processes and central representations involved in motor control, for which sensory influences play a much less dominant role. To clarify, *open-loop control* as a construct is not opposed to closed-loop control; rather, each is crucial to successful performance. This chapter discusses evidence that supports open-loop control, but that is not to say that sensory feedback is not important. Anyone who has tried to chew after their mouth has been numbed at the dentist can attest to the importance of sensation to motor control.

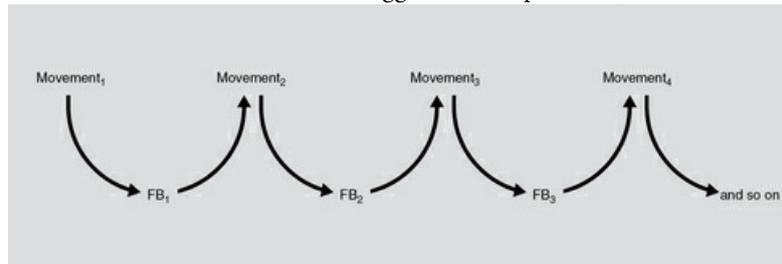
Figure 6.1 Elements of the typical open-loop control system.



## Response-Chaining Hypothesis

One of the earliest explanations of movement control was the *response-chaining hypothesis* (sometimes called the *reflex-chaining hypothesis*) proposed by the 19th- and 20<sup>th</sup>- century psychologist William James (1890). The basic idea is illustrated in [figure 6.2](#). James assumed that a movement began with a muscular contraction caused by an external or internal signal. This first contraction generated sensory information (which he termed *response-produced feedback*), which we discussed in detail in chapter 5. James regarded this feedback as stimulus information (just like that from any other stimulus such as light or sound), which served as the *trigger* for the next contraction in the “chain.” The second contraction then produced its own response-produced feedback, which triggered the third contraction, and so on until all the contractions in the sequence were completed. The feedback could come from various sources (e.g., muscle spindles, joint receptors, or even vision or audition), and it could trigger responses in the same or in different limbs. With such a mechanism, James hypothesized how certain actions appear in the proper order in skills, as the chain ensured that the second contraction did not occur before the first one. Also, James thought that this mechanism could account for the *timing* among the various contractions so important for skilled actions; such timing would be determined by the temporal delays in the various sensory processes and could be relatively consistent from response to response to produce stereotyped actions. Although such a model seems appropriate for serial tasks (starting the car, buttoning a shirt), there is no conceptual reason why the model could not explain discrete actions, such as speech and throwing, by assuming that the responses triggered are the contractions of individual motor units. Viewed in this way, the response chain shown in [figure 6.2](#), which consists of four units of behavior, might last only 100 ms, or it might continue for a few seconds.

Figure 6.2 The response-chaining hypothesis. (The response-produced feedback from earlier portions of the action serves as a trigger for later portions.)



James (1890) recognized that when *skilled* movements were produced, they did not seem to require much consciousness for their control. Under the response-chaining hypothesis, movements could be viewed as requiring attention only for the initiation of the first action, with the remainder of the actions being run off “automatically.” Also, in James’s view of *learning* motor skills, the acquisition of the associations between a given feedback event and the next action is the fundamental basis for improvement in skill.

The response-chaining hypothesis is a variant of an open-loop control mode, in spite of the presence of feedback. Remember that in a closed-loop system (see chapter 5), the executive level is acting on the *error* that is produced, and such errors are computed as the difference between the actual state and the desired state defined by the reference of correctness. In the response-chaining hypothesis, though, there is no reference of correctness against which feedback is compared—the feedback simply serves as the trigger for the next act in the sequence. It is open loop because the original stimulus sets the chain in motion, and the following events are determined by the learned associations between feedback from movement  $n$ , to the triggering of movement  $n + 1$ . Also, open-loop movements cannot be modified if something goes wrong or if the environment changes, as is the case for a closed-loop model.

One way to test the response-chaining hypothesis is to examine the role of *sensory* information in the production of movement. Of course, if the sensory information is eliminated (or delayed or degraded in quality), then the result should be a loss of skill, or even paralysis, because the *trigger* mechanisms have been disrupted. In the next sections, we review some evidence about feedback degradation in relation to this hypothesis.

## Deafferentation

There are both temporary methods for interrupting the flow of sensory information into the spinal cord (e.g., the blood pressure cuff technique, the injection of local anesthetics) and permanent procedures, such as *deafferentation*. Nearly all of the afferent input to the spinal cord enters through the dorsal roots on the posterior side of the spinal cord. In an operation called a *dorsal rhizotomy*, the back of the animal is entered surgically, and the muscles are carefully moved to expose the dorsal roots. Then, at the particular spinal level of interest, the dorsal roots are cut, essentially preventing any sensory information at that spinal level from reaching the cord in the future. Note that this procedure leaves intact the *effluent* (or motor) part of the system, which exits the cord via the ventral roots, and allows the muscles to be activated as before the operation; but, of course, it eliminates the feedback from the muscles. This procedure can be done at a single spinal-cord level or at multiple levels—with additional deafferentation at each successive level progressively eliminating more and more of the animal’s sensations from the periphery. The operation can be done unilaterally or bilaterally, thereby eliminating the feedback from one or both sides of the body. These procedures have been performed on mice, cats, monkeys, and numerous other species in order to study the movement control that occurs in the deafferented state.

While normally these procedures are limited to animal experiments, a number of examples of deafferented humans have also been reported. Lashley (1917), in a study we will describe in detail later, assessed a patient with a gunshot wound to the lower spine. The lesion had the same effects as surgical deafferentation, and it left the motor innervation of the participant intact. Also, patients with complete or near-complete loss of sensory information due to degenerated afferent pathways (*sensory neuropathy*), but with intact motor systems, have made

significant contributions to this area (e.g., Bonnet, Carello, & Turvey, 2009; Gordon, Ghilardi, & Ghez, 1995; Rothwell et al., 1982; Sanes, 1990; Teasdale et al., 1993). Finally, Kelso, Holt, and Flatt (1980) have studied arthritic patients who have had the finger joints replaced with artificial ones. This operation removes the joint and the joint capsule in which the joint receptors are located. Thus, while this is not really a deafferentation procedure in the strictest sense, it does provide a situation in which joint-receptor feedback from the moving limb is disrupted.

### *Deafferentation Studies*

One of the earliest investigations using surgical deafferentation was conducted by Sherrington (1906). He severed the dorsal roots in a monkey so that only the sensations from a single forelimb were lost; the remainder of the body had normal sensory feedback. A major finding was that after recovery from surgery, the monkey never used the limb, keeping it tucked against the chest and using the other limbs to eat and ambulate. For decades, this finding was regarded as support for the response-chaining hypothesis, because eliminating the feedback seemed to eliminate movement altogether, as it should if the hypothesis is correct.

But Sherrington's conclusions were later challenged by a number of separate lines of evidence. Considerable research was completed on the control of locomotion in lower organisms such as fish, snakes, frogs, insects, and birds (see Grillner, 1975; Pearson, 1976, for reviews of this early work.). Some of this research involved severing the efferent (sensory) pathways for various segments of the animal's system. The conclusions generally were that movements are not seriously disrupted. For example, Wilson (1961) deafferented locusts, stimulating the insect electrically with a pulse near the head region, and wing movement patterns resembling flying resulted. The patterns were decreased in amplitude and frequency as compared to normal flight patterns, but clear rhythmic activity nevertheless continued.

Why were the locust's movements so well accomplished, when Sherrington's monkey did not move the deafferented limb at all? Could it be that monkeys are fundamentally different from the lower species in terms of their motor systems? This is probably not the answer, as studies subsequent to Sherrington's on humans and monkeys have tended to show that some movements are not strongly interrupted by deafferentation. For example, Lashley (1917), in his study of the patient in whom a gunshot wound to the spine had rendered one leg deafferented, asked the patient to perform various positioning movements without vision. While sitting on the edge of an examination table, the patient was asked to extend the knee to 45°, and the error in producing the movement was compared to that of a "normal" control participant. Lashley found that the deafferented participant and the normal participant could do the positioning task about equally well.

How can the apparently contradictory findings of Sherrington and Lashley be reconciled? One possibility is that the deafferented monkey *chose not* to use the affected limb, which is quite different from saying that the monkey *could not* use it. You know how it feels when you sleep on your arm the "wrong way" (this is a temporary deafferentation), or when your jaw is anesthetized after a trip to the dentist; the sensation is strange and unpleasant, and we might prefer not use these effectors in these situations unless it was important to do so.

### *Later Deafferentation Studies*

In a series of studies, Taub and his colleagues (see Taub & Berman, 1968, or Taub, 1976, for reviews) and Bizzi (e.g., Polit & Bizzi, 1978) used surgical deafferentation affecting various portions of monkeys' bodies. After Taub and Berman's monkeys had both forelimbs deafferented and had recovered from the operation, they were able to move the limbs *nearly* normally—activities such as climbing, swinging, eating, and grooming were different only in minor ways from those of the normal animals. The deafferented monkeys did, however, show some deficiencies in very fine manipulations, such as those that would be required to pick up a small piece of food. Perhaps this is related to the role of the cutaneous receptors in these movements (see chapter 5; see also Frank, Williams, & Hayes, 1977). The conclusion to be drawn from these studies is that feedback from the moving limb is not *essential* for movement to occur, but that it undoubtedly aids the accuracy of movement in most situations.<sup>1</sup>

However, these findings do seem to contradict the expectations of the reflex-chaining hypothesis, which claims the necessary involvement of feedback in the normal conduct of movement.

The role of sensory feedback in motor control should not be an either- or distinction. The loss of feedback has serious ramifications for skilled performance. At the same time, highly learned actions can be produced even though feedback has been compromised. It is widely believed that people possessed brain networks that could adapt to practice and contained what might be called a representation of the skill (today called an internal model or a motor program). For example, Wolpert et al. (1995) posited that the central nervous system utilizes an internal model, based on position and velocity, along with feedback and efference copy (motor commands) to control a movement trajectory. With practice the internal model relies less on feedback.

### *Deafferentation in Humans*

Provins (1958) studied the role of joint receptors from the fingers by injecting anesthetic directly into the joint capsule. Although the participants could not feel the movements of their fingers, there was nevertheless a strong capability to move; but the accuracy suffered somewhat compared to that in the condition without the anesthetic. Very similar findings were obtained by Kelso (1977; Kelso et al., 1980) in studies involving the joint afferents from the hand. When the feedback from the joint afferents was blocked either by Laszlo's (1967) cuff technique (discussed later in this chapter; Kelso, 1977) or in patients who had artificial finger joints (Kelso et al., 1980), little or no loss in movement positioning accuracy occurred without vision. Of course, these studies involved normal afferent feedback from the muscle spindles located in the finger muscles in the forearm, and it could be that this was the source of feedback that allowed for accurate control. Thus, the joint afferents are not essential for movement, as is often believed (e.g., Adams, 1977).

Using an anesthetic block of the gamma loop and other pathways from the right arm in humans, J. Smith (1969; Smith, Roberts, & Atkins, 1972) found that dart throwing and grip strength tasks were only minimally disrupted by this kind of deafferentation. Although some impairment in performance occurred, the most important point is that the movement could be produced even though feedback was not available from the moving limb. For example, with an active anesthetic block, participants could not break their elbow and shoulder movement to lick an ice cream cone; the ice cream contacted the face and nose. Although this example may be humorous, it highlights this important distinction: Feedback might not be crucial for movement initiation, but is important for endpoint accuracy.

Many studies have been done using the so-called cuff technique popularized by Laszlo (1967). Here, a blood pressure cuff is inflated around the upper arm, blocking blood flow to the lower arm; after about 20 min, the feedback sensations from the lower arm and hand are temporarily lost; but for a few minutes, the motor capabilities remain largely intact. In a series of studies using tasks such as rapid finger tapping, handwriting, aiming, and limb positioning, impairments were found in performance under the cuff conditions. However, the movements, although impaired, still could be produced, contrary to the expectations from a response-chaining hypothesis (see also Chambers & Schumsky, 1978; Kelso, Stelmach, & Wannamaker, 1976; Laszlo & Bairstow, 1979).

Studies involving patients with sensory neuropathy have yielded similar conclusions, although these individuals often have severe difficulties in performing many activities of daily living. For example, the patient studied by Rothwell and colleagues (1982) reported that he had trouble feeding and dressing himself and could not hold a pen in his hand. The patient could control his hands to touch the thumb to each fingertip sequentially without visual feedback, at least for a short period of time. However, this activity could not be maintained for very long. Performance had deteriorated considerably after 30 s.

Another example involves a woman known in the literature as GL, who is completely without information about touch, tendon vibration, and proprioception but has normal visual feedback and efferent pathways. GL is able to carry out her activities of daily living quite well using constant visual feedback (Bard et al., 1999; Blouin, Gauthier, Vercher, & Cole, 1996; Hepp-Reymond, Chakarov, Schulte-Mönting, Huethe, & Kristeva, 2009).

From the perspective of the response-chaining hypothesis, sensory neuropathy patients demonstrate remarkable capabilities to perform skilled actions (Sanes, Mauritz, Dalakas, & Evarts, 1985).

## Ian Waterman and the Role of Proprioception in Motor Control

Ian Waterman was a 19-year-old young man working in a butcher store in England when he contracted a flu-like virus. Upon awakening one morning, he could not feel his body. Physicians believed that the virus caused an autoimmune response that destroyed the dorsal nerves, which carry sensory information to the central nervous system. Through dogged determination and a keen sense of his motor control processes, Ian learned to move based on using visual information to deliberately plan his movements in a response-chaining method. The cost of Mr. Waterman's strategy was a loss of rapid movement. Visual feedback processing is slow, but it is reliable. Even though one would consider walking a well-learned skill and not very dependent on feedback, Ian Waterman had to see his feet in order to control locomotion. The British Broadcasting Company (BBC) produced a documentary about Mr. Waterman called *The Man Who Lost His Body*. Interested readers can search for it online to learn more.

## Implications for the Response-Chaining Hypothesis

Even though work with various kinds of deafferentation has shown that feedback from the responding limbs is not necessary in order for actions to occur, the evidence was sometimes taken incorrectly to mean that feedback in general is *never* used in movement control. The deafferented animals were not completely normal in their movement, especially when the fine control of finger action was required. We saw (in chapter 5) the effects of having the fingertips anesthetized on performance of simple tasks such as striking a match. Also, it is possible, as Adams (1971, 1976b) has said, that other kinds of feedback (e.g., vision) could be substituted for the lost sensations in the deafferented animal. And finally, there are many cases in which feedback is almost certainly used in movement, such as those that we discussed in chapter 5. On strict experimental grounds, the evidence does not allow us to infer that the response-chaining hypothesis is incorrect. Rather than an either-or question about the role of feedback, we must explore the necessary conditions that require feedback control compared to open-loop control in order to gain the best understanding of control of movement.

# Central Control Mechanisms

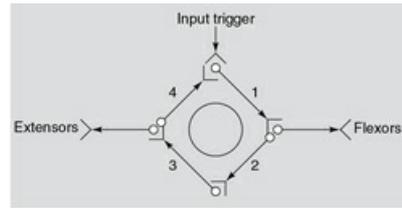
We need motor control mechanisms that explain how movements can occur in the absence of sensory feedback in order to deal with some of the evidence just described. In the next sections, the role of sensory processes is more or less reduced in prominence. Keep in mind, however, that various mechanisms of motor control can be isolated for study in the various paradigms, although none seems to operate independently during most everyday activities. It is important for students to understand these mechanisms, but the real problem in understanding motor behavior is to appreciate how these processes work together toward smooth, elegant, and energy-efficient performance (see also Cruse, Dean, Heuer, & Schmidt, 1990).

## Central Pattern Generators

A number of extensive reviews summarize the evidence about the control of locomotion and gait in a variety of animals (Dietz & Duysens, 2000; Grillner, 2007; Grillner & Wallén, 1985, 2002; Goulding, 2009; Marder, Bucher, Schulz, & Taylor, 2005; Pearson & Gordon, 2000a; Zehr & Stein, 1999) and humans (Zehr, 2005). One important topic in this literature concerns so-called *spinal preparations* in cats and other animals. In this procedure, the spinal cord is cut at a level below the brain so that the higher (supraspinal) centers cannot influence lower ones, and often the spinal cord is deafferented below the level of the cut as well (see Pearson & Gordon, 2000b). If the prepared cord is then stimulated only briefly below the cut, the cord displays a definite *periodicity* in terms of the activity in the efferent fibers emerging from its ventral side. Thus, the spinal cord is capable of producing rhythmic output from the motoneurons that is present even without input from the brain or higher centers and without feedback from the limbs. With reference to gait patterns, a popular view, termed the *half-center* model (Brown, 1911), suggests that interneurons (neurons within the spinal cord, which synapse only within the cord) alternately stimulate the flexor and extensor motor neurons in a pattern more or less like the one that would be displayed in locomotion. Apparently, the spinal cord has neural circuitry capable of producing these oscillations. These circuits are called *central pattern generators (CPG)*.

A schematic diagram of how such a simple spinal generator might be structured is shown in [figure 6.3](#). Many alternatives exist, and the central pattern generator illustrated in [figure 6.3](#) is only a simple illustration. In this structure there could be a neural network in the cord made up of four interneurons (the cord undoubtedly uses many more). Input from some higher center (a chemical or electrical signal for the spinal animal) initiates a cyclical pattern of excitatory motor neural activity. Neuron 1 is activated, which activates neuron 2, and so on, until neuron 4 activates neuron 1 again to start the cycle all over again. This continuous cycling process would go on indefinitely or until some other process turned it off. Further, if neuron 1 synapses with another neuron that drives the flexor muscles, and neuron 3 synapses with another that drives the extensors, every time around the cycle the flexors and extensors will be activated. This basic concept of simple oscillating circuits helps to illustrate how a neural network could be expected to produce rhythmic patterns of activity such as gait or breathing in animals.

Figure 6.3 A simple possibility for the connections of interneurons forming a central pattern generator.



Showing that the spinal cord has some slow rhythmic capability is interesting but to what extent is this activity involved in gait control? A very important surgical preparation in cats has allowed considerable insight into this process. This preparation is called the mesencephalic (midbrain) preparation (Shik, Orlovskii, & Severin, 1968). The cat receives a cut of the spinal cord in the midbrain, which totally severs the lower levels of the cord from the higher, supraspinal centers. The cerebellum, the small structure behind the midbrain, is functional and is still connected to the spinal cord side of the cut. In this state, the cat is (presumably) unable to sense any stimulation from the body (because the afferent pathways to the cortex are severed) and is unable to perform voluntary movements of the legs. Shik and colleagues used a harness that supported the cat above a treadmill.

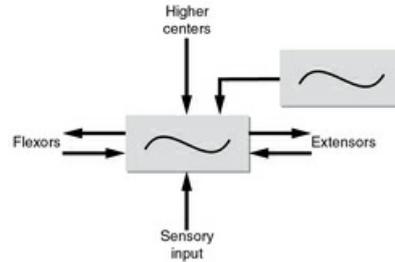
A number of important observations have come from this preparation. First, when stimulated with a brief electrical current or a chemical at the level of the surgical cut, the animal on a moving treadmill produces stepping movements that resemble normal locomotion in cats. This stepping continued for some time after the stimulus was discontinued. As the treadmill sped up, the cat walked faster, even trotting or galloping. It appears that some spinal generator(s) for walking must be activated by a higher source and that, once initiated, the pattern of flexion and extension continues without further involvement from the supraspinal centers. Because the mesencephalic animal cannot sense the activity occurring in its limbs, such stepping activity must be independent of the animal's feedback of the activity.

As it turns out, a stimulus from the higher center in the midbrain is not the only way to initiate the spinal generators for stepping. Using the same apparatus, Shik and Orlovskii (1976) studied the cat's behavior when the treadmill was turned on. At first, the legs would trail off behind the animal; then suddenly the animal would initiate stepping, with the total pattern of activity generated as a unit. As the treadmill increased in speed, the animal would walk faster, with only minor differences in the pattern of activity from that observed in the normal cat, plus some unsteadiness. As the treadmill increased in speed further, the cat would suddenly break into a trot pattern. Occasionally the cat could be made to gallop. (Remember, there is no control from the higher centers and no stimulus from higher levels in the cord to turn on the spinal generators.) These results indicate that the afferent input from the feet and legs, which are at first dragged by the treadmill, is sufficient to initiate stepping. Once the pattern generators are activated, the speed of the oscillation appears to be controlled by the rate at which the treadmill moves the cat's legs and feet. When the limbs are being moved so rapidly by the treadmill that a walk pattern is no longer effective in keeping up, the afferent information presumably triggers a new pattern—the trot. An analogous set of findings has been produced by Smith and her colleagues (Carter & Smith, 1986; Smith, 1978; Smith et al., 1986).

As a result of this evidence, as well as the evidence reviewed by Grillner (1975), several models of gait have emerged. The general features of these models are shown in [figure 6.4](#). The box in the center of the diagram represents a central pattern generator, and it can be activated or deactivated by supraspinal centers. In some cases, this higher-level input appears to be but a single pulse that will turn on the generator, with no further higher-level activity necessary in order for the oscillator to continue to operate. In other cases, a continuous input (not necessarily a rhythmic one) appears to be necessary, with the action in the generator continuing only as long as the input continues.



Figure 6.4 Spinal generator model for gait, showing input to oscillators from sensory sources, from higher centers, from other oscillators, and from moving limbs.



The activity in the generator can also be turned on by sensory input. While the generator is operating, the activities in the flexor and extensor muscles are coordinated, and feedback from the responding limbs also can serve to modify the output; this is shown by the two-way arrows from the various muscles to the spinal generator. And, finally, a number of spinal generators are thought to exist, perhaps one for each of the four limbs in the stepping cycle of the cat, so that the operation of the separate oscillators must be coordinated (coupled) by interneurons. Thus, in the diagram a connection is shown from another oscillator to indicate this kind of control.

A number of important concepts emerge from this work on pattern generators. First, for the control of gait and other stereotyped actions in a variety of species (e.g., swimming in lamprey; tail flipping or escape reactions in lobsters; grooming in mice), strong evidence exists that these patterns are controlled by “prewired” pattern generators that can handle most of the details of the actions. They can be turned on by a variety of sources of stimulation, and they can continue until they “run down” or are stopped by some other source of input. Although the basic pattern is quite stereotyped, in “higher” animals (such as cats), extensive modification of the basic pattern is possible, either from higher centers to make the whole pattern more rapid or more forceful or from lower feedback sources (e.g., from the leg or foot) that serve to alter the particular pattern of force applied to conform to variations in terrain. Finally, these pattern generators do not require the conscious awareness of the animal in order to operate. Once initiated, they can apparently continue without involvement of the higher centers. However, in the operation of these generators during running, for example, attention seems to be required, perhaps to evaluate the upcoming terrain or to keep the oscillator running (e.g., Duysens & Van de Crommert, 1998; Van de Crommert, Mulder, & Duysens, 1998).

## Fictive Locomotion

A strong line of evidence supporting the idea that neural circuitry exists to produce rhythmic output analogous to locomotion comes from an area known as fictive locomotion (Grillner, 2006; Pearson, 1996). In fictive locomotion, alpha motoneurons are no longer synapsing with muscle fibers and the sensory receptors have been disconnected from the spinal cord. Either through brain stem stimulation (done in the cat), or direct electrical stimulation (done in the lamprey) the motoneuron is stimulated. This stimulation sets up a self-sustained oscillation of the motor neurons of the flexor and extensor muscles. It is called “fictive” (created by imagination) because the spinal machinery is cut off from the motor apparatus, but the motoneuron output *looks* as though it is producing locomotion.

Fictive locomotion provides strong evidence that rhythmic motor output for locomotion, breathing, or chewing could be driven centrally by endogenous self-sustaining oscillatory circuitry. This circuitry seems to be hardwired (Grillner, 2006) and most likely the result of evolutionary pressures. Whether evidence for these structures in rhythmic activities implies that with learning the central nervous system uses software to build representations for well-learned skills (such as HNZ’s tennis backhand) is still up for debate (Turvey, 1990).

## Reflex Involvement in Locomotion

Throughout the history of motor skills research, considerable debate has centered on the role of reflexes, and our

discussion about genetically defined activities such as locomotion would be incomplete unless we considered reflex involvement (see also chapter 5). The following sections present some of these diverse viewpoints.

### *Maintaining the Original Pattern*

The focus in the next few sections concerns how feedback activity cooperates with the central programs for action. We are only now beginning to understand the important principles of these sensory–motor interactions.

An older notion of control in locomotion was that the patterns of limb action consisted of fundamental reflex activities (e.g., Easton, 1972). This was somewhat different from the reflex-chaining hypothesis in that the component reflexes were thought to be the identifiable, genetically defined patterns that we see so often in infants, whereas the reflex-chaining hypothesis involves any chained activity—even those that are learned. A good example of these genetically defined reflexes is *reciprocal inhibition*, whereby the flexors of a joint tend to be automatically inhibited when the extensors are activated. With the *crossed-extensor reflex*, the extensors of one knee are activated when the flexors of the opposite knee are called into action. When we step on a tack, the flexors in the affected leg take the weight off the tack, while the extensors in the opposite leg help to prevent falling. Another example is the *tonic neck reflex*, in which turning the head to the right causes facilitation in the arm flexors on the left and in the arm extensors on the right.

That these reflexes *exist* is not in question. They are especially easy to identify in infants, and they have been used in the diagnosis of various neurological disorders. But to say that gait and other movement behaviors *consist* of the various reflexes implies a model in which the motor system is always *reacting* to peripheral stimulation. A more reasonable viewpoint, based on the evidence on central pattern generators, is that reflexes ensure that the pattern of activity specified by the central pattern generator is carried out effectively in the face of unexpected changes in the environment. The muscle spindle and gamma systems seem to fill this role. One function of the gamma system is to maintain muscle stiffness (i.e., its mechanical, spring-like properties) in the face of various unexpected changes in muscle length because of changes in joint position(s) (Nichols & Houk, 1976). If an animal steps on a patch of ground that is higher than expected, the “springy” muscles allow extensors to yield without collapsing, maintaining a smooth gait without a fall. The view is that reflexes are *prepared* to operate if the system is perturbed but do not have a particularly important role under normal circumstances (Grillner, 1975).

### *Reflex-Reversal Phenomena*

An important variation of the concept of triggered reactions (see chapter 5) is the concept of reflex reversals described in relation to locomotion (Forsberg, Grillner, and Rossignol, 1975). In the locomoting cat, when a light touch or a weak electrical shock is applied to the top of the foot during the flexion portion (the swing phase) of the gait cycle (i.e., the time at which the animal is lifting the foot in preparation for the swing forward), an abrupt increase in the flexion response occurs (with an extension response in the opposite foot), as if the cat were trying to lift its foot to avoid an obstacle (such as a rock) that would cause it to trip. (This crossed-extensor pattern is not voluntary, as it can be shown to exist in the mesencephalic cats described earlier; thus, the response is spinal in origin.) However, when the *same stimulus* is applied to the foot during the stance (extension) phase of the gait, essentially no reaction, or perhaps a slight extra extension, takes place in the stimulated foot—a response *opposite* that shown in the swing phase of the step cycle. Because the same stimulus causes two different patterns of action depending on the phase of the stepping cycle, this effect has been termed the *reflex-reversal phenomenon*.

Frequently (but see some exceptions in chapter 5), a reflex is thought of as a *stereotyped response* caused by a particular stimulus (e.g., the blink of an eye when a puff of air is presented). Yet the evidence just cited in locomotion indicates that the response to the stimulus depends on the location of the limb in the stepping cycle and is not simple and stereotyped. Thus, a simple view of reflex control cannot explain these effects. This kind of evidence has been explained (e.g., Grillner, 1975) based on the assumption that the spinal generators for locomotion, in addition to providing efferent commands to the relevant musculature, also provide feedforward signals to other locations in the cord that serve to modify (called gating) the actions of various reflexes. The sense of this control is that if the pathways to the extensors of the right leg are being activated (during the stance phase),

then the reflex that would serve to lift the leg in response to a tap is inhibited by the central generator. However, this pathway is activated when the flexors are activated (in the flexion phase). In this way, the pattern generators involve the already structured reflex pathways so that they contribute maximally to the animal's overall movement goals (see also Hasan & Enoka, 1985).

The role of reflexes in human posture and locomotion is also starting to emerge. Zehr and Stein's (1999) excellent review on the topic identified a number of situations in which the role of reflexes changes either as a function of the *task* being performed or due to a *specific phase* of the activity within the current task. For example, pain reflex responses are diminished during standing as postural load is increased (a task-related modulation of the cutaneous reflex), whereas the functional importance of cutaneous and muscle reflexes changes between the parts of the step cycles within the task of locomotion. Cutaneous reflexes involved in corrections for a stumble and foot-placing reactions dominate the swing and swing-to-stance phases of the step cycle. Muscle reflexes involved in weight support, stability, timing, and unloading dominate the stance and stance-to-swing phases (see Zehr & Stein, 1999, for details).

Other studies of the role of reflexes in humans have been conducted in research on the motor control of speech (Abbs & Gracco, 1983; Abbs, Gracco, & Cole, 1984; Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984). These are also discussed in chapter 5. Participants in the study by Kelso and colleagues said simple sentences, such as "It's a /baez/ again" or "It's a /baeb/ again," and received an unexpected downward perturbation to the jaw during the target syllable /baez/ or /baeb/. When /baez/ was to be spoken, a perturbation to the jaw evoked a rapid compensation in the tongue muscles but not in the lip, whereas the same perturbation during /baeb/ produced the reverse pattern—a compensation in the lip but not the tongue; this compensation occurred on the *very first* trial. As in the work on locomotion, the same stimulus (here the jaw perturbation) produced rapid responses (about 30 ms latency) that were very different depending on the action being produced (i.e., the specific word). But, unlike the changes observed in the locomotion studies, these speech modifications were probably learned along with speech, as it is difficult to imagine how this capability could have been a part of an inherited pattern as was the case for locomotion. These rapid sensory–motor processes seem to serve the general purpose of ensuring that the overall *goal* of the particular movement being attempted at the time is maintained, with the modifications necessarily being different for different movement goals (Schmidt, 1987).

## “Smart” Spinal Cord

Early in the thinking about motor control, the spinal cord tended to be viewed as a “freeway” that simply carried impulses back and forth from the brain to the peripheral receptors and muscles. Gradually, as many spinal activities were isolated and studied (e.g., Sherrington, 1906), the spinal cord came to be regarded as considerably more complex—and has even been considered as an organ. The evidence that the spinal cord contains central pattern generators for gait and other movements continues to point toward the cord as a complex organ where much of motor control is structured. Furthermore, it appears that the spinal cord is responsible for considerable integration of sensory and motor information, as shown by the following example.

Consider a frog making a wiping response to a noxious stimulus placed on the “elbow.” Fukson, Berkinblit, and Feldman (1980; Berkinblit, Feldman, & Fukson, 1986), like others before them, showed that the frog is capable of performing these hindlimb responses when spinalized (i.e., with a transection that separates the cortex from the intact spinal cord). The response always begins with a movement of the hindlimb toe to the region of the shoulder area, followed by a rapid wiping action that is aimed at the elbow. It is interesting that the animal can use sensory information from one part of the body (the elbow) to trigger an action pattern in some other part (the hindlimb), even when spinalized. What is of more interest, however, is that the animal produces different wiping movements depending on the location of the elbow at which the response is aimed. That is, the central pattern generator for this response appears to modify its action depending on the sensory information from the forelimb indicating the position of the stimulus—the cord “knows” where the limbs are. Remember, the frog had no cortical involvement in this response, and thus, no awareness of the limbs' actions, so this integration of sensory information was done at very low levels, perhaps completely within the spinal cord. Such observations indicate that the spinal cord is a very “smart” organ indeed.

Another example, from the work of Smith and colleagues (1986) on spinalized cats, is particularly impressive. When a piece of tape was placed on the walking cat's hind paw, a stereotyped paw-shake program was initiated in which the cat lifted the foot and shook it rapidly and violently for about 10 to 13 cycles, apparently for the purpose of shaking the tape loose. Of course, because of the spinal section, this stereotyped program must have been initiated through peripheral stimulation from the foot and controlled by the spinal cord. But even more remarkably, the spinal cat could walk on the treadmill (another program) and shake the paw at the same time, triggering the paw shake when the limb was in the swing phase of locomotion and turning it off when the foot was on the ground in support. Somehow the spinal cord, without the help of a higher center, "knew" how to coordinate these two actions simultaneously to achieve the double goals of removing the tape and walking without falling.

## Human Skills

The evidence and ideas presented that support the concept of a central pattern generator were produced in animals. Suggestions that central pattern generators also operate in humans have sparked considerable debate, and to date the evidence is not entirely clear on the issue (MacKay-Lyons, 2002). We might expect that central pattern generators likely would operate in humans to some extent (see Zehr, 2005, for more discussion).

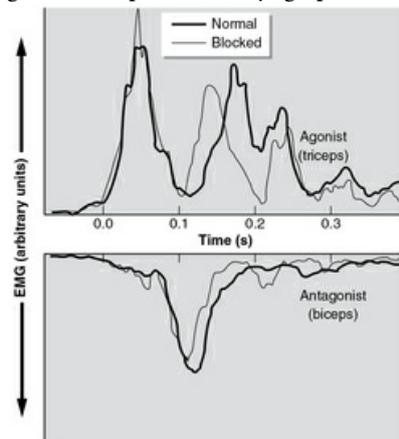
The movements studied in the cat mentioned previously are probably genetically defined and "prewired." To what extent are motor programs for movements like throwing a football structured in the same way? Are there programs in the spinal cord that can handle the production of a football pass if they are activated by a pulse from the midbrain, or do programs that are not genetically defined have some different origin? These questions are difficult to answer, as almost no research with animals has used tasks or skills that we could consider learned, or that are not genetically defined. One hypothesis is that the control of learned and genetically defined actions is fundamentally the same, but no good evidence is available on this question. Instead, we turn next to evidence about the role of central control mechanisms—*motor programs*, specifically—that has been generated in behavioral studies with humans.

## Central Control of Rapid Movements

Consider a very rapid limb movement in which the pattern of action is initiated and completed in less than 150 ms. There are many examples of movements like this, such as a key press in typing (<100 ms) and, in sport, the bat swing in baseball (~140 ms) and boxer Muhammad Ali's left jab (40 ms). Because these discrete tasks are so highly represented in our everyday activities, they have been studied in laboratory settings in an attempt to understand how they are controlled.

A laboratory study might involve beginning with the elbow in one position and then rapidly extending it so that the hand comes to rest at or near a target 30 cm away. Although at first this movement appears to be very simple, the kinds of neurological activities associated with it are elegant and complex. Although many examples could be presented, one in a study by Wadman, Denier van der Gon, Geuze, and Mol (1979) makes the point particularly well. [Figure 6.5](#) shows a pattern of electromyographic (EMG) activity in this elbow extension task; this kind of pattern is common in many investigations using fast movements such as this. The EMGs from the triceps (the agonist) and the biceps (the antagonist) are shown. The "raw" EMGs from the muscles have been *rectified*, meaning that the negative swings of the EMG signals have been changed to positive values, and these positive values are plotted as a function of time in the action. The occurrence of peaks in the rectified EMGs represents periods of heightened activity in the muscle in question. Also, the record for the biceps (the antagonist) has been turned "upside down" so it can more easily be compared to the triceps record.

Figure 6.5 Agonist (triceps) and antagonist (biceps) electromyographic activity in a rapid elbow extension action.



Reprinted from W.J. Wadman, 1979, "Control of fast goal-directed arm movements," *Journal of Human Movement Studies* 5: 10. By permission of W.J. Wadman.

The distinctive triple-burst EMG pattern is prominent in [figure 6.5](#), first identified in the 1920s by the German physiologist Wachholder (see Sternad, 2001; Sternad & Corcos, 2001). A burst of the agonist (triceps) muscle occurs first, and then the agonist is turned off and the antagonist (biceps) is turned on, presumably to bring the limb to a stop. Then, near the end of the action, the antagonist muscle is turned off and the agonist comes on again, probably to cause the limb to be “clamped” at the target, dampening the oscillations that could be produced. The exact nature of this pattern of EMG activation depends on various task-related parameters (Sternad & Corcos, 2001).

A question of interest for these kinds of actions is how the motor system controls the timing of these events—how does it “know” when to turn off the triceps activity and turn on the biceps activity? This question becomes much more complex when applied to skills for which many muscles turn on and off at particular times, such as in pole-vaulting, as well as swinging a sledgehammer. The closed-loop account of movement behavior involving the stages of information processing could account for these features of the movement by indicating that the system monitors the position of the limb (perhaps by sensing the joint angle) and waits until the limb is at some particular position before turning off the triceps and turning on the biceps. That is, the system could use the feedback from the responding limb to trigger the end of activity in one muscle and initiate activity in the other.<sup>2</sup> However, a number of fundamental difficulties arise with this idea about the control of actions, as discussed next.

## Degrees of Freedom Problem

One difficulty for the closed-loop model, and for any other model holding that the contractions of the various muscles are handled by direct commands from higher centers, was raised by the Russian physiologist Nikolai A. Bernstein (see “Nikolai A. Bernstein” in chapter 1). Bernstein’s idea was that if the information-processing system were involved in the production of all the decisions about each of the muscles participating in a motor act, it would be difficult to imagine how this would explain all of the mental work involved in producing even a simple act like that shown in [figure 6.5](#). The fundamental concern is that the system has too many *independent states* that must be controlled at the same time. These independent states are called *degrees of freedom*.

As an example, consider a simple arm movement. Each joint is capable of moving independently, having at least one degree of freedom that must be controlled in an action. And some joints have two degrees of freedom, such as the shoulder, which can (a) allow the hand to move in a half sphere with the elbow “locked” and (b) rotate the shaft of the arm, independently. The degrees of freedom problem is compounded further because each joint has a number of muscles acting on it, and each of these muscles is made up of hundreds of motor units that also must be controlled. All of the independently moving parts would lead to an impossible situation for the central nervous system if it had to control these degrees of freedom individually by conscious decisions (see also Greene, 1972; Whiting, 1984).

In searching for answers about how we control movement, a good question is *How can the very many degrees of freedom of the body be regulated in the course of activity by a minimally intelligent executive intervening minimally?* (Kugler, Kelso, & Turvey, 1980, p. 4). The idea is that an executive level should not be thought of as having much responsibility for the control of the many degrees of freedom; there are simply too many degrees of freedom for even an intelligent executive to control and yet still have capability left over to do anything else.

On other grounds, for many years scientists have thought that *actions* are controlled, not the individual degrees of freedom such as muscles or motor units. When we perform an action, we seem to be aware of the goal of the movement, its global action pattern, and its effect on the environment; but we are hardly aware at all of the particular muscles used and are never aware of the particular motor units involved. Therefore, if the executive does not have the responsibility for controlling the degrees of freedom, how *are* the many degrees of freedom controlled, and how can the elegant, skilled organization of the muscles and joints be achieved?

This general question has been of fundamental concern since scientists began to think about movement skills. One solution has been to postulate a structure, subordinate to the executive, which can account for the particular organization required among the separate degrees of freedom. These theoretical structures, called *motor programs* by many (e.g., Brooks, 1979, 1986; Henry & Rogers, 1960; Keele, 1968, 1986; Keele, Cohen, & Ivry, 1990; Lashley, 1917; Schmidt, 1975b, 1988), have the capability to influence the activity of the many independent degrees of freedom so that they act as a single unit. If this temporary organization can be imposed on the system, then the problem for the executive will have been simplified so that only a single degree of freedom will need to be controlled. In other words, the executive level is thought to control the selection of a motor program, ready it for action, and initiate it at the proper time. Once under way, the program controls the activity of the individual degrees of freedom involved in the movement. In this sense, the executive is freed from the task of solving the degrees of freedom problem.

This kind of solution to the degrees of freedom problem sounds very simple—in fact, too simple. Explaining how all the degrees of freedom are controlled by inventing some theoretical structure (here, the motor program) does not really answer the question of control at all. The question of exactly how the various degrees of freedom are coordinated still must be addressed. The debate about the nature of this reduction in controllable degrees of freedom—in terms of what variables are controlled, when, and how—represents a truly fundamental problem for researchers in motor control. We will consider some of these questions later in this chapter and again in chapters 7 and 8.

## Agonist–Antagonist Patterning

Another argument against the idea that some executive level *directly* terminates the triceps burst of EMG and initiates the biceps burst (see [figure 6.5](#)) relates to the time available for generating these events. In the information-processing model considerable time is required to produce a response to an environmental stimulus, such as the offset of the triceps EMG and the onset of the biceps EMG. Although this model might be acceptable for very slow movements, if the action is of limited duration (as in the example in [figure 6.5](#)), the movement will be over before one of these stimulus–response processes can be completed. Something else must be involved in the activation of the various muscle groups.

This argument, however, does not rule out the possibility that the patterning has been influenced by reflexive adjustments, handled at lower levels in the motor system. As discussed in chapter 5, such processes are far faster than those involved in the stages of processing, and they might be rapid enough to account for the control entailed in these very fast actions. A number of models based on lower-level reflex control have been proposed (e.g., Adamovich & Feldman, 1984; Feldman, 1986), and considerable debate has centered on this question. Some available data, however, seem to suggest that these models are not correct either.

Wadman and colleagues' (1979) experiment had a very important, additional condition that we have not yet described. When the participant had become accustomed to the apparatus and movement task (a rapid, 150 ms, elbow extension to a target), on particular trials the lever was unexpectedly *locked* mechanically at the starting

position so that no movement of it could occur. [Figure 6.5](#) shows the EMG patterns available from these “blocked” trials, superimposed on the patterns from the “normal” trials. For approximately 110 ms after the initial agonist EMG burst, the two EMG patterns were nearly identical, with only minor modifications in the patterning afterward. The most important feature of [figure 6.5](#) is that the onset of the antagonist (biceps) EMG occurred at the expected time on these “blocked” trials—that is, it occurred at approximately the same time in the blocked trials as it did in the “normal” trials. Magill, Schmidt, Young, and Shapiro (1987) and Shapiro and Walter (1982) obtained similar results for fast movements.

Several have argued that unexpectedly blocking the limb from moving would result in reflex-like responses from various proprioceptors, and hence the EMG patterning of the blocked action cannot tell us about the originally planned pattern of action. We agree, to a point. But, what impresses us is essentially the reverse of this: The antagonist (here, biceps) EMG is turned on even though no movement of the limb occurred. The fascinating question is thus, *What process turned on the EMG in the antagonist?* Feedback (e.g., vision) from the movement could not have been processed by the stages of processing; the stages are too slow and, in any case, there was no movement. Reflex activities associated with joint movement could not do this, as there was no movement and hence no usable output from the various proprioceptors. The dynamics of the moving limb cannot be responsible for activating the antagonist, as the limb did not move and, in addition, had its dynamics severely disrupted. We are left with one theory that can handle these findings: The motor program for action was prepared in advance to govern the timing in the action, and this program continued to “run” even though the limb was blocked. That is, the answer to the question “What turned the antagonist on at the proper time (even though the limb was blocked and prevented from moving)?” is *The motor program did.*

Using considerably slower movements, Angel (1977) found that the antagonist EMG disappeared when the movement was blocked; this suggests that sufficient time was involved for feedback to higher levels, or reflex activities, or both to have an effect on the action. This also provides evidence for the long-held view that “fast” and “slow” movements are controlled in fundamentally different ways. Simply, fast movements seem to be controlled open loop, whereas slow movements appear not to be. We will return to these ideas several more times later.

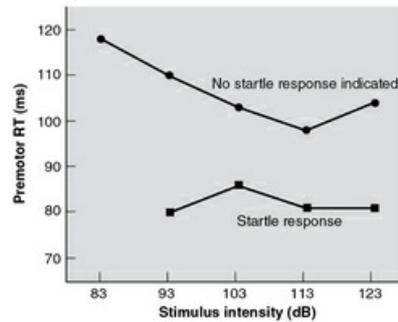
## Startled Actions

Another line of evidence, using a very different experimental paradigm, supports the conclusions we have just drawn from the study by Wadman and colleagues (1979). Our usual reaction to a very loud, unexpected sound signal is a *startle response*, which is characterized by a sudden, fast, automatic, generalized, stereotypical reaction that includes a rapid eye blink and flexion of the neck muscles; this response is clearly one of the reflex-like actions that result from certain stimuli. Valls-Solé, Rothwell, Goulart, Cossu, and Muñoz (1999) required participants to perform a large number of trials involving a movement task similar to the task used by Wadman and colleagues (1979). On a few of these trials, the visual stimulus was accompanied by a very loud (130 dB) auditory signal. As expected, the loud stimulus produced the typical startle reflex responses. Unexpectedly, however, the startle response was also accompanied by the action that the participants were prepared to make—all of the features of the triple-burst pattern seen in “normal” trials, including magnitude and timing of the EMG patterns, were also observed in these “startle” trials. However, the response was initiated about 100 ms *earlier* than in the “normal” trials! The premotor reaction times (RTs) (see chapter 2), which had averaged 171 ms on the normal trials, were reduced to 77 ms on the startle trials. And, even though the participant also produced the typical startle response (eye blink and neck reflexes), all of the movement events, including magnitude and timing of the EMG patterns, were identical to those in the normal trials.

One interpretation of these findings is that the prepared movement was still released “voluntarily,” just much earlier because auditory stimuli result in faster RTs than do visual stimuli or because the more intense stimuli produce faster RTs than less intense stimuli (Woodworth & Schlosberg, 1954). Carlsen, Dakin, Chua, and Franks (2007) provided evidence against such an interpretation, however, when they separated startle trials that produced an accompanying EMG activation in the neck (sternocleidomastoid muscle) from those trials that did not (presumably, the former trials were ones in which an actual startle response occurred). [Figure 6.6](#) illustrates their main results. Even though louder auditory stimuli produced a faster premotor RT than softer stimuli (by about 20

ms), the trials that produced a neck response (indicating a startle) resulted in premotor RTs that were 20 to 30 ms shorter than in trials without the startle response indication. Also, responses in these “true” startle trials were independent of the loudness of the stimulus—all stimuli that produced a true startle response had premotor RTs of about 80 ms. This suggests that a startle had a role in these findings.

Figure 6.6 Increases in stimulus intensity produce faster premotor reaction times (RTs) in the absence of a startle response. In the presence of a startle response indicator (sternocleidomastoid muscle electromyographic activity), premotor RTs were reduced by 20 to 30 ms and immune to stimulus intensity effects.



Adapted from Carlsen et al. 2007.

Because the visual and auditory stimuli were presented at the same time, it is possible that an intersensory facilitation effect occurred, in which the two stimuli somehow “combined” to produce facilitation (Gielen, Schmidt, & van den Heuvel 1983; Schmidt et al., 1984). However, two pieces of evidence argue against such an interpretation. First, the premotor RT (77 ms) and observed RT (104 ms) were much shorter than would be expected for a voluntary response. Second, in the postexperiment questioning, two-thirds of the participants claimed that “something other than their own will was making them move” (Valls-Solé et al., 1999, p. 935), even though none of the participants was aware of the speed-up.

Valls-Solé and colleagues (1999) argued that the motor program is stored in subcortical structures of the brain (see Valls-Solé, Kumru, & Kofler, 2008, for a review of the evidence). The presentation of the startle stimulus results in an involuntary “release” of the motor program, in advance of the voluntary initiation that would have occurred in response to the regular (visual) stimulus. Valls-Solé and colleagues’ (1999) procedures and findings have been replicated using similar tasks (e.g., Carlsen, Chua, Inglis, Sanderson, & Franks, 2004; Oude Nijhuis et al., 2007; Siegmund, Inglis, & Sanderson, 2001) and also using saccadic eye movement responses (Castellote, Kumru, Queralt, & Valls-Solé, 2007). Another implication of the Valls-Solé interpretation is that response execution and selection are processes occurring early in information processing as the motor program is just waiting to be “triggered.” These results provide another convincing line of support for the idea that fast movements are organized in advance via motor programs.

## Inhibiting Actions

In the next sections we examine some of the evidence about the performer’s capabilities to *inhibit* a movement, even before it has been initiated. This information is closely related to the findings presented in chapter 4 (e.g., psychological refractoriness), and the two kinds of findings seem to blend well to provide a picture of what happens during the course of a rapid action.

### *Anecdotal Evidence*

Evidence from personal experience is quite difficult to interpret, for the strong possibility exists that what we think we do is not what actually occurs, leading to a false picture of movement control processes. Even so, some of our common observations guide us to experiments in which the ideas can be studied more carefully.

Long after his work with the wounded patient, Lashley (1951) provided an example of a skilled pianist playing a piano with a broken key that could not be depressed. As the pianist played a string of notes, the attempts to press the broken key did not interrupt the sequence of actions at all. In fact, only after the entire sequence was completed did the individual notice and remark that the key was broken. This suggests that the actions do not appear to be structured with feedback to “verify” that a certain finger movement has been made before the next one is commanded. The feedback appeared to be only minimally involved in the production of the movement

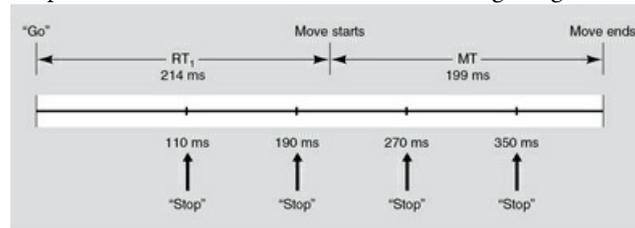
sequence (see also Gordon & Soechting, 1995). Another example is buttoning a shirt, an activity that sometimes continues in its fine detail even if a button is missing. Again, feedback from the fingers is probably not critically involved in the production of this sequence of movements. But, this seems to contradict the finding that striking a match was seriously impaired by anesthetic applied to the cutaneous receptors of the fingertips. More work is needed in this area to resolve these uncertainties.

The British psychologist Bartlett expressed similar views about the lack of role for feedback in certain ball sports. Bartlett (1958) suggested that the “launching” of an action signals a *point (or region) of no return*—beyond which attempts to modify the action are largely unsuccessful. In the next sections, we describe some experimental approaches to examine these issues.

### *Inhibiting Rapid Discrete Actions*

Henry and Harrison (1961) presented one of the first experimental analyses of these questions. Participants placed a finger on a key located at their hip and, at a “go” signal, moved the arm forward and upward to trip a string located in front of their right shoulder. Participants moved as quickly as possible. The simple RT in these control trials was 214 ms on the average, and the movement time (MT) was slightly shorter at 199 ms. On some trials, a second “stop” signal would occur, indicating that the participant should *avoid* tripping the string or at least try to begin to slow the limb as quickly as possible. The “stop” signal could come on at one of four times: 110, 190, 270, and 350 ms after the “go” signal. [Figure 6.7](#) shows the timing of the essential details of the experiment, indicating where the “stop” signals could come on relative to the observed RT and MT durations.

Figure 6.7 A timeline showing the critical events in the Harry-Harrison experiment. (“Stop” signals were presented at various times after an initial “go” signal.)



The primary result of interest to Henry and Harrison was the time taken to *begin* to decelerate the limb after the “stop” signal was presented. They found that only when the “stop” signal was given at the very earliest of the presentation times (the 110 ms location) was there a tendency for the participants to even *start* to slow the movement before it had been completed. But the more interesting feature of these data is the participant’s response in the 190 ms condition. Notice here that the “stop” signal came on 24 ms *before* the movement even started, and yet the movement was carried out without interruption. That is, a signal presented before the movement was not effective in modifying that particular movement, even when the movement lasted for 199 ms (see Gao & Zelaznik, 1991, for a different inference and analysis).

If the information-processing stages are too slow to be involved in the details of a particular action, and segmental reflexive control is not involved either, then (as we have argued earlier in this chapter) these movements must be *preprogrammed*, structured in advance, and run off as a unit without much modification from events in the environment. An additional interpretation is that, once some internal “go” signal is issued, the action occurs and cannot be stopped, as in pulling the trigger on a gun. The initiation of the internal “go” signal represents the point of no return. When the (external) “stop” signal was presented 104 ms before the overall response was to begin, the response began anyway, and an additional 110 ms or so was required to even begin to modify it.

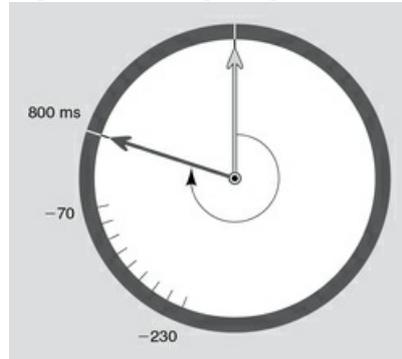
Logan has performed many of the recent experimental and theoretical analyses using this “stop signal” paradigm (reviewed in Boucher, Palmeri, Logan, & Schall, 2007; Logan, 1994; Verbruggen & Logan, 2008). In one of these studies, skilled typists typed phrases as rapidly as possible but to stop their typing upon presentation of a “stop” tone (Logan, 1982). In general, the typists produced one to two additional letters after the “stop” tone occurred (about 200 ms of MT), regardless of the specific position within the word at which the tone was presented. However, there were several notable exceptions; one occurred with the word “the.” Logan (1982) found that typists would almost always produce the entire “the,” and the *space* after it, and that this occurred even when the “stop” signal was provided on the last letter of the previous word. Given that “the” is the most frequently used word in the English language (Kucera & Francis, 1967), typists have probably developed a very highly overlearned motor program for typing it—one whose entire execution is difficult to inhibit after the internal “go” signal has been issued. At what point in the RT to a signal are we committed to action? In other words, when does the point of no return occur? An experiment by Slater-Hammel (1960) helps to answer this question; as well, it supports some of the other points just made about movement programming.

### *Inhibiting Anticipatory Actions*

In Slater-Hammel (1960) participants watched a sweep timer that made one revolution per second and responded by lifting a finger from a key to stop the clock at the moment when the timer reached “8” on the second revolution (i.e., 1.8 revolutions after the clock hand started). The participant could not, of course, wait until the clock hand had actually arrived at “8” before planning and initiating the movement, because the finger lift would be far too late. So the participant had to anticipate the movement of the clock hand, together with the lags in the information-processing and neuromuscular systems, so that the finger was lifted at precisely the correct time. Slater-Hammel added an interesting condition, however. Occasionally, unpredictably from the viewpoint of the participant, the experimenter stopped the clock hand before it reached “8.” The participant was instructed to *not* lift the finger from the key if this happened—that is, to do “nothing.” Slater-Hammel set up the experimental conditions such that the primary task (stopping at the “8”) was required on about 75% of the trials. On the

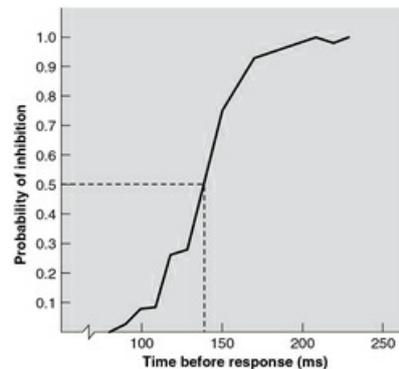
remaining trials, the clock hand could stop randomly at some point prior to the target point at “8.” The critical events of the experiment are illustrated in [figure 6.8](#).

Figure 6.8 The task used by Slater-Hammel (1960). The sweep hand of the chronoscope normally made a full revolution in 1 s (1,000 ms). The participant's primary task was to stop the sweep hand of the chronoscope on its second revolution precisely on the 800 ms mark by lifting a finger off a response key. If, however, the sweep hand stopped prior to the 800 ms point, then the participant was to try to inhibit the finger lift.



The measure of most interest to Slater-Hammel was the probability of the participant's *inhibiting* the finger lift successfully as a function of the time before "8" when the clock hand was stopped by the experimenter. [Figure 6.9](#) presents the probability of successful inhibition as a function of the time before "8" when the clock hand stopped. If the clock hand stopped 250 ms before "8," the participant would probably have had no trouble inhibiting the movement, as the stages of processing would seem to have ample time to inhibit it. Conversely, if the clock hand stopped only 50 ms before the clock reached "8," the participant should never have been able to inhibit the movement. That is essentially what Slater-Hammel found. But notice that as the time before "8" decreased from about 170 ms, the probability of successfully inhibiting the movement decreased sharply; the probability was about 0.5 when the interval before "8" was 140 ms. Another way to state this finding is to say that if the clock hand stopped 140 ms before "8," the participant could successfully inhibit the response about half the time. In our interpretation, this result says that, at 140 ms before the finger lift (on average), the participant irrevocably triggered the action.

Figure 6.9 The probability of successfully inhibiting anticipated finger lift as a function of the interval before the critical event.



However, this number needs to be adjusted slightly. Although this median (50%) point occurred at 140 ms before “8,” Slater-Hammel’s participants responded a little late on average (constant error = +26 ms, responding at the 826 ms point on the clock, rather than at the “8,” or 800 ms mark). Because our first estimate of the point of no return (140 ms) presumed that participants responded to the primary task with no error (i.e., assuming a CE = 0), we must therefore add (as Slater-Hammel [1960] did) the 26 ms to the 140 ms to obtain 166 ms as the estimate of the time before “8” that the internal “go” signal must have been produced. Thus, these data provide one estimate of a point of no return at 166 ms before the action.

A number of important interpretations may be derived from this thinking. First, the finding that the participant could not inhibit a movement once it was internally planned and initiated supports the observations made about the Henry and Harrison (1961) study and the typing of the word “the” shown by Logan (1982). Apparently, once the participant has *committed* to action, the movement occurs even when some signal is presented in the environment shortly afterward indicating that the action should not be performed. As mentioned in chapter 4, inhibiting preplanned actions requires time and attention, an idea supported by these data.

Students do this experiment in the laboratory sections of our courses; they *see* that the clock hand has stopped, but their hand then responds anyway. The subjective feeling is that they do not have control over the hand, where “they” refers to “their consciousness.” The point of no return appears to represent the point at which conscious control of the hand has been transferred, with the hand now subservient to the motor program instead (Osman, Kornblum, & Meyer, 1990; see also De Jong, Coles, Logan, & Gratton, 1990). These ideas of conscious control, and related concepts such as “intention” or “will,” which were the source of philosophical debate for centuries, have resurfaced in recent years (e.g., Haggard, 2008; Libet, 1985) thanks to modern techniques used to record what the participant is doing in various “stop signal” tasks. Among such measures are the EMG activity of the effectors (McGarry & Franks, 1997), including activities in the motor neuron pools in the cord (H-reflexes; McGarry, Inglis, & Franks, 2000), and various measures of neurophysiological activity (Band & van Boxtel, 1999). Sometimes actions are either completely inhibited or not (i.e., they are performed as originally intended). In other instances, however, researchers have identified responses that have been interrupted, for example, by means of a partial reduction of motor neuron pool activation (e.g., McGarry & Franks, 1997). Findings such as these have resulted in a controversy regarding the location of the point of no return—some arguing that the location is at a high level of the central nervous system such as the cortex (Band & van Boxtel, 1999; van Boxtel & Band, 2000), with others suggesting that it is at a lower level in the central nervous system (McGarry & Franks, 2000).

Regardless of the exact neural location of the point of no return, a theory of how the process works applies equally well. The theory, developed by Logan (1994; Band, van der Molen, & Logan, 2003; Boucher et al., 2007; Logan & Cowan, 1984), regards the inhibition of action as a kind of *horse race*. One horse, the “start horse,” represents a command that is sent to the motor neuron pool to execute the preprogrammed response. The other horse, the “stop horse” represents a command sent to halt the execution. The horse that reaches the “finish line” first (here, the lower centers involved with movement production) “wins”—thereby determining whether or not the

movement is executed or inhibited. In this way, it is possible to model situations in which total and partial inhibition and execution occur (Boucher et al., 2007; McGarry, Chua, & Franks, 2003; McGarry & Franks, 1997). Extensions of this research have been used to explain more complex actions, such as “checking” a swing in baseball batting (see “The Checked Swing in Baseball”).

## Programming Rapid Movements in Advance

In chapter 3, we introduced the idea that in a response-programming stage the person selects, organizes, and initiates a program of action that will produce a series of muscular activities resulting in an action. According to this model, the program must be structured completely (or almost completely) in advance, before the movement can be initiated, and very little modification will occur in the movement for the next few hundred milliseconds or so. We saw evidence for this also in situations in which the limb was blocked from moving, with the pattern of EMGs being unaffected (as compared to unblocked moves) for the next 100 ms or so (Wadman et al., 1979). We also saw evidence that a startling stimulus can “release” a complete, preplanned action far earlier than would be the case if it was released “normally” via the stages of processing (Valls-Solé et al., 1999). Another line of support for this hypothesis is the evidence that certain variables, related to the “complexity” of the movement to be made (i.e., the number of limbs or movement segments, the movement’s duration, or both), tend to affect the time between stimulus and the beginning of the movement (i.e., the RT; Henry & Rogers, 1960). More complex, and longer-duration (but still rapid) movements produce a longer RT (Christina, 1992; Klapp, 1996). Researchers think these effects occur because the complexity of the movement affects the duration of the stage necessary for completing this preprogramming (Henry & Rogers, 1960; Schmidt, 1972b; Schmidt & Russell, 1972). Many of these ideas are far from new; the original notion dates back to thinking by James (1890) and Lashley (1917), and more recently to Henry and Rogers (1960), Keele (1968), Schmidt (1976a), and Brooks (1979). Early thinking on how motor programs might be structured is credited to Karl Lashley (see “K.S. Lashley on ‘Motor Programs’”; see also Rosenbaum, Cohen, Jax, Weiss, & van der Wel, 2007). However, remember the earlier description of the program as an encapsulated package that is just triggered. This viewpoint would not lead us to expect any effects of complexity on RT.

As a result of this thinking, at least two levels can be distinguished in the motor system: (a) an executive level (including the information-processing stages) for selecting, organizing, and preparing and initiating a complex pattern of muscular activities and (b) an effector level (motor programs and the muscular system) for actually controlling or producing the patterns as they unfold. Gentile (1998) also made a similar distinction. Her model has an internal representation of the spatial-temporal structure of the movement, and it has a force control module responsible for the actual execution processes, much like the manner in which we have described the motor program. We can further distinguish these two levels by examining two distinct types of errors that can occur in performance, which we describe later in the chapter. That said, however, we have already presented evidence that such a view can explain only a limited set of movement situations, as many examples can be cited in which feedback processes seem to interact with open-loop processes in the production of movement. A more complete approach to motor programming would be to ask *how* the sensory processes operate together with (i.e., cooperate with) these open-loop processes to produce skilled actions. We turn to some of these ideas in the next sections.

## Sensory Information and Motor Programs

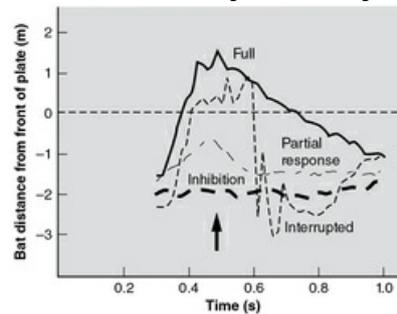
The next sections deal with various functions of feedback in movement control. We can conceptualize these functions as acting before a movement, during a movement, and after a movement.

### The Checked Swing in Baseball

Batting in baseball is a good example of a case in which inhibitory processes are likely to operate. In baseball it is not uncommon to observe a “checked swing”—the batter has started to swing, but at some point after the pitcher has released the ball, the batter tries to stop the swing instead. If the “inhibit swing” decision occurs soon enough, the bat can be stopped before it crosses the plate (after this point, if the ball is not contacted, the swing is considered an attempted swing and is called a strike). But how is this inhibition process carried out?

Recall that Slater-Hammel measured only two kinds of behavior—release of the key or not. In baseball batting, these two behaviors would be analogous to (a) the full swing and (b) the nonswing, or fully inhibited swing. However, studies of baseball batting have revealed two other types of swing behavior, called (c) *partial response* and (d) *interrupted outcome* (Gray, 2009a; McGarry & Franks, 2003). The partial response occurs when the batter initiates bat movement toward the contact point with the ball (above the plate) but with less velocity than in the full swing (see the lighter dashed line in [figure 6.10](#)). With the interrupted outcome, the swing is initiated with the same velocity as the full swing but undergoes a sudden alteration in kinematics prior to its completion (see the darker dashed line in [figure 6.10](#)).

Figure 6.10 Sample bat displacement–time profiles for four types of baseball batting swings: full, interrupted, partial, and fully inhibited. The arrow represents the point when the ball crossed the plate.



Adapted, by permission, from R. Gray, 2009, "A model of motor inhibition for a complex skill: baseball batting," *Journal of Experimental Psychology: Applied* 15: 91-105. Copyright © 2009 by American Psychological Association.

Using a batting simulation task in which batters were instructed to swing only at pitches that were predicted to arrive in the strike zone, Gray (2002, 2009a) found that "stop signals" were executed based on pitch predictions and three distinct types of ball information. Gray modeled pitch predictions (pitch speed and location) using variables that baseball players frequently rely upon to make predictions about an upcoming pitch (e.g., the ball–strike count; location and speed of recent pitches). The earliest ball information used to determine if a pitch would arrive out of the strike zone was the *launch angle* of the ball as it left the pitcher's hand; this was used most frequently for pitches that resulted in a fully inhibited swing. The discrepancy between the predicted and actual *speed* of the pitch as it approached the strike zone was used in the majority of cases that resulted in a partial response. And the discrepancy between the actual and predicted *horizontal height* (above the plate) of the pitch was the information picked up latest in the ball flight trajectory, resulting in the most frequent occurrence of interrupted outcomes.<sup>3</sup>

Of most importance for the batter, however, were the results of these attempts to inhibit the swing—95% of the partial responses resulted in a successfully checked swing (i.e., stopped before the bat crossed the plate), whereas only 41% of the interrupted outcome swings were checked successfully. Therefore, different ball flight characteristics (speed and location) were most frequently associated with specific inhibitory processes (partial responses and interrupted outcomes, respectively), which dramatically affected the probability of swinging at a pitch that was out of the strike zone. These analyses provide an understanding of how inhibition processes are regulated in everyday, complex activities based on the interaction of visual information and prior expectations.

## K.S. Lashley on "Motor Programs"

### Research Capsule

Karl Lashley's (1951) paper, "The Problem of Serial Order of Behavior," represented a death blow to the behaviorists' influence on views of motor control. In this seminal paper, Lashley described an early and very clear implication for an open-loop central control mechanism. Although he did not specifically refer to the term "motor program," Lashley set the stage for a strict view of the motor program. An early definition was "a set of muscle commands that are structured before a movement begins, and that allows the entire sequence to be carried out uninfluenced by peripheral feedback" (Keele, 1968, p. 387).

Lashley said, "A series of movements is not a chain of sensory-motor reactions . . . I had the opportunity to study a patient who had a complete anesthesia for movements of the knee joint, as a result of a gunshot

wound of the cord (Lashley, 1917). In spite of the anesthesia, he was able to control the extent and speed of movements of flexion and extension of the knee quite as accurately as can a normal person. The performance of very quick movements also indicates their independence of current control. "Whip-snapping" movements of the hand can be regulated accurately in extent, yet the entire movement, from initiation to completion, requires less than the reaction time for tactile or kinesthetic stimulation of the arm, which is about one-eighth of a second, even when no discrimination is involved. Such facts force the conclusion that an effector mechanism can be preset or primed to discharge at a given intensity or for a given duration, in independence of any sensory controls" (pp. 122-123).

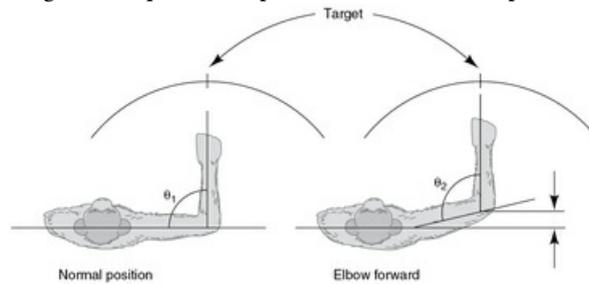
He also said, "I believe that there exist in the nervous organization, elaborate systems of interrelated neurons capable of imposing certain types of integration upon a large number of widely spaced effector elements. . . . These systems are in constant action. They form a sort of substratum upon which other activity is built" (pp. 127-128).

### *Prior to the Movement*

One of the major roles of sensory information is almost certainly to provide information about the initial state of the motor system prior to the action. Consider this simple example: You must know whether you are standing with your left or right foot forward in order to initiate a walking pattern (Keele, 1973). The spinal frog requires sensory information from the forelimb in order to direct the hindlimb to the elbow during the wiping response. Such information is presumably provided by afferent feedback from the various proprioceptors, and it would seem to be critical for the selection and adjustment of the proper action. We argued in chapters 2 and 3 that these processes are very important for open types of skills, for which the nature of the environment is unpredictable or constantly changing.

Polit and Bizzi (1979), using deafferented monkeys, showed that when the initial position of the shoulder changed prior to the elbow action, a systematic error in pointing to the target position occurred. This is understandable from [figure 6.11](#), because changing the shoulder angle as shown necessarily affects the *elbow angle* (from  $\theta_1$  to  $\theta_2$ ) required for pointing at a target in a given position in space. If the monkey programmed a given elbow angle, then the *equilibrium-point mechanism* (chapter 7) would achieve that angle, and the arm would not be pointing to the proper target. These monkeys did not learn to point to the target, even after considerable practice. By contrast, normal, intact monkeys learned in a few trials to compensate for the shifts in the shoulder position. The interpretation is that the intact animals had feedback from the shoulder joint and could adjust the angle at the elbow to compensate for the change in the shoulder angle. Thus, feedback about the initial positions of the joints is required when pointing to a position in space if the environment is not perfectly predictable.

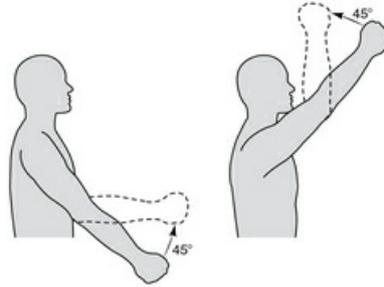
Figure 6.11 In pointing to a target, the equilibrium point of the elbow is dependent on the angle at the shoulder.



Reprinted, by permission, from M.H. Polit and E. Bizzi, 1979, "Characteristics of motor programs underlying arm movements in monkeys," *Journal of Neurophysiology* 41(1): 183-197.

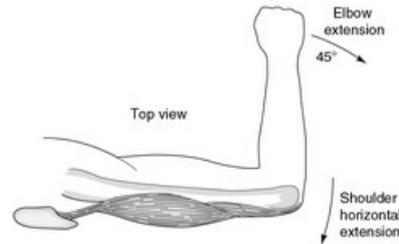
Another role of afferent information has been called *functional tuning* (Fitch, Tuller, & Turvey, 1982; Turvey, 1977). Recall that the spinal apparatus and resulting limb force output could be affected by change in the head position, much as would be expected on the basis of the idea that the tonic neck reflex was involved in the action (Hellebrandt, Houtz, Partridge, & Walters, 1956). In this example, afferent information from the neck influences the spinal mechanisms prior to action, thereby facilitating or inhibiting them. But a more compelling reason for assuming that premovement tuning occurs relates to some simple facts about the nature of the motor apparatus. In [figure 6.12](#) are two diagrams of a hypothetical rapid movement. In both cases, the movement involves flexion of the elbow, a distance of  $45^\circ$ , beginning with the arm straight. On the left, the upper arm is positioned  $45^\circ$  below the horizontal, so that a flexion of the elbow will result in the forearm's being horizontal at the end. On the right, the upper arm is  $45^\circ$  above horizontal, so that the forearm will be vertical at the end. The same command signal delivered to the biceps muscle group will not "work" in both situations, for two reasons. First, a force is required to hold the forearm against gravity at the target position in the first situation, but not in the second. Second, more force is required to move the forearm against gravity in the first example relative to the second. A logical conclusion from this simple example is that the motor system must account for the position the shoulder is in prior to the action so that the command to the elbow flexors can produce the required  $45^\circ$  movement. How this happens is not entirely clear, but *that* it happens seems nearly obvious.

Figure 6.12 Two 45° elbow flexion movements that appear to require different commands for the action and different forces at their end points because of the effects of gravity.



Consider another complicating factor facing the motor system in producing a movement. [Figure 6.13](#) is a schematic diagram of the muscle attachments involved in a simple movement. This time, imagine that the movement is an extension movement in which the elbow is to be moved through 45°. Notice that the triceps muscle, which is the primary elbow extensor, is attached to the humerus in two places (internal and external heads) and to the scapula of the shoulder area (the long head). Thus, the triceps muscle performs two actions when it contracts: It extends the elbow and it tends to extend the shoulder joint, pulling the humerus back. Therefore, when the triceps is contracting to produce the 45° movement, one of the muscles that flexes the shoulder must contract so that the shoulder joint is stabilized and only the elbow moves. Thus, during this simple extension movement, the motor system must “know” that a two-jointed muscle is involved and produce some compensatory stabilization. The amount of stabilization will be dependent on the shoulder angle because of the length–tension relation (see chapter 7).

Figure 6.13 Complexity in a 45° elbow extension movement caused by the fact that the triceps muscle both extends the elbow and horizontally extends the shoulder.



The picture that emerges from these observations is that a “simple” 45° movement of the elbow joint is not really that simple at all, at least in terms of the motor system. In addition, other complicated aspects of the muscle need to be considered by the motor system, such as the nonlinear relationship between the muscle force and limb velocity, together with aspects of the contraction process that make the motor system very difficult to predict and control (Partridge, 1979, 1983). We all know that our nervous system controls our limbs beautifully in these “simple” situations. How it does so is exciting to ponder.

Bernstein (1967) also recognized the problem that the central nervous system has in determining muscle activation. Imagine drawing a circle repetitively on a tabletop with a pencil. Now imagine performing the same task while drawing on a wall. In the first case, on the tabletop, the limb attached to the pencil does not have to worry about gravity. However, in performing the same task in the anterior–posterior plane when moving down, gravity is speeding up the movement; when moving up, the opposite occurs. This observation leads to the inference that simply having an internal memory model for the EMG pattern for circle drawing will fail, because the central nervous system needs to comply with the changing gravitational influence. Such problems have caused other theorists to question the motor program as a prescription for muscle commands (Michaels & Carello, 1981; Turvey, 1990).

One role that feedback seems to have during movement production is a monitoring function, whereby the feedback from the movement is taken in and processed but not necessarily used in the control of the action unless something goes wrong. It is probable that a long string of actions dealing with finger movements in piano playing is programmed and carried out open loop. Feedback from the fingers is returned to the central nervous system for analysis, as if the central nervous system were “checking” for errors. If no errors appear, then the feedback is ignored. But if the feedback indicates that an error has occurred, attention can be directed to that feedback source, and an appropriate correction may be initiated. Reflexive corrections may also be generated, as discussed in chapter 5.

A second way to view feedback is that it may be intricately involved in the physical control of the limb. We mentioned a number of examples of this in the preceding chapter. The possibility exists that a constantly changing reference of correctness is specified by the gamma motor neurons to the muscle spindles and that their actions result in a continuous set of corrections to keep the movement on the proper course. The feedback could be involved in the determination of the end location of a movement if the reference of correctness were set for this position. And in repetitive movements, the feedback from early segments of the sequence can provide adjustments for the later segments.

### *Following the Movement*

Extensive feedback is also delivered to the central nervous system after a movement. Such information can be evaluated, presumably, by the stages of information processing in order to determine the nature (or “quality”) of the movement just made. Information about whether or not the movement achieved the environmental goal and about its smoothness, its level of force or effort, or its form or style is derived from sensory feedback. A major role for such information is in the adjustment of the movement on the *subsequent* trial, perhaps to reduce the errors made on the present trial. As such, this information has a considerable relevance to the acquisition of skills, as

discussed in the final part of this book dealing with motor *learning* (chapters 12 and 13 in particular).

## Types of Motor Program Errors

If, as we suspect, the motor system can be conceptualized as consisting of two major parts (an executive level and an effector level), we can ask about the origins of errors in each—including their causes, their detection, and their correction. We conceptualize the motor system as being capable of making essentially two distinct types of errors. Each of these errors involves feedback in distinctly different ways for their detection and correction. We discuss these two kinds of errors in the next sections.

When a person makes a rapid movement, there are really two goals (Schmidt, 1976a). First, there is an environmentally defined goal, such as changing gears in a standard transmission car or doing a somersault from a diving board. A second goal (or subgoal) can be defined in terms of the muscular activities required to produce the desired outcomes in the environment—that is, to produce the first goal. For example, a person must contract the muscles in the arm and torso in one of a limited number of ways in order to change gears smoothly, and only certain patterns of muscular activity will result in a somersault. Essentially, how to generate such a subgoal is the problem facing the performer.

We can view the subgoal as a pattern of action that is structured in both space and time. Such a pattern of action will determine where a particular part of the body will be at a particular time after the movement starts. If this spatial–temporal pattern in the muscles and limbs (the subgoal) is produced accurately, then the environmental goal will be achieved. This process can go astray in essentially two ways.

### *Errors in Program Selection*

Given the assumptions about the spatial–temporal goal, the first kind of error that the person might produce can be defined as an error in *program selection*. This kind of failure to achieve the environmental goal results from the performer's choice of action. This error can happen in a number of ways (Reason & Mycielska, 1982). First, the person can produce the wrong pattern of action: for example, heading versus kicking a ball in soccer, moving right when a left move is appropriate, or moving when it might be important to stand still. The outcomes are the result of apparently intentional decisions about what to do and, in our terms, represent inappropriate *choices* of a program of action. Such errors can arise from a variety of sources, such as a faulty perception of the environment (e.g., the speed of an oncoming car by a pedestrian crossing the street) or an error in the choice of a goal (e.g., to pass to teammate A when a pass to teammate B would have been better).

How does a person make a correction for an error in program selection? According to the evidence presented earlier, the person must issue a *new* motor program, as the “old” one will not achieve the goal in the environment. Hence, the information-processing stages must be initiated again; a new program must be selected in the response-selection stage, and it must be programmed in the response-programming stage. Because all of these stages are time consuming, the result is that a new pattern of action in a rapid motor skill usually cannot be selected before the movement has been completed and the error has occurred. If the movement has a somewhat longer MT, however, then a correction for an error in selection is possible during the action.

### *Errors in Program Execution*

An error in program execution is fundamentally different from an error in program selection (Schmidt, 1976a). An error in execution can occur if the person produces a program of action appropriate for the environment but some unexpected event occurs that disrupts the movement. This can happen, for example, if the contractions specified by the motor program are not quite achieved by the muscles, perhaps because of inconsistencies in the spinal cord where it is determined which of the many motor units are to be activated. The basketball player attempting a free throw shot selects the proper action (making no selection error), but random noise in the central nervous system often causes the shot to miss its target because of an error in execution. Sometimes the mass or

friction of the objects in the environment is not estimated quite accurately before the action, such as when you pick up a nearly empty milk carton that you thought was nearly full; the initial part of the action is much too rapid. Sometimes the resistance offered by the environment increases unexpectedly, slowing the action and making it miss its mark. Many other examples can be used of course, including one that occurs occasionally in driving (see “Pedal Misapplication Errors”).

## Pedal Misapplication Errors

The concept of two types of errors (selection and execution) has a wealth of applications to real-world situations, one of which is automobile accidents. Consider the following situation.

A driver enters his car (with automatic transmission) and prepares to drive forward. He reports that he started the car, placed his right foot on the brake, and shifted the transmission to Drive. The car roared away under what seemed to be full throttle, and the brakes were completely ineffective in stopping the car (“The brake pedal went to the floor”) until the car struck a wall after about 8 s of travel. The driver claims that the car malfunctioned, but a subsequent inspection of the vehicle (by experts, car makers, three federal government agencies, or independent research firms) reveals nothing wrong with the car. Incidents essentially like this have occurred more than 10,000 times since the mid-1980s and are now referred to as *unintended acceleration* cases, involving *pedal misapplication errors*. What can be going on here?

A leading theory to explain these events is that the driver in some way placed his foot on the accelerator pedal rather than the brake (see Reinhart, 1994; Schmidt, 1989b, 1993). But why would a driver with, in some cases, 50 years of driving experience choose the wrong pedal after never having done so before? The important word in this question is “choose.” It is certainly difficult to imagine that the driver made an error in the choice of the accelerator pedal rather than the brake—what we call here a selection error—and, in fact, the driver emphatically claims not to have done so.

Rather, imagine that the driver intends to press the brake as usual, and the executive level programs and initiates an action to do so. The executive passes control to the program, and the program controls the muscles and limbs, while the executive shifts attention to vision or other sources of information relevant for driving. However, (a) because the driver is slightly misaligned after having just entered the car or (b) because of variability in the neuromuscular processes (see chapter 7, impulse variability)—or because of both—the foot on this occasion turns out to be aimed at the accelerator rather than the brake (the intended goal) and a pedal error occurs. This represents an error in execution, as the correct action was selected and produced, but it was executed or aimed (or both) inappropriately. Now, when the shift lever reaches Drive, the car lurches forward, and the startled driver’s response is to press harder on the “brake”. But, because his foot is actually on the accelerator, the car goes faster, he presses harder, it goes even faster, and so on, until the car hits the wall.

In these situations, the driver “knows” (incorrectly, however) that his foot was on the brake because that is where the executive level ordered the foot to go. Lower-level processes have caused the error, and the executive level has no information about them. The driver’s response to the unexpected acceleration is to make a very fast correction at the execution level (to press the “brake” harder), a kind of triggered reaction that actually makes the situation worse. Because of the hypervigilance (or “panic”; see chapter 4) associated with the unexpected acceleration, he does not consider that the foot is on the accelerator, hence does not make any of a number of actions that would stop the car (e.g., switch off the ignition, shift to Neutral, etc.), which would have required initiation of a new action (see also Schmidt, 2010).

Such views are now commonly accepted in examples of unintended acceleration (e.g., Department of Transportation, 2000; Lococo, Staplin, Martell, & Sirfrit, 2012). These analyses of such automobile

accidents have involved our current understanding of the separation between errors in selection and errors in execution, the factors that control their corrections, and the separation between levels of hierarchical control. These concepts are critical in a number of analogous real-world situations.

These influences do not make the *originally* intended movement pattern incorrect, as some compensation that will achieve the originally planned spatial–temporal goal will still result in the achievement of the environmental goal. Thus, the correction for an error in movement execution may not require a new motor program, since the original pattern of action defined by the “old” program will be correct if the motor system can compensate for the unexpected environmental influences. This implies that because the system does not have to select a new motor program, the correction for an error in execution does not require all the stages of information processing and will be far more rapid than correcting for an error in program selection.

What is the evidence for this kind of correction, and is the correction for error in execution fundamentally different than that for an error in selection? Consider the example from Dewhurst (1967; [figure 5.14](#)) presented in the preceding chapter; recall that the participant was instructed to hold a weight with the elbow at a right angle. When weight was suddenly added, a correction followed in the biceps EMG within about 30 ms, and a more sustained correction followed in about 50 to 80 ms. The corrections were far faster than can be explained by the production of a new program of action; hence it seems reasonable to believe that the original program of action was modified in some way. More importantly, the person did not have to select a new program of action to compensate for the added weight, as the original spatial–temporal goal was still appropriate; the goal before the weight was added was “Hold the elbow at right angles,” and the goal afterward was still the same; the participant seemed only to require additional muscular tension in order to comply with the “old” goal. Thus, it appears that the corrections served the purpose of maintaining the *original* pattern of action and did not result in the generation of a new one. Consequently, the corrections had a far shorter latency than would be expected if it had been necessary to produce a new pattern (see chapter 5 for other examples).

What about the role of consciousness in corrections for errors in selection? Henry (1953) asked participants to try to maintain the position of a lever in response to unexpected changes in the pressure it exerted against the hand. He showed that participants were able to compensate for changes in position that were some 20 times smaller than changes they could consciously detect. The participants were responding to changes in position that they could not perceive—that is, they were responding *unconsciously*. Also, Johansson and Westling (1984; Westling & Johansson, 1984) showed that if participants began to lose grip on an object held between the fingers, compensations (in the fingers and in the elbow) could be made in approximately 30 ms, apparently without conscious awareness. In these examples, the person did not have to select a new program of action when the stimulus occurred, because the original pattern of action was still acceptable. Force changes within the context of this pattern of behavior were required, however, to maintain the movement’s overall goals. These were accomplished very quickly and without awareness and can be thought of as corrections for errors in execution.

### *Program Selection Errors Versus Execution Errors*

[Table 6.1](#) summarizes some of the fundamental features of errors in program selection and program execution, listed so that their differences can be seen more easily. These differences are important, because without testable distinctions between these error categories it would make little sense to consider them as separate classes (see also classifications of reflex responses in chapter 5 for a similar analysis, especially [table 5.1](#)).

Characteristic	Selection	Execution
Latency of correction?	120-200 ms	30-50 ms
Old spatial-temporal goal OK?	No	Yes
New program selected?	Yes	No*
Attention required?	Yes	No
More than one at a time?	No	Yes
Hick's law apply?	Yes	No?

\*Provided that the deviation from the spatial-temporal goals is not very large.  
Adapted from Schmidt 1983, 1987.

From [table 6.1](#), we can see that the latencies of the two kinds of corrections are quite different; the selection errors require 120 to 200 ms or more in order for a correction to begin, and the execution errors can be corrected far more quickly, in 30 to 50 ms. Also, a new spatial-temporal goal is needed to correct an error in selection, whereas the original pattern of action can continue while an error in execution is being produced. We know that selecting and initiating a new motor program (needed to correct an error in selection) requires attention and consciousness in the sense defined in chapter 4, and that this process will interfere greatly with certain other (cognitive) processes attempted at the same time; hence only one such correction can be done at a time. Correcting for an error in execution, on the other hand, is automatic with respect to cognitive information-processing activities, and many such corrections could presumably be done at the same time in parallel and without interference—some in the arms, some in the legs, and so on. Hick's law clearly applies when one is correcting for errors in selection (see chapter 3), with the latency increasing as the number of possible corrections increases. For errors in execution, on the other hand, the number of possible errors is probably not a factor, and so Hick's law would not be expected to apply.<sup>4</sup> All these differences, taken together, clearly argue that corrections of motor program errors are of at least two fundamental types.

### *Triggered Reactions*

The classification scheme in [table 6.1](#) is now rather old (Schmidt, 1976a, 1983), and newer research suggests it may be somewhat too simple to account for all the evidence. One good example involves triggered reactions, as discussed in chapter 5. We saw that triggered reactions were faster than RT, did not seem to require conscious processing, and did not seem to involve the selection of a new movement program—all of which would at first glance seem to place them into the category of corrections for errors in execution. But the notion of errors in execution implies that the correction serves to bring the limbs back to the original spatial-temporal goal, or *trajectory* originally selected, after a perturbation (Cooke, 1980). Yet the evidence on triggered reactions shows that the response to various perturbations is a *new* pattern of action, with a trajectory fundamentally different from the one that was occurring before the stimulus. When a given perturbation was applied, we saw altered lip and tongue trajectories in human speech (Abbs et al., 1984; Kelso et al., 1984), new hindlimb trajectories in cat locomotion (Forssberg et al., 1975), and different, coordinated patterns of elbow and finger movements in lifting tasks (Johansson & Westling, 1984; Westling & Johansson, 1984), all with very short latencies.

It is tempting to suggest that triggered reactions ensure that the *original goal* of the action is achieved—not necessarily that the *original trajectory* of the limbs is achieved. This suggestion implies that a particular trajectory of the limbs may not be as important as achieving the environmental goal. Of course, there are many ways in which the motor system can achieve a particular environmental goal; and when perturbed, the system seems to shift from one of these alternatives to another, with a very short latency. This capability to solve a problem with several action patterns is often termed *motor equivalence*. This combination of features seems to suggest that triggered reactions fall somewhere between correction for errors in execution and correction for errors in selection, sharing features of both categories or perhaps even forming a third category. It may be that when the perturbation is small, a correction for an error in execution can occur to bring the limbs back on the target trajectory; if the perturbation is somewhat larger, a triggered reaction results in another trajectory but without the need for reprogramming the movement using the stages of information processing; and if the perturbation is even larger, a correction for an error in selection is generated, which of course involves the stages of processing.

## Hierarchical Levels of Control

From the previous sections it is clear that there is considerable evidence for a central open-loop mechanism, structured before the movement is initiated, that serves to organize and control limb movements in coordinated actions. Yet substantial evidence also suggests that feedback from the responding limbs can, through a variety of mechanisms, modify the movement in various ways. Some of the lower-level reflex activities serve to keep the movement “on track,” and triggered reactions and reflex reversals alter the trajectory quickly while seeming to maintain the overall movement goal in the environment. Feedback from the touch receptors in the skin can also modify the ways in which the gamma loop functions in movement control (Merton, 1972).

This large body of evidence suggests a centrally organized structure that is capable of handling most of the details of the action but is also very sensitive to movement-produced sensory information from a variety of sources. One way to view this blending of open- and closed-loop functioning is to consider hierarchical control, in which a higher-order, open-loop control structure has “under” it a set of closed-loop processes that ensure the movement’s intended goal in the face of various perturbations. If a signal appears in the environment indicating that the higher-order program is no longer relevant, the highest levels in the system (the stages of processing) become involved in stopping it, or initiating a different program, or perhaps both. But if smaller perturbations occur that do not involve an alteration in the fundamental movement goal, these can be handled by lower levels in the hierarchy, presumably while the original higher-level program continues to operate. This is a classic example of one form of *hybrid control* in which a closed-loop system is embedded within an open-loop system.

These thoughts lead to a modified, less restricted definition of a motor program, one that is in keeping with the literature on feedback process but yet retains the essential feature of the open-loop concept: *The motor program is an abstract representation of action that, when activated, produces movement without regard to sensory information indicating errors in selection.* Once the program has been initiated, the pattern of action is carried out even if the environmental information indicates that an error in selection has been made. Yet during the program’s execution, countless corrections for minor errors in execution can be produced that serve to ensure that the original goal is carried out faithfully. Grillner (1975) has said essentially the same thing with respect to the control of gait:

Perhaps it is useful to regard the relevant reflexes as *prepared* [italics added] to operate but without any effect as long as the movement proceeds according to the set central program. At the same instant when the locomotor movements are disturbed (small hole, a slippery surface, etc.) the reflexes come into operation to compensate. (p. 297)

This idea is similar in many ways to the concept of a *coordinative structure* discussed by Greene (1972), Fitch and colleagues (1982), Turvey (1977), and Berkinblit and Feldman (1988). In both the motor program and coordinative structure concepts, the many degrees of freedom in the musculature are reduced by a structure that organizes the limbs to act as a single unit. Also, both notions involve the tuning of spinal centers, corrections for errors in execution, and freedom of the executive level from the details of what occurs at lower levels in the motor system.

Similar ideas along these lines were expressed many years ago by Bernstein (see “Nikolai A. Bernstein” in chapter 1). In one of his works, Bernstein (1996) described in detail a four-level, hierarchical system that was responsible for providing the capability for dexterity without overwhelming the role of consciousness. Level A in Bernstein’s scheme refers to neck and trunk tone, responsible for the automated control of posture. Level B (the level of muscular–articular links) refers to the level at which coordinative structures, or *synergies*, operate (Turvey & Carello, 1996). The higher levels—C (space) and D (actions)—are devoted to the problems of perception and intention, respectively (Turvey & Carello, 1996).

Greene’s (1972) point of view was similar to Bernstein’s and emphasized the hierarchical nature of motor control. Greene suggested that at the highest levels of the system, the global aspects of the movement are represented in the form of a goal (e.g., shoot a basket). The control of movement is passed down through progressively lower levels until all the particular decisions about which motor units to fire are defined at the muscle level. The higher levels

in the system do not have any direct control over muscle contractions; they have control only over adjacent levels of control that eventually result in those contractions. This idea is related to the motor program view, stated earlier here, in which only two levels exist—an executive and a program or effector. Greene’s view suggests that there are more than these two levels.

Along these lines, the highest level specifies what Greene called a “ballpark” movement, which would result in any of a number of movements that are generally capable of producing the intended goal; they are “in the ballpark,” as Americans would say. As the system passes control to lower levels, the individual details of the actions are defined by the initial conditions of the limbs, the posture of the performer, the relations with respect to gravity, and a host of other factors of which the highest level of the system is not aware. These lower functions then determine the ultimate movement that will result, on the basis of these lower-level interactions with feedback, tuning, and other factors. In short, the “ballpark response” becomes increasingly more specified at each lower level in the motor system.

## Problems With the Motor Program Notion

The advantage of the motor program notion as a theory of movement control is that it seems to provide order to a large number of separate findings, such as the inability to use certain kinds of feedback and the kinds of corrections that can and cannot be made. But the ideas about programs that we have stated so far have other logical drawbacks that must be considered. The next section deals with two of the most important: the *storage problem* and the *novelty problem*.

### *Storage Problem*

Given that an animal can produce a motor program “on command” and initiate it, *how many* such programs must the organism have at its disposal in order to move as it does? Recall that a motor program is thought to result in commands to muscles that define a particular pattern of action. In this view, if the pattern is to be changed (e.g., from an overhand to a sidearm throwing pattern), then a totally new program must be produced. Imagine all the ways to produce a throwing action, each of which must have a separate program.

MacNeilage (1970) identified this problem in the context of speech production. According to programming theories of speech, each sound that a human can produce (called a *phoneme*) is governed by a separate program; in order to speak, we string together these separate programs in a way that follows the “rules” of intelligible speech. This solution seemed to be a good one—since there are only about 44 sounds in English, we should require only 44 programs. The difficulty is that the actions of the mouth, jaw, tongue, and so forth for a particular sound are different depending on the sound that precedes it, as well as the sound that is to follow it. That is, to make the sound of a *t*, the musculature must make one of two different movements depending on whether the word is “eat” or “boat,” as you can easily discover for yourself when you say these two words and note the actions of your own tongue. And, depending on the previous sound, the program for the next sound must vary for similar reasons. Thus, the 44 programs for tongue movement for the various sounds must be multiplied by the number of different sounds that could precede and follow each of these sounds. This notion—called *context-conditioned variability*—led MacNeilage to estimate that a very large number of programs must be stored in memory in order for us to speak as we do. Considering all the various accents, inflections, and combinations, as well as any foreign language sounds, he estimated that about 100,000 programs would be required for speech alone.

It is possible that the brain *can* store 100,000 programs for speaking, of course, as long-term memory has a very large capacity. But when we consider the number of ways in which we move other than for speech, and the interaction of previous and subsequent states for each of these movements, there would have to be a nearly countless number of programs in long-term memory. How (and where) are all of these programs stored in the central nervous system?

This original motor program notion stated earlier seems unwise for several reasons. First, many mechanical or electronic control systems can have a serious storage problem, and it is crippling to them; examples are libraries

that have to cope with tons of paper and computer systems that have to store programs for every kind of computation. They simply run out of room for storage. A second reason relates to the belief that our motor system evolved in such a way that it was simple to operate and efficient in terms of storage. To store a complex program for every movement is not a simple and elegant way for a system to have evolved (e.g., Schmidt, 1975b; Turvey, 1977). There must be a better way to conceptualize the storage of motor programs.

### *Novelty Problem*

The next concern about this original motor program notion is related to the storage problem, but it takes a slightly different form. The basic issue is not how we retain learned movements, but rather how we make *new* movements. Consider a movement like this: Beginning in a standing position, jump up from both feet, touching your head with the right hand and your leg with your left hand before you land. Certainly, most of us could do this on the first try. If you had never done that particular movement before and if the action required a previously learned program for its execution, then where did the program come from? It is difficult to assume that the program was genetically defined (as walking might be), because such an action does not seem particularly essential to our survival. And you could not have learned it through practice, as this was the first time that you produced this action. A logical dilemma arises about the motor program notion when we consider novel movements.

The same sort of problem exists for more common skills. If you were to study a series of 50 shots in tennis, examining the fine details of the feet, hands, and body, you would probably find that no two movements were *exactly* the same. This is compounded by the fact that the ball never has exactly the same velocity, the same location on the court, or the same height on two occasions. Therefore, it is unlikely that any two tennis strokes could be exactly the same. If no two shots are exactly the same, then the programs must also be different. Thus, according to this analysis at least, every shot is “novel” in the sense that it has never been produced in exactly that way before. When you make a movement, you do not simply repeat a movement that has been learned earlier.

On the other hand, a given golf or tennis stroke is certainly very similar to strokes that you have made in the past. For example, some people have an atypical style of hitting a golf ball that is characteristic of them and no one else, and a popular touring (golf) professional’s style is easily recognized (e.g., Jim Furyk or Ryan Moore). Thus, it is not fair to say that every golf stroke is absolutely new, as considerable practice and experience have led to the production of that action, and this experience tends to make the actions similar and characteristic of that individual.

Writing more than 80 years ago, Bartlett (1932) made the following observation about tennis strokes: “When I make the stroke I do not, as a matter of fact, produce something absolutely new, and I never repeat something old” (p. 202). His point summarizes the issues in this section very well. When making a stroke, you do not make a movement that is absolutely new, because that movement will depend on your past learning. But you do not exactly repeat an old movement either, as any particular movement will be slightly different from all the others that you have made in the past. In this sense, the stroke is considered novel, yet at the same time, dependent on previous experience.

One weakness of the earlier idea about the motor program notion is that it does not explain how the individual can produce a novel movement or how a movement, such as a particular tennis stroke, is somehow slightly different, yet characteristic of all earlier ones. If our theories about movement programs are to have an application to everyday motor behavior, then they must be able to explain these common phenomena.

### *Need for Revision*

These two rather persistent problems—the storage problem and the novelty problem—pose rather severe limitations for the motor program idea as it has been stated previously. One solution has been to introduce a modification to the fundamental programming notion, one that retains all the attractive aspects of programming that have been discussed so far but also provides a solution to the two problems. This kind of thinking led to Schmidt’s idea (1975b, 1976a) that a motor program should be considered to be *generalized*.



# Generalized Motor Programs

The idea of a *generalized motor program* (GMP) is that a motor program for a particular *class* of actions is stored in memory and that a unique pattern of activity will result whenever the program is executed. In order for the program to be executed, certain *parameters* must be supplied to the program that define how it is to be executed for a particular instance. The program is considered generalized because choosing different parameters will alter the output, in terms of movements of the limbs, but these movements will differ in only certain ways. But, before we describe how such a system might operate, it will be helpful to consider an example of a generalized program for a different application.

## A Computer Model

Perhaps the best example of a generalized program comes from computer science. Consider a program that calculates means, such as the “function” feature in Microsoft Excel. This type of program is “generalized” in such a way that it will calculate the mean for sets of values that differ in terms of the number ( $n$ ) of them to be considered. Note that the set of operations that is to be done with these values is fundamentally similar regardless of the number of scores we have; that is, add up all of the values and then divide by the number of them you have. To run the function you simply specify the number of data points over which the mean is to be calculated—the number of values is one of the *parameters* that must be applied to the execution of the statistical function. Once these are specified, the program is executed for this particular number of scores.

How does this kind of program solve the storage and novelty problems? First, the storage problem is reduced because, for this class of computing problem, only one program needs to be stored in the system for each function (i.e., calculating the mean), and each program can generate its results for a wide range of possible numbers of data points. So, rather than having separate programs to calculate the mean of 2, 3, 4, 5, . . . , 1,000 numbers, we need only one program that is generalized; providing it with a parameter value (e.g., 8 or 800 data points, or some different number) enables the generalized program to produce the result easily.

With respect to the novelty problem, notice that the program for means and standard deviations can produce results for data that it has never been used for previously. One simply specifies the proper parameters, and the program is executed perfectly. The program can compute the mean for a number of scores that it has never confronted previously. In this sense, the generalized program provides one kind of solution to the novelty problem—it can produce a result it has never produced before.

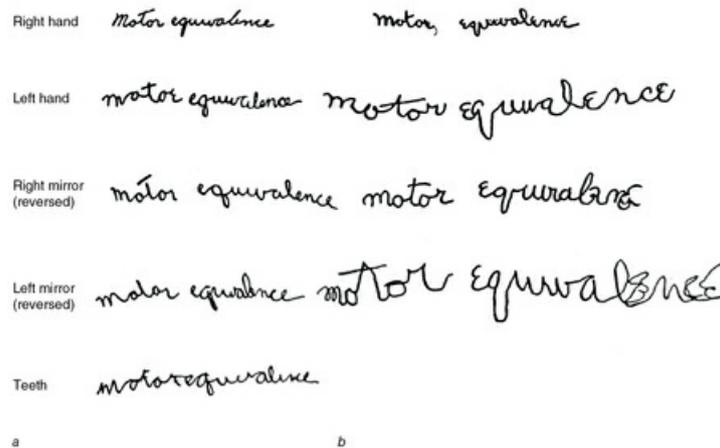
## Invariant Features

A motor program is thought to be responsible for the production of a pattern of action, expressed in both space and time. When we examine patterns of action carefully, we see that various aspects of them are easy to change while other aspects remain almost completely fixed from movement to movement. It is not always obvious which aspects of the movement are fixed and which are easily changed; but examining the movement in certain ways, or with certain theoretical biases, can reveal these features (Schmidt, 1985).

A classic example of ways in which movements demonstrate both fixed and modifiable features is *handwriting*. This demonstration was presented many years ago (apparently independently) by Lashley (1942; see Bruce, 1994) and Bernstein (1947; reproduced in Keele, Cohen, & Ivry, 1990 [their [figure 3.5](#)]), and by Merton (1972) and Raibert (1977). All these demonstrations suggest basically the same thing. [Figure 6.14](#) is a reproduction of the handwriting samples published by Lashley (1942). Two right-handed, blindfolded participants wrote the words “motor equivalence”<sup>5</sup> normally (with the right hand), with the nondominant (left) hand, and with either hand attempting to produce a mirror image of the words (these have been reversed in the figure to appear as normal). The participant represented in [figure 6.14a](#) even wrote the words with the pencil held by the teeth.



Figure 6.14 Examples from two participants writing the words "motor equivalence" with different effectors.



From K.S. Lashley, 1942, The problem of cerebral organization in vision. In *Biological symposia. Vol. VII. Visual mechanisms*, edited by J. Cattell (Lancaster, PA: Jaques Cattell Press), 301-322.

These handwriting samples are different in obvious ways—they are of different sizes and show a different amount of “shakiness” in some cases. The time taken to complete each word was probably not the same either. But in all samples for each individual, there are many remarkable similarities. A certain “style” is seen in all of them, such as the little curl at the start of the *m* for the participant illustrated in [figure 6.14a](#), and the way the downstroke of the *q* is made by the participant in [figure 6.14b](#). Some aspects of these written words appear to be *invariant*, even when the effector used or the size or speed of the writing is changed. In this figure, it appears that the spatial pattern was invariant—the shapes of the letters. Lashley noted:

In spite of the clumsiness, the general features of the writing, individual differences in the forming of letters and the like, are characteristically maintained. The mechanics of writing is a sequence of movements in relation to bodily position, not a set pattern of special groups of muscles. (1942, p. 317)

You can see a similar phenomenon if you do this yourself. First, write your signature in the “normal” way, as if signing a document or a check. Second, write your signature roughly 10 times larger on a dry erase board. Just by looking at the two signatures, you should be able to see that they are the “same,” signed by the same person. (If you want to be more elegant, take a digital photo of both signatures and enlarge or reduce one of them so that they are the same size, and then overlay them.) Now, note that you usually write the small signature with your fingers, with the “heel” of your hand fixed to the writing surface; naturally, with your hand fixed, your elbow and shoulder are fixed also. But, in the dry erase board signature, your fingers are mainly fixed, and the writing is done with the elbow and shoulder. The “same” signature was written by completely different joints and muscles.

Although the interpretation of these kinds of demonstrations has been called into question (Latash, 1993, 1999), in-depth analyses support the conclusion that something in the performer’s memory is common to all these handwritten samples (Wright, 1990). Some abstract structure has expressed itself, regardless of the variations in handwriting speed or size or in the particular limb or muscles used to write the words. Schmidt (1976a) theorized that those features that are invariant, and that in some ways are *fundamental* to these written words, are structured in the GMP; those aspects of the movement that are relatively superficial (speed, size, the limb used) are thought to be parameters of the program. Remember the computer analogy: The ways in which the means are calculated is invariant and fundamental to the program—the number of scores to be averaged is not fundamental, and this constitutes a parameter of the program. These examples with handwriting seem to be showing something similar and perhaps invariant.

If these observations are correct, how can the structure of the motor program be conceptualized so that the invariant features of handwriting are held constant across a wide variety of other changes? In the next section, we consider one possibility that has abundant evidence to support it—the *impulse-timing view*.

## Impulse-Timing View

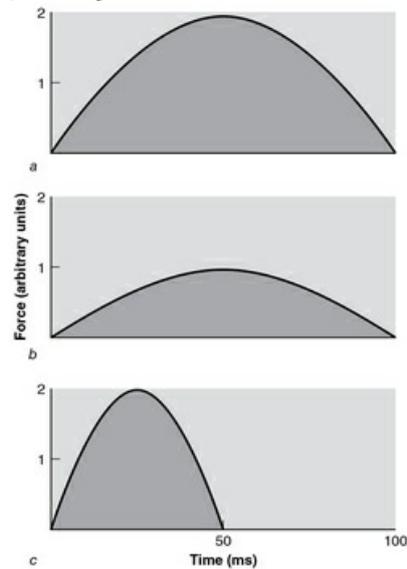
One straightforward viewpoint about the structure of GMPs is the *impulse-timing view*. The fundamental idea is that the motor program provides pulses of motor neuron activity to the relevant musculature. These pulses produce patterns of contractions in the muscles that can be seen in EMG records or in records of force produced. The amount of force produced is related in a complex way to the amount of neurological activity, and the duration of the force and its temporal onset are determined by the duration of the neurological activity and the time of its occurrence. The major role of the motor program is to “tell” the muscles when to turn on, how much force to use, and when to turn off. Thus, the motor program ultimately controls force and time.

### *Impulses*

The combination of (or the product of) force and time constitutes what is called an *impulse* in physics. A common physical principle is that the amount of movement produced in an object (such as a limb) is determined by the force(s) acting on it and the duration over which the force acts; the impulse is the product of force and time. According to the impulse-timing view the GMP controls movement by controlling impulses—bursts of force spread out over time to the appropriate muscles.

In [figure 6.15](#) are three hypothetical, idealized records of the forces produced by a muscle over the time that this muscle is acting on the limb. At each moment of the contraction, the muscle is producing a different force against the bone; the resulting curve in [figure 6.15](#) is called the *force–time curve*—a record of the force produced over time. The impulse is the shaded *area* under the force–time curve.

Figure 6.15 Hypothetical impulses seen as the area under force–time curves. (Impulses *b* and *c* have half the size that impulse *a* does, but impulse *b* is achieved by halving the force with time constant, and impulse *c* is achieved by halving the time with force constant.)



In the figure, notice that the area under the force–time curve for impulse *a* can be reduced in half by changing the amplitude of the force for a given amount of time (as in impulse *b*), by changing the duration of the impulse for a given amplitude (as in impulse *c*), or both. From physics, the velocity of the object (or limb, beginning at rest) after the impulse has ended its action will be directly proportional to the size (the area) of the impulse. Thus, impulses *b* and *c* in [figure 6.15](#) would theoretically produce the same velocity at the end of their respective actions (because their areas are equal). And the velocity of the limb with impulse *a* would be twice as large as for the other two, because its area is twice as large. According to this view, the motor program controls a feature of muscular contraction that is known to be a direct cause of movement—impulses.

If it is correct that the motor program determines impulses, then it is reasonable to assume that the motor program is capable of producing a group of impulses, each one in a different muscle group and each one at a different time, resulting in a pattern of activity that produces a complex, skilled movement. Remember, producing impulses in muscles is really nothing more than defining the time of onset and offset (i.e., the durations) of the relevant contractions, as well as their forces. Once these are defined, the movement is defined, given a fixed environment of course. Even so, defining these impulse sizes and durations should not be seen as simple, because many factors must be considered by the central nervous system, as discussed earlier (see [figures 6.12](#) and [6.13](#)).

### *Invariant Features and the Impulse-Timing View*

Given a model of impulses patterned in time to produce a movement, what features of the action must remain invariant? What aspects of these impulses are the same from one handwriting sample to another, and which of them can vary while maintaining a given pattern of activity? The evidence favors two, and perhaps three, features that remain invariant.

### Order of Events

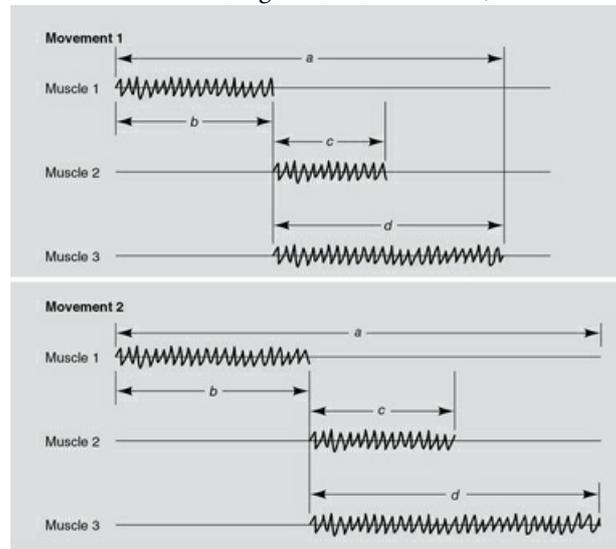
One aspect of the patterns shown in [figure 6.14](#) that seems not to vary is the sequence or *order* of events (Lashley, 1951). In each sample, some event occurred before some other event in making a letter or word, and this order was fixed for all of the samples. We assume that the order of muscular contractions associated with the sequence of events in a given program is fixed. A basic assumption of the impulse-timing view of motor programming is that within the structure of a given program is an invariant order of the various elements. Notice that this is not the

same as saying that the order of *muscles* contracting is fixed in the program. The muscles that produced the writing with the teeth are obviously different from those that produced the writing with the hand, and yet the sequence and the pattern were the same. Clearly, the motor program does not contain the order of muscles; rather, it seems to order the *events* (here, upstrokes, downstrokes, etc.) that occur during the movement.

### Relative Timing

A second aspect of the program that is thought to be invariant is the *temporal structure* of the sequence, usually termed *relative timing*. The temporal structure of a series of events (in this case, a series of actions) can be represented in a number of ways, but one of the most common is to evaluate the structure in terms of what is called *relative time*. In [figure 6.16](#) are hypothetical examples of records taken from two similar actions. This particular record contains EMGs, but the record could have been defined in terms of movements of the limbs, the forces produced, or other characteristics that capture in some way the nature of the movement pattern produced. The hypothetical muscles whose EMGs are shown were chosen because they act at different times in the movement sequence. The sequence begins with a strong burst of EMG from muscle 1; then muscle 1 appears to be turned off and muscles 2 and 3 are activated, with muscle 2 ceasing its activity before muscle 3 does. How can this temporal pattern of events in these three participating muscles be described?

Figure 6.16 Hypothetical electromyogram (EMG) records from two similar movements differing only in movement time (MT). (Phasing, or relative timing, is defined by the ratios of the EMG durations for various muscles, e.g.,  $b/c$ ,  $c/a$ , and so on.)



One method is to measure the durations of the various elements within the sequence. Shown in the figure are two similar movements, but one of them (movement 2) has a longer MT than the other. If these two records are evaluated with respect to the durations of the relevant contractions (EMGs), then interval  $a$  can be defined as the duration of the contraction of the muscles in the entire action, interval  $b$  is the duration of contraction of muscle 1, interval  $c$  is the duration of contraction of muscle 2, and interval  $d$  is the duration of contraction of muscle 3. One way to evaluate the temporal structure of these events is to compute the ratio of the event durations. The sequence for movement 1 has a ratio of interval  $c$  to interval  $d$  of 1:2, or 0.50. That is, interval  $d$  is twice as long as interval  $c$ . Also, interval  $b$  is one and one-half times as long as interval  $c$ , making their ratio 1.5:1, or 1.5. Similar ratios can be computed for any two intervals in the sequence.

Another common ratio is that of an element in the sequence relative to the overall length of the sequence. For example, in the movement 1 sequence the ratio of interval  $d$  to the overall length of the sequence (interval  $a$ ) appears to be about 0.60; thus, muscle 3 is contracting for about 60% of the entire movement. This is the usual use of the term “relative time” or “relative timing”: the duration of one event divided by the duration of the entire action.

The fundamental idea taken from these ratios is this: The temporal structure is measured by (or characterized by) the values of these ratios. If all the ratios for analogous pairs of events are the same in two separate movements, then we say that the temporal structures are the same. Thus, any two movements with the same order of contractions (perhaps that shown in [figure 6.16](#)) and the same ratios of muscle action to total MT (e.g., 0.45, 0.30, and 0.60 for muscles 1, 2, and 3) have the same temporal structure. Further, these two movements are assumed to be produced by the same GMP, for which relative timing is invariant (or fixed).

Movements 1 and 2 in [figure 6.16](#) have this characteristic. The proportion of total MT for each muscle is the same in the two movements, even though the *amount* of time that each muscle is contracting is different for the two movements. Movements 1 and 2 are thought to be governed by the same motor program because their relative timing is the same. According to this idea, if two movements have different relative timings, then they are governed by different GMPs.

### Relative Force

A third important feature of GMPs is *relative force*, which simply means that the amounts of force produced by

any two muscles remain in constant proportion from movement to movement. If in movement 1, muscle 1 produced 2 kg of peak force and muscle 2 produced 4 kg, the ratio of these two forces would be 1:2, or 0.50. In another movement using the same program, these proportions should be the same but perhaps with forces of 2.5 kg for muscle 1 and 5 kg for muscle 2. The ratio remains 1:2, or 0.50.

This feature (relative force) of the movement sequence would seem to remain invariant for the patterns of handwriting in the examples in [figure 6.14](#). We can see this in two ways. First, in this kind of model, the height of a given letter is determined in part by the amount of force applied to the limb during the impulse applied by the motor program. But the heights of the letters remain in almost constant proportion to each other as the various letters in a given sentence are considered. For both participants in Lashley's example (see [figure 6.14](#)), the *t* is always about twice the height of the *o* that follows it. The forces that produced these letter heights may have been in constant proportion in the sequence as well.

### *Phonograph Record Analogy*

It is sometimes helpful in understanding motor control theories to consider a *model* that has many of the same features as the theory. A good model for the GMP is the phonograph record. For those younger readers, you might need to ask parents or grandparents about a phonograph record, or just look it up in Wikipedia. On the record, structured as invariant features, are three things. First is the order of the events, for example, specifying that a drumbeat comes before a guitar riff, and so on. Next is the relative timing. Think of relative timing as the rhythm, so that the time between any two events on the record divided by the total record time is a constant. For phonograph records, the ratio between the durations of any two events is always fixed. Also, the relative force is fixed. For example, the first drumbeat may be twice as loud as the second one. What is embedded on the record is a code that is translated into sound when the record is played on an audio system. It may be helpful to conceptualize GMPs as records, because in many ways they behave in the same general way, and these similarities allow us to visualize the GMP idea more vividly.<sup>6</sup>

But we know that the recording can be played in various ways to produce different sounds. It can be played rapidly or slowly, loudly or softly, with the sound equalizer adjusted in various ways, and so on. Yet a given song can still be recognized because the *pattern* of the sounds produced is invariant, even though some of the superficial features of the pattern may have varied. The actual muscles that produce the action (here, the particular speakers that will be driven) are certainly not “on” the record, because the record can be played on any audio system. In the next section, we discuss some of these more superficial features of movements. These aspects of movement are considered the *parameters* of the GMP.

## Parameters of Generalized Motor Programs

Motor program theorists have argued that there are a limited number of parameters that can be applied to a GMP. The evidence is strongest for parameters that are responsible for establishing the overall duration, the overall force, and muscle selection. We discuss these next.

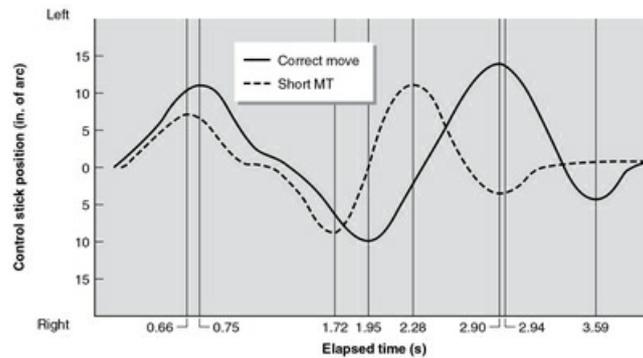
### *Overall Duration Parameter*

The basic idea of an overall duration parameter is that, although the motor program contains relative timing and sequencing information, it can be executed slowly or rapidly depending on the overall duration parameter assigned, just as increasing the speed of the phonograph turntable speeds up the entire sequence of sounds as a unit.

Initial evidence for an overall duration parameter appeared in an unpublished study by Armstrong (1970b). Participants learned to move a lever through a particular spatial–temporal pattern. [Figure 6.17](#) shows a tracing of the position of the lever as a function of time in the 4 s movement. Armstrong noticed that when the participant made the movement too rapidly, the entire sequence was made too rapidly, as if the entire movement record was

“compressed,” with all parts of the movement shortened by the same relative amount, or in the *same proportion*. Although Armstrong did not compute relative timing, the time interval between some peak *a* and some other peak *b* divided by the time for the entire movement is about the same in the two movements shown in the figure. Such findings gave initial insight into the possibility of an underlying GMP, with an overall speed parameter that retained the invariant relative timing in the movement pattern, which could be parameterized to allow the total duration of the movement to be made longer or shorter (see Pew, 1974a, for an early discussion of this work).

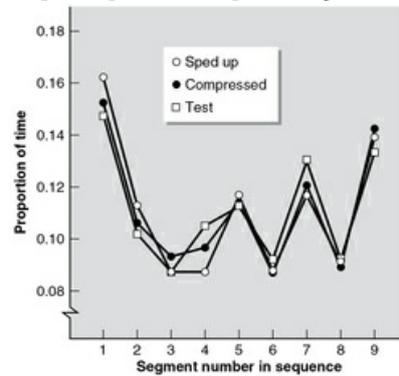
Figure 6.17 The position–time record of an arm movement task, showing the correct move and a move in which the overall movement time (MT) was too short.



Reprinted from T.R. Armstrong, 1970, "Training for the production of memorized movement patterns," *Technical Report 26*: 35.

Following Armstrong's (1970b) and Pew's (1974a) suggestions, Summers (1975) and Shapiro (1977, 1978) examined similar questions in tasks in which the experimenter could instruct the participant to change the overall speed intentionally (remember that movement durations made by participants in Armstrong's study changed accidentally). Shapiro's paradigm involved practice at a task that required precise spatial–temporal patterning of pronation/supination of the wrist. Thus, to be successful the participants had to make a series of actions with criteria defined in both space and time. The temporal structure of the action for Shapiro's (1977) study is shown in [figure 6.18](#), here called the "test" trials. The proportion of the total MT (which was 1,600 ms) occupied by each of the nine wrist-twist segments is plotted as the line marked with open squares. After considerable practice, participants increased speed but attempted to keep the pattern the same; the pattern of proportions for these "compressed" trials is shown as the line with filled circles in [figure 6.18](#). Notice that the proportions of time for the various segments were almost exactly the same for the "test" trials and the "compressed" trials, but that the MT in the latter was decreased to 1,300 ms, on the average. Essentially, Shapiro showed that the participants could decrease the time of this well-learned movement sequence as a unit, keeping the relative timing in the movement (defined by the proportions) constant. Again, these findings support the view that a movement-duration parameter can be applied to some fundamental program so that the given pattern can be sped up or slowed down as a unit.

Figure 6.18 Proportion of total movement time (MT) required to traverse each segment in a wrist-twist movement. (Normal trials had a goal of 1,600 ms; compressed trials were sped up using the same phasing; speed-up trials were sped up while participants attempted to ignore the earlier-learned phasing.)



Adapted from Shapiro 1977.

Even more remarkable was another finding that both Summers (1975) and Shapiro (1977, 1978) obtained. Participants were required to produce the movement as rapidly as possible and to *ignore* the relative timing that they had learned in the earlier practice trials. On these sped up trials the pattern of proportions was almost identical to that for the normal trials. Participants were able to speed up the movements, but they were apparently unable (or at least unwilling) to do so with a different relative timing (see also Carter & Shapiro, 1984; Verwey & Dronkert, 1996).

There are many other examples of absolute and relative timing in the literature. Terzuolo and Viviani (1979, 1980) studied the typing of various words, examining the relative timing characteristics. The study examined various temporal records in typing the word “enclosed,” when the word was embedded in various places in standard prose. Although the absolute duration of typing the word enclosed was influenced by the text to be typed before and after the target word, the relative timing of the interkeystroke intervals was maintained.

Similar findings have been produced by Shaffer (1980, 1984) in a study of typing and piano playing, by Roth (1988) using an overarm throwing movement and by Heuer, Schmidt, and Ghodsian (1995) using a bimanual task in which each arm produces a different pattern, with the two arms being coordinated. All these data support the notion that a given overall sequence can be sped up or slowed down as a unit while the relative timing in the sequence is maintained (i.e., relative timing was invariant). Again, these data are consistent with the view that the same GMP produced the different instances of typing the word “enclosed” by applying a slightly different duration parameter each time the word was typed.

One more type of research paradigm has provided evidence that is important to consider. A series of studies by Wulf, Shea, and colleagues used a research strategy in which variables known to affect learning produced different effects depending on what was learned or measured (much more will be described about learning variables in chapters 10 and 11). This strategy attempts to look for patterns of *dissociations* in learning (see also the same idea in the study of the two visual systems, discussed in chapter 5), such that a particular learning variable has different effects on the learning of relative timing (a measure of GMP performance) as compared to its effects on overall duration (a measure of parameterization) (DeJaeger & Proteau, 2003; Shea & Wulf, 2005). According to some studies, experimental variations of practice have the effect of *increasing* the accuracy of relative timing (as measured in retention and transfer tests) (Lai & Shea, 1998; Lai, Shea, Wulf, & Wright, 2000; Shea, Lai, Wright, Immink, & Black, 2001; Wright & Shea, 2001; Wulf & Schmidt, 1989; Wulf, Lee, & Schmidt, 1994; Wulf, Schmidt, & Deubel, 1993). At the same time, these studies also showed that those same experimental variables degraded the scaling of absolute-duration performances (see also Wulf & Schmidt, 1996), which is a measure of the accuracy of parameterization. The overall findings appear to show some inconsistencies (cf. Wulf & Lee, 1993; Wulf & Schmidt, 1994b, 1997), however, and more work seems needed to clarify these effects. But overall, there is ample evidence that some factors have different effects on the learning of relative timing versus the parameterization of movement duration, justifying their theoretical separation (see Shea & Wulf, 2005, for a review).

These results are examples of *double dissociations* as we discussed in chapter 5. Such double dissociations provide very strong evidence that two proposed theoretical structures are actually different empirically. The interpretation is that variables affecting the learning of program variables (such as relative timing, relative force, and sequencing) are not the same variables as those that affect the learning of parameter-assignment processes. Hence, these kinds of results strongly support the theory that program development and parameter assignment are theoretically (and actually) separate processes.

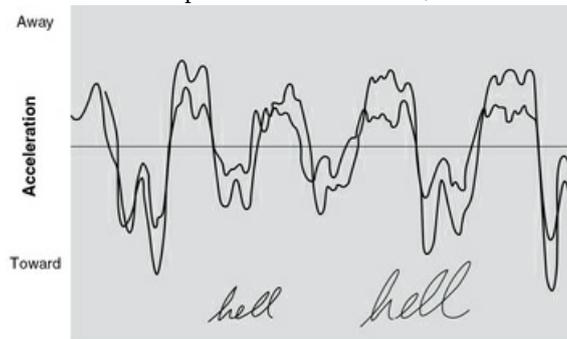
### *Overall Force Parameter*

A second parameter proposed for implementing a GMP is an overall force parameter that modulates the amounts of force produced by the participating muscles. The force parameter is involved with determining how strongly the relevant muscles will contract when they are recruited by the program. The evidence for the existence for such a parameter is weak, but logically a force parameter is included in the model (see also Schmidt, 2003).

Pew (1974a) described, as an example, a post office in which a conveyer belt carried small packages to be sorted by an employee. The person picked up the package and, with a “set shot” that might be considered good form for a basketball player, tossed the package into one of about 15 equidistant bins for later delivery to different postal zones. This package-sorting “system” required a number of processes on the part of the performer. First, because the bins were equal distances from the person, the final velocity (as the package left the hand) of each package needed to be approximately the same in order for each package to reach its bin, regardless of its weight. But a package with a larger mass will require the application of more force at a *given* duration in order to achieve the desired terminal velocity. Thus, the performer must choose a force parameter that can be applied to the generalized “set shot” program. Presumably, the person would pick up the package, heft it to determine its mass, and then select a force parameter for the generalized program that would achieve the proper goal. The program could be run when the force and duration parameters had been selected.

Another example that supports the concept of an overall force parameter comes from Hollerbach (1978). [Figure 6.19](#) shows the acceleration tracings from a participant writing the word “hell” two times, one being twice the size of the other. The accelerations are, of course, directly proportional to the forces that the muscles are producing during the action. The tracings have the same temporal pattern, yet the accelerations in the tracing for the larger word are uniformly larger than those for the smaller word. It appears that the forces applied to the pen were simply increased (scaled) while the original temporal pattern was maintained. Of course, increasing the force leads to increased distance that the pen travels; hence, the word is larger with the same spatial–temporal pattern. Similar interpretations can be made from a study of handwriting by Denier van der Gon and Thuring (1965), who showed that when the friction of the pen on the writing surface was increased, a systematic decrease in the writing size resulted but with no change in the pattern of letters produced.

Figure 6.19 Vertical accelerations produced in writing the word “hell,” with one word having twice the amplitude of the other. (The tracings show a remarkable degree of temporal agreement, with systematic differences in amplitude of acceleration.)



Reprinted, by permission, from J.M. Hollerbach, 1978, *A study of human motor control through analysis and synthesis of handwriting*. Unpublished doctoral dissertation (Cambridge, MA: Massachusetts Institute of Technology).

In the examples just cited, the overall force parameter applies to all of the participating muscles proportionally, keeping the relative forces applied to the limb proportional. This concept is very much like the overall-duration parameter, which is applied to the sequence as a whole. A less restrictive view is that the force parameter can be applied to various actions in the sequence without affecting other actions in the body. For example, walking with a heavy backpack would seem to require that more force be applied to the muscles that operate against gravity in walking, but the muscles that cause the foot to move through the air in the swing phase would not need to have extra force applied to them. Perhaps a force parameter is selected that applies only to those aspects of the program that require extra force. However, this idea has the disadvantage of requiring the motor system to do more “computing” in order to move. Consequently, there appears to be less overall support for the separation of absolute and relative forces than has been seen for the other features of the GMP theory.

### *Interaction of Duration and Force Parameters*

There is a further argument with respect to the necessity for a force parameter, but it is less obvious than the one just given. Consider a movement in which you begin with your elbow straight, flex the elbow to 90°, and then extend it to the straight position again, completing all of the movements in an overall MT of 300 ms. The motor program presumably determines the relative timing of the biceps, the cessation of the biceps and the initiation of triceps (for the reversal), and then the contraction of the biceps again to “clamp” the limb in the final target position. Now consider what would happen if you simply decreased the duration parameter of the program without changing a force parameter. Selecting a shorter duration parameter would cause the program to move through the biceps–triceps–biceps sequence more rapidly while keeping the forces produced by these muscles constant. What would happen to the movement? Because the impulses will be shorter in time, the impulses will be smaller, and the limb will not have moved as far in the time allowed for biceps activity; thus, the movement will reverse itself short of the 90° position. Decreasing a duration parameter while holding a force parameter constant would result in an inappropriate movement in terms of its extent.

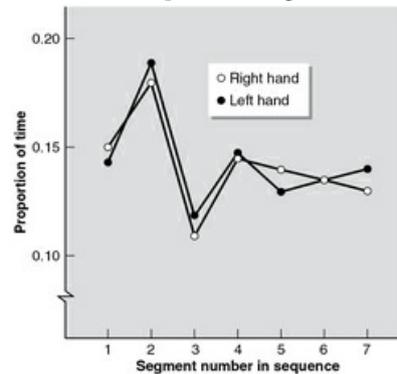
One possible remedy is to choose the duration parameter so that the overall MT is correct, and then to choose an overall force parameter that will be sufficient for the limb to move to 90° before reversing itself (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). If the force parameter is too large, the movement will go too far in the proper amount of time; if the force parameter is too small, the movement will not go far enough. Thus, with this view, movement distance for a given program is determined by a complex combination of duration and force parameters. Clearly, duration and force parameters must complement each other. The selections of the force and duration parameters are not independent, as the particular value of the force parameter will depend heavily on the chosen duration parameter.

### *Muscle-Selection Parameter*

In the analysis of the handwriting examples shown in [figure 6.14](#) (from Lashley, 1942), we argued that the muscles for the particular action could not be stored “in” the GMP, because the same program produced movements in entirely different limbs. Thus, the sequential ordering embedded in the motor program is considered to be *abstract*, with the specific joints and muscles added during the *preparation* (and *parameterization*) of the program. In this case, it is reasonable to think of the specification of muscles (or joints) as another parameter of the motor program.

Additional evidence for this view comes from numerous experiments using a *bilateral-transfer* paradigm. For example, Shapiro (1977) used a wrist-twist task similar to that described earlier, having participants practice this sequence with the right hand for five days. Then the participants practiced the same movements with the left hand, which had never been used for this pattern before. She found a pattern of activity shown in [figure 6.20](#), in which the well-practiced right-hand pattern is indicated by the open circles and the novel left-hand pattern is indicated by the closed circles. The two patterns are nearly identical, and the case can be made that the program that was generated by practice with the right hand could be produced with the left hand. Further evidence for the preservation of sequence learning during transfer to different effectors has been shown by Keele, Jennings, Jones, Caulton, and Cohen (1995; see also Jordan, 1995; Keele et al., 1990).

Figure 6.20 Proportions of total movement time (MT) required to traverse various movement segments in a wrist-twist task. (The pattern is similar for the practiced right hand and for the unpracticed left hand.)



Adapted from Shapiro 1977.

In another variant of the bilateral-transfer paradigm, Park and Shea (2002) found that relative force and time transferred from one limb to the other but absolute force and time did not. Therefore, this could be interpreted to suggest that positive bilateral transfer of the invariant features occurred, not the movement parameters. Stated another way, since bilateral transfer of the properties of the GMP was high this finding supports effector independence of the GMP, but since bilateral transfer of the parameters was low, this finding suggests effector specificity in bilateral transfer of movement parameters (see also Park & Shea, 2003, 2005; Wilde & Shea, 2006). These findings are reminiscent of Lashley's (1942) handwriting examples shown in [figure 6.14](#): The essential features of the handwriting were maintained when limbs were switched, although the "smoothness" was affected dramatically.

### *Changing Parameters and Programs*

Additional evidence supporting the GMP comes from experiments in which some aspect of the movement has to be changed during the movement. For example, Quinn and Sherwood (1983) had participants make elbow flexion or extension movements of 400 ms. Occasionally an auditory signal, administered in different blocks of trials, would instruct the participant to either (a) move faster or (b) reverse the movement. The findings, similar to those from earlier studies in this same general paradigm (Gottsdanker, 1973; Vince & Welford, 1967), showed that the latency of the corrections (the interval from the auditory stimulus until the first EMG change) was 100 ms shorter when the movement had to be sped up than when it had to be reversed. Theoretically, with a reversal, the participant has to stop running a given program and select, parameterize, and initiate a different one that will reverse the movement. However, when the movement is sped up, the existing program can be retained, and only a new set of parameter values is necessary (e.g., with adjusted overall duration and force parameters); the stages involved in program selection and initiation can be bypassed.

Roth (1988) has shown that these principles hold for sport skills studied in the laboratory. For example, the RT to change a tennis ground stroke to a lob (presumably requiring a different program and different parameters) was estimated to be about 600 ms, whereas the RTs to change the direction or length of the ground stroke (presumably requiring only new parameters) were estimated to be about 200 ms less. Analogous results were provided for table tennis and volleyball skills, suggesting that the difference between program *plus* parameter selection versus only parameter selection is general across a variety of movement behaviors (see also Obhi, Matkovich, & Gilbert, 2009; Wright, Black, Park, & Shea, 2001).

## Concerns About Generalized Motor Programs

The GMP theory was first proposed more than 40 years ago, and there have been numerous empirical and theoretical examinations of its predictions since then. In general, the theory has held up well. However, as with all theories, some data and analyses do not provide support.

The most contentious issue with regard to GMPs has been the concept of *invariance*, especially as it relates to relative timing. We argued earlier that in order for a timed segment to be considered invariant, its duration, relative to the total duration of the activity, must be constant over a series of separate executions of the program. But have another look at the relative timings for each letter of the word “enclosed”. Although the relative durations for each letter show rather consistent relative timings, there are still some deviations. The questions that arise are these: *Are these deviations meaningful? And how do you decide what is a meaningful deviation?*

### *Statistical Invariance*

A qualitative answer to these questions is to draw a straight line through the center of a set of data points. If the data were *perfectly* invariant, then all the individual data points would fall exactly on vertical lines—the more data points that are observed off the line, the weaker is the evidence for invariance. In reality, there is very little chance that motor behavior will ever show true, perfect invariance. Therefore, the question becomes, how much deviation from perfection can be tolerated before we *reject* a conclusion that the data reveal invariance?

One solution to this debate was provided by Gentner (1987). He proposed two statistical methods for assessing relative invariance in a set of data. One method, called the *constant-proportion* test, uses statistical *regression* to assess whether or not the relationship between MT and relative timing has a slope that deviates from zero. (See chapter 2 for discussion about regression methods.) If relative timing is invariant, then the slope of the regression line will not deviate from zero, either positively or negatively. Gentner’s (1987) analysis provided an objective, statistical solution to the problem of assessing invariance. Using these methods, Gentner reanalyzed some previously published data sets and found that, while some studies found support for invariant relative timing, others did not. More recent experiments, using the methods suggested by Gentner, have also produced evidence that is weighted against *perfect* statistical invariance (Burgess-Limerick, Neal, & Abernethy, 1992; Maraj, Elliott, Lee, & Pollock, 1993; Wann & Nimmo-Smith, 1990; see also Franks & Stanley, 1991).

Are statistical tests appropriate to assess the invariance predictions of relative timing in GMP theory? The answer is unclear. Several questions can be raised from a statistical point of view, such as (a) the appropriateness of accepting the null hypothesis when significant effects are not found (which would be evidence in support of invariance) and (b) the level at which to set the cutoff point for rejection of the null hypothesis. Gentner suggested that a level of  $\alpha = 0.05$  is appropriate; however, a case could be made for more or less stringent levels.

### *Central Versus Peripheral Invariance*

Heuer (1988, 1991) has raised another important issue. He suggested that, even in the absence of *measured* invariance, there might still be *central* invariance. Heuer’s argument uses the Wing and Kristofferson (1973a, 1973b) distinction between central and peripheral timing as a basis (see chapter 7). The idea is that the timing observed at the output or peripheral level is a combination of a central mechanism that periodically triggers an effector into action and the (somewhat variable) motor delays (such as neural delays and muscle recruitment time) that occur following a central trigger. Heuer (1988) demonstrated that a variable motor delay could result in an absence of invariance in observed performance even though the relative timing of a central timing signal had no variance at all.

Thus, perhaps because of complexities in the muscle properties in fast movements (e.g., Heuer & Schmidt, 1988; Gielen, van den Oosten, & ter Gunne, 1985; Zelaznik, Schmidt, & Gielen, 1986), it is possible that one might not detect invariance at the level of the GMP by searching for invariances in motor output. We will return to the discussion of invariant relative timing when we discuss how the system regulates the coordination of two or more activities at the same time (in chapter 8).

### *Doubts About Motor Programs*

A broader question that has been asked, not just specific to GMP theory, is whether or not the motor program

concept remains a relevant or viable theoretical construct at all (Morris, Summers, Matyas, & Ianssek, 1994; Summers & Anson, 2009). A number of alternative motor control positions have been described in the past 40+ years, and these have received considerable theoretical and empirical support. Some of these views suggest that the motor program view ascribes too much “intelligence” to a central command center—that much of the evolution of a movement as it unfolds in the course of an action occurs as a natural consequence of the dynamic interactions of the central nervous system, the effectors, the environment, and the task at hand. In other words, the argument is that a complex plan of action that serves to control movement need not be stored in memory and recalled prior to initiating movement.

We share some of these concerns about motor programs, especially as they relate to the ongoing regulation of coordination skills. In chapter 8 we discuss some theoretical alternatives regarding how these skills might be controlled (including a GMP account). However, we also note that many researchers who express doubts about motor programs usually study motor tasks that involve continuous skills, often rhythmical or cyclical (or both) with relatively long durations, for which ongoing regulation, using feedback from the environment and body, would seem critical to successful performance. Of these critics of the motor program concept we ask how, for example, might a *decentralized* theory of motor control (i.e., a theory that does not involve a central motor program) explain the findings of Wadman and colleagues (1979; discussed earlier), in which the complex coordination of agonist and antagonist muscle firings was preserved when the limb was blocked in position and prevented from moving at all? If the movement is shaped by the ongoing dynamics, then how could the “normal” pattern of muscle activations occur in the absence of any movement at all? Similarly, how could the findings of Valls-Solé and colleagues (1999), in which an acoustic-startle stimulus “released” a prepared movement almost 100 ms earlier than for a normal RT, be reconciled by a theory in which plans for action do not have a prominent role?

Regarding the divide that separates different theoretical perspectives on how movements are regulated, Steve Keele wrote: “To a large degree we are simply talking about different kinds of phenomena, and those phenomena have generated very different databases that are not addressed by both classes of theory. It is difficult to pit two ‘theories’ or perspectives against each other if they do not speak to the same phenomena” (Keele, 1998, p. 404). As we see it, the criticisms of the motor program concept lose strength in argument when a decentralized concept must come to terms with how rapid, ballistic-type tasks are controlled. At the very least, for actions such as these, we believe that the motor program concept provides the most complete and parsimonious account of the research evidence.

## Summary

The response-chaining hypothesis proposed by James (1890) was the first open-loop theory for motor control. It held that each action in a sequence is triggered by the movement-produced feedback from the immediately preceding action. Research on the role of feedback in movement performance under various deafferentation conditions has tended to show that sensation from the moving limb is not *essential* for motor performance, although it contributes to the smooth control of many actions. Thus, the response-chaining hypothesis cannot be universally correct.

Motor control scientists have three reasons for believing that movements are controlled by programs: (a) the slowness of the information-processing stages, (b) the evidence for planning movements in advance, and (c) the findings that deafferented animals and humans can produce skilled actions without feedback. This is not to say that feedback is not used in movement. Feedback is used (a) before the movement as information about initial position, or perhaps to tune the spinal apparatus; (b) during the movement, when it is either “monitored” for the presence of error or used directly in the modulation of movements reflexively; and (c) after the movement to determine the success of the response and contribute to motor learning.

An early definition of motor programs as structures that carry out movements in the absence of feedback was found to be inadequate to account for the evidence about feedback utilization during movement. Also, problems were associated with the requirement for storage of many different motor programs (the *storage problem*), as well as with the means by which the motor program could create a novel action (the *novelty problem*). For these reasons, the motor program is thought of as *generalized*—containing an abstract code about the *order of events*, the *relative timing* (or temporal structure) of the events, and the *relative force* with which the events are to be produced.

These generalized motor programs (GMPs) require *parameters* in order to specify how the movement is to be expressed in the environment. Such parameters are the *overall duration* of the movement, the *overall force* of the contractions, and the *muscle* (or limb) that is used to make the movements. With such a model, many different movements can be made with the same program (reducing the storage problem), and novel movements can be produced through selection of parameters that have not been used previously (reducing the novelty problem).

### Student Assignments

1. Prepare to answer the following questions during class discussion:
  - a. Describe the open-loop operation of any human-made device of daily living (e.g., a microwave oven).
  - b. Use an example from sport that illustrates the concept of point of no return.
  - c. Provide an example from food preparation activities in the kitchen that illustrates the difference between errors of selection and errors of execution.
2. Find a research article that uses relative timing as the main dependent measure. What theoretical issues are investigated with use of this measure in your article?

### Notes

<sup>1</sup> Four of Taub’s monkeys were reexamined 12 years after their surgery, and all revealed considerable functional reorganization of the brain structures responsible for sensory representation (Pons et al., 1991). Thus, it seems that motor and sensory systems may have both short- and long-term methods for adapting to the loss of sensory feedback.

<sup>2</sup> This view could also be related to the reflex-chaining hypothesis. The difference is that the closed-loop model would have the feedback evaluated against a reference of correctness, whereas the reflex-chaining view would have the feedback from the movement trigger the next action directly.

<sup>3</sup> Note that Gray (2002, 2009a) did not manipulate the vertical deviation of the pitch from the strike zone in

these batting simulations (i.e., “inside” or “outside” of the strike zone).

<sup>4</sup> The generalizations that errors in execution can be corrected (a) without interference from other similar corrections and (b) with latencies unaffected by the number of possible corrections have not been studied carefully and should be considered with caution.

<sup>5</sup> Lashley had a good reason for choosing these particular words to be written; the term *motor equivalence* refers to the idea that different effectors can be used to achieve the same goal.

<sup>6</sup> Not long ago, a teenaged niece of R.A.S. asked him, “What’s a phonograph?” Although the question raises some doubt about the longevity of this analogy, we note that phonograph records have made a resurgence in popularity in recent years.

# Chapter 7

## Principles of Speed and Accuracy

One of the most common errors of movement control occurs when we try to perform a task faster than “normal.” Attempts to thread a needle rapidly, to type an e-mail in a hurry, or to pour a glass of milk quickly often result in an increased number of *errors*. These are errors based often on a lack of precision. They are usually (but not always) studied in tasks involving arm and hand movements.

In this chapter we focus on the fundamental *principles* that pertain to various movement variables and some theoretical ideas that have emerged from them. Such principles are critical to any science, as they describe the interrelationships of measures of the objects under study. As such, many of the basic *laws* of motor behavior may be seen as analogous to the fundamental principles of physics. The laws relating the mass, velocity, and acceleration of objects when forces are applied to them (the principles of mechanics), for example, have served as the cornerstone of the physical sciences and therefore deserve a special status. In the same way, the field of motor behavior has analogous principles that are somehow fundamental to all the rest: principles that describe, for example, the relationship between the speed at which a limb moves and the resulting accuracy, or the relationship between movement distance and movement time.

Whereas a neat set of simple, elegant principles can be stated for various branches of the physical sciences, we should not expect the same for the behavioral sciences, or for motor control in particular. For a number of reasons, in motor control we find far fewer statements possessing sufficient generality and supporting evidence to have attained the status of a “law.” One reason is that the motor control principles have been far more difficult to discover, as they are on data from biological systems that are more variable (“noisy”) and complex than the physical systems. Often the relationships are not obvious and must be “teased apart” from the background noise or variability in order to be observed. The situation is complicated further when different principles are observed for different people (termed individual differences), which seems to suggest that different laws should exist for different individuals or for different classifications of people (e.g., children vs. adults). Even so, these motor control principles hold well in many separate sets of data and generalize to a variety of practical situations, and thus represent statements of fundamental knowledge about skilled performance.

One of the most common occurrences in daily activities is known as the *speed–accuracy trade-off*. Common sense tells us that, as we move more rapidly, we become more inaccurate in terms of the goal we are trying to achieve. For example, trying to type too fast or pour a glass of milk too quickly generates annoying mistakes; the adage “haste makes waste” has been a long-standing viewpoint about motor skills. As we will see, however, the speed–accuracy trade-off exists in different forms for different types of movement tasks; the principles of speed–accuracy trade-offs are specific to the goal and nature of the movement tasks.

Three specific types of trade-offs are presented later in this chapter. These relate to situations in which spatial or temporal accuracy, or both, are the primary demands of the movement. Theories of movement control that relate to these trade-offs are presented later in the chapter.

# Fitts' Law: The Logarithmic Speed–Accuracy Trade-Off

The first class of speed–accuracy trade-off functions occurs in situations in which the goal is to move a limb (or some other “effector”) as quickly as possible to reach or touch a target, with a minimal amount of error. Such is the goal in tasks like typing; moving a mouse-driven cursor to a desktop icon; moving the foot to the brake pedal in driving; and numerous other activities that require rapid movements to push, touch, grasp, intercept, or displace an object.

## Early Research

The first major attempt to study scientifically the relationship between the speed of a movement and its resultant accuracy is attributed to Woodworth (1899; see chapter 5 and “R.S. Woodworth on Manual Aiming”), although Fullerton and Cattell (1892) preceded his work. This work was far ahead of its time in terms of both the ideas examined in experiments and the techniques used. Woodworth proposed that aiming movements are made up of an *initial-adjustment* phase that propels the limb toward the target in an open-loop mode of control (see chapter 6) and a *current-control* phase based on visual feedback that causes the limb to “home in” on the target (see chapter 5).

At the time Woodworth’s experiments were conducted, sophisticated electronic recording techniques were not yet available; so clever methods were devised that provided practical yet precise measurements to answer the research questions. The tasks used by Woodworth involved simple repetitive line-drawing movements to a target. The participant’s task was to make the next movement the same distance as the previous movement. Movement speed was varied by changing the frequency of a pacing metronome. Studies were done with various distances, with the right and left hands, and with the eyes closed and open, in an attempt to uncover some of the fundamental relationships between speed and accuracy. Generally, Woodworth found that inaccuracy (measured as absolute error) increased as the movement speed increased, that the left hand was less accurate than the right hand (in right-handed participants), and that the increase in accuracy with decreased speed was greater when the eyes were open than when they were closed (see “R.S. Woodworth on Manual Aiming,” and [figure 5.5](#)). Most of his results have not, in general terms at least, been contradicted in more than a century of research conducted since Woodworth published his results in 1899 (Elliott, Helson & Chua, 2001). Fifty-five years later, the nature of this speed–accuracy relationship was described as a formal mathematical law by Paul M. Fitts (1954; “Paul M. Fitts” in chapter 1).

## Fitts' Research

In 1954, Fitts published a systematic analysis of the relationship between speed and accuracy that has become one of the landmark publications in the history of motor behavior research (Kelso, 1992). In the typical *Fitts' paradigm* (or *Fitts' task*), a person taps a handheld stylus (a pencil-shaped object) alternately between two target plates as rapidly as possible for a predetermined duration (e.g., 20 s). The two targets are usually rectangular and oriented as shown in [figure 7.1](#). Both the width of the targets ( $W$ ) and the distance between the center of the two targets ( $D$ ) are under the control of the experimenter and therefore can be altered to produce a large number of combinations of  $D$  and  $W$ . The task is scored as the number of taps (regardless of whether they are correct) in 20 s, but participants are instructed to limit errors (missed targets) to a minimum (in practice the error rate should be less than 1/20, i.e., 5%). A more general view of the experimental setup is shown in [figure 7.2](#).

Figure 7.1 The Fitts' paradigm. (The performer taps a stylus alternately between two targets of width  $[W]$  separated by a distance  $[D]$ .)

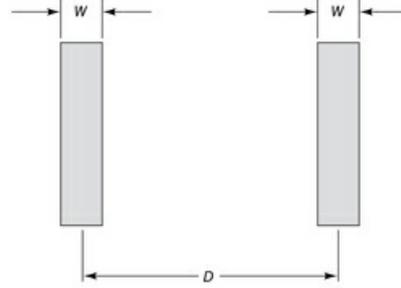
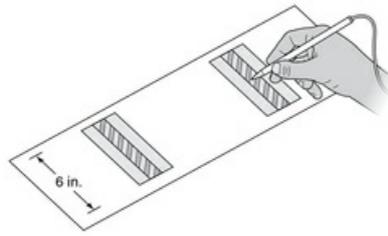


Figure 7.2 A participant performing the Fitts' tapping task.



Reprinted P.M. Fitts, 1992, "The information capacity of the human motor system in controlling the amplitude of movement," *Journal of Experimental Psychology: General* 121(3): 262-269.

### *Fitts' Law Defined*

Fitts found that the relationship between the distance ( $D$ ) of the movement, the target width ( $W$ ), and the resulting average movement time ( $T$ ) was given by the following equation:

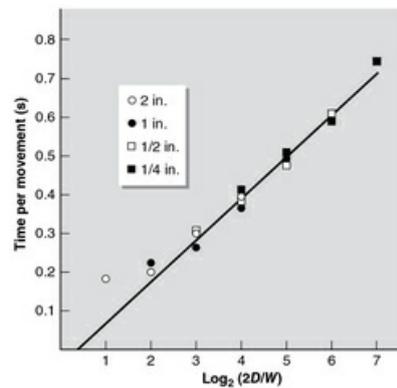
$$T = a + b[\text{Log}_2(2D/W)] \quad (7.1)$$

where  $T$  is the *average* movement time for a series of taps, computed as the trial duration (e.g., 20 s) divided by the number of taps completed in that time. For example, a 20 s trial duration divided by 50 taps in the trial yields  $20 / 50 = 0.4$  s/tap, or 400 ms/tap as the average  $T$ .

The Fitts' equation has the general form of a *linear* equation ( $Y = a + bX$ ), where  $Y$  is average  $T$ ,  $X$  is represented by the term  $\text{Log}_2(2D/W)$ , and  $a$  and  $b$  are the empirical constants of a linear equation.<sup>1</sup> (See also the section on linear empirical equations in chapter 2 and the discussion of Hick's law in chapter 3.) Therefore, a graphical plot of average  $T$  against  $\text{Log}_2(2D/W)$  should be linear (a straight line).

The data from one of Fitts' original experiments are presented in [figure 7.3](#). The values of  $D$  and  $W$  were varied experimentally by changing the arrangement of the target board (see [figures 7.1](#) and [7.2](#)) for different blocks of trials, and the resulting  $T$  was measured after participants had received some practice at these tasks. [Figure 7.3](#) illustrates the average  $T$  as a function of  $\text{Log}_2(2D/W)$ , where each of the latter values is computed by taking the values of  $D$  and  $W$ , dividing them, and looking up the value of the  $\text{Log}_2(2D/W)$  in the table of logarithms (see appendix). For example, one of the data points in [figure 7.3](#) is associated with a value of 5 on the  $x$ -axis. The task values for this particular data point had a target distance ( $D$ ) of 4 in. (10.2 cm) and a target width ( $W$ ) of 1/4 in. (0.64 cm). Thus, the value  $2D/W = 2(4) / 0.25 = 32$ .

Figure 7.3 Average movement time (T) as a function of the index of difficulty (ID) ( $\text{Log}_2 [2D/W]$ ).



Data from Fitts 1954.

As can be seen in [figure 7.3](#) for the various combinations of  $D$  and  $W$  used in Fitts' experiment, the average  $T$  lies almost perfectly on a straight line, except perhaps for the leftmost three data points (representing movements with very small ratio of  $2D/W$ ). Notice, for example, that two conditions for which the  $\text{Log}_2 (2D/W) = 6.0$  had virtually identical values for  $T$  (representing two tasks, one with  $D = 16$  in.,  $W = 1/2$  in., and another task with  $D = 8$  in.,  $W = 1/4$  in.). There are similar situations with the other data points plotted for a given value of  $\text{Log}_2 (2D/W)$ , such as 3, 4, and 5.

### Interpreting Fitts' Equation

What does it mean that the  $\text{Log}_2 (2D/W)$  plots linearly with the average  $T$  in the Fitts' task? A closer look at each of the components makes Fitts' equation easier to understand.

### Index of Difficulty

First, notice that the value of  $\text{Log}_2 (2D/W)$  seems to determine how much time was required for each of these movements, so this value seems to be related in some way to how "difficult" the particular combination of  $D$  and  $W$  was for the participant. For this reason, Fitts called this value the *index of difficulty (ID)*, which is expressed in terms of bits, taken from information theory (discussed later; see chapter 3 for a fuller discussion). Thus, in Fitts' terms, the "difficulty" of a movement task was related jointly to the distance that the limb moved and to the narrowness of the target at which it was aimed. In fact, the relationship is even more restrictive than this, as the "difficulty" of the movement is theoretically the same for any combination of  $D$  and  $W$  that has the same *ratio*. Doubling  $D$  and doubling  $W$  at the same time result in a value of  $2D/W$  that is the same, and hence the same value of  $\text{Log}_2 (2D/W)$  and the same predicted average  $T$ . Another way to say this is that the average  $T$  is linearly related to the ID, where  $\text{ID} = \text{Log}_2 (2D/W)$ .

### Empirical Constants ( $a$ and $b$ )

Next, the values  $a$  and  $b$  are the empirical constants—they are required in order for the mathematical equation of the line to fit the observed data from the experimental setting. The constant  $a$  is the *y-intercept*, referring to the value of  $T$  where the line of best fit crosses the  $T$  axis. Specifically, the constant  $a$  is the value of  $T$  when the ID is zero. But what does it mean to say that a movement has "zero difficulty"? This has been a serious problem for the understanding of the ideas surrounding the Fitts' task (see Welford, 1968, for a more thorough discussion). For our purposes, a movement with "zero difficulty" is one with a ratio of  $2D/W$  of 1.0 (because  $\text{Log}_2 [1] = 0$ ).

Therefore, the intercept refers to the situation in which the amplitude is one-half the target width, which results in targets that overlap, so that the participant's task of tapping "alternately" from one target to another actually

involves tapping up and down as quickly as possible, with essentially no accuracy requirement.

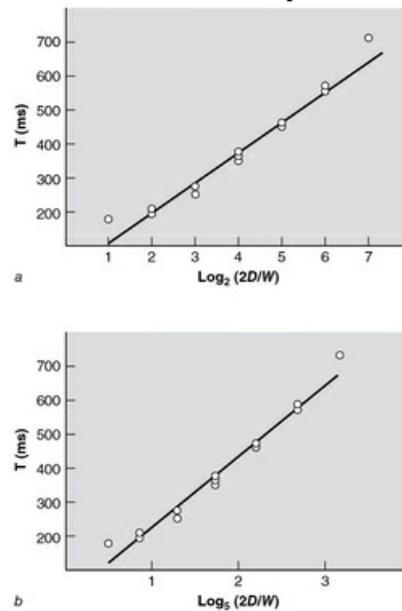
The constant  $b$  is the slope, and it is far more straightforward in its interpretation. Here, the slope refers to the added  $T$  caused by increasing the ID by one unit, which is one *bit* (binary digit; see chapter 3). In this sense, the slope refers to the *sensitivity* of the effector to changes in the ID. An example of this comes from Langolf, Chaffin, and Foulke (1976), where the results from a number of different movement situations using the Fitts' task were compared. Langolf et al. found that the slope increased progressively as the effector used was changed from the finger to the wrist to the arm. The data from Langolf and colleagues suggest that the larger and more cumbersome limbs (the arms) are more sensitive to the changes in the ID than are the fingers, which can be controlled more precisely.

Differences in the slopes of the Fitts' equation have also been shown to be sensitive to many other factors. For example, higher slopes in the Fitts' equation are typically found in older adults. (Goggin & Meeuwesen, 1992; Pohl, Winstein, & Fisher, 1996; Walker, Philbin, & Fisk, 1997; Welford, Norris, & Shock, 1969). The slope of the Fitts equation' also can be reduced considerably with practice: B. Kelso (1984) found that the slope was reduced to nearly zero following 40,000 trials conducted over 20 days of practice. Thus, the slope of the Fitts' equation represents an interaction of ID with the "controllability" inherent in the system (e.g., the effector characteristics, age of the participant, skill level). However, it is important to keep in mind that even though the slopes and the  $T$  values may be different under various conditions or with different individuals, Fitts' law still holds for any one of these. That is, the average  $T$  for any given limb still plots linearly with the ID but with different values of  $a$  and  $b$ .

## Log Term

Next, why is a Log term used in the equation, and why is the Log given to the base 2? When the idea was originally published, the theoretical rationale and interpretation was based on a dominant theme of the day—the *information theory* of communication (Shannon & Weaver, 1949; see "Uncertainty and Information Theory" in chapter 3). Recall the discussion of Hick's law of choice reaction time (RT) in chapter 3; the equation for that relationship also had a  $\text{Log}_2$  term. The  $\text{Log}_2(N)$ , in which  $N$  was the number of equally likely stimulus–response alternatives, was a measure of the amount of *information* (in bits) required to resolve the uncertainty about  $N$  alternatives. The  $\text{Log}_2$  term in Fitts' law can be seen in a similar way:  $2D/W$  is related to the number of possible *movements*, and the  $\text{Log}_2(2D/W)$  is the information required (in bits) to resolve the uncertainty among them. However,  $\text{Log}_2$  is not a special base. The relation between  $T$  and  $\text{Log}_n(2D/W)$  would be linear regardless of the base of the logarithm.  $T$  is a negatively accelerating function of  $(2D/W)$ , and this function is linearized with any log transformation. In [figure 7.4](#) we plot  $T$  as a function of  $\text{Log}_2(2D/W)$  as well as  $\text{Log}_5(2D/W)$  and show that the strength of the linear fit is unchanged. Thus, although  $\text{Log}_2$  has significance in terms of information theory, we will need a principled account that generates a  $\text{Log}_2$  prediction to emphasize the importance of ID.

Figure 7.4 Original data from Fitts (1954) experiment 1, stylus tapping task.



## Speed–Accuracy Trade-Off

Fitts' law implies an inverse relationship between the “difficulty” of a movement and the speed (i.e., the time) with which it can be performed. Increasing ID decreases speed (i.e., increases  $T$ ). One way to think about this is that the individual in some way “trades off” speed against accuracy, and this trade-off is done so that the rate of information processing ( $ID/T$ ) is held constant. In addition to this strict view in terms of the constancy of information processing, people presumably have some control over their strategy in moving. They can move very quickly at the “expense” of being less accurate, or they can move very accurately at the “expense” of being slower. In this way, Fitts' law has been fundamental in describing one particular aspect of the *speed–accuracy trade-off*, or the performer's capability to change the control processes so that speed and accuracy are kept in some balance. In the case of Fitts' law, the participants were told to “emphasize accuracy rather than speed,” and error rates averaged less than 5%. Thus, Fitts' law describes how  $T$  is traded off, under different values of ID, in order to maintain accuracy. In a later section, we will see how errors are traded off in order to determine the speed of limb movement.

## Subsequent Research on Fitts' Law

It may not be obvious why so much attention has been paid to a single principle of motor performance. There appear to be several reasons. First, as we have seen so often, human motor behavior is complex and challenging to understand. Because of this, it is very difficult to provide precise mathematical descriptions of behavior that have general applications. Yet Fitts' law provides just that, and Fitts created it when almost no precise mathematical work was being done in motor behavior. Second, the law applies in many different situations and a number of variations of the original Fitts' task. Thus, it appears to represent some fundamental relationship that governs many examples of motor behavior. Third, since the publication of Fitts' law, no investigations have shown it to be fundamentally incorrect, although there now exist alternative ways of dealing with the relation between speed and accuracy. (One way is to change the temporal and spatial accuracy demands of the task, which is described later in this chapter.) In the next few sections we document some diverse research directions and applications that have been inspired by Fitts' law during the past 60+ years.

### *Modifications to the Fitts' Equation*

Modifications to the basic Fitts' equation have been made in an attempt to achieve a better *fit*—which refers to the amount of variance in the experimental data that can be explained by the equation. Modifications to the definition of the ID by Welford (1968; Welford et al., 1969) and MacKenzie (1989) provided slightly better fit, as too did a consideration of the width of the effector (e.g., a dowel inserted into a target hole) that was being moved into the target area (Hoffmann & Sheikh, 1991). In contrast to the logarithmic relationship between  $D$  and  $W$  proposed by Fitts, an exponential relationship described in terms of a *power law* was suggested by Kvålseth (1980), where

$$T = a(D/W)^b \quad (7.2)$$

Numerous other modifications to the Fitts' equation were reviewed by Plamondon and Alimi (1997). Although many of these have served to improve the overall fit, it should be kept in mind that the Fitts' equation often explains well over 90% of the variance in most, if not all, data sets. Thus, the improvement in accuracy gained by changes to Fitts' equation is relatively small. Fitts' original equation for ID has been very useful in explaining the performance of both one-dimensional tasks (see [figure 7.1](#)), and two-dimensional tasks, such as the angular moves of a cursor on a computer screen (Murata, 1999). For three-dimensional movements, however, Murata and Iwase (2001) found that Fitts' original definition of ID explained only 56% of the variance in the data. They found a much better fit of the experimental data with an additional term in the definition of ID, compared to Fitts' equation. The inclusion of an additional term that considered the angle of deviation (from vertical) in the  $z$ -dimension toward the target [ $\sin(\theta)$ ] improved the amount of explained variance to 73%.

### *Discrete Fitts' Task*

Can the fundamental principle of Fitts' law be applied to other, more “natural” movement situations? Fitts and Peterson (1964) showed that the principle could be applied to a discrete-aiming task in which a stylus is aimed at a target in a single, discrete move. The task required a single move as quickly and accurately as possible to a target of fixed distance ( $D$ ) from a starting position and with a given target width ( $W$ ). Consequently, Fitts and Peterson (1964) suggested that people trade off speed for accuracy in discrete tasks in much the same way they do for continuous, cyclical movements. However, recent research suggests that the issue is much more complicated than this (Guiard, 1993, 1997; Schaal, Sternad, Osu, & Kawato, 2004; Smits-Engelsman, Van Galen, & Duysens, 2002). Other research since the time of Fitts' original work has extended his ideas in a number of different ways.

### *Generality of Fitts' Law*

Since the publication of Fitts' law, investigators have studied it in a variety of contexts, revealing that the principle shows remarkable generality and very few exceptions (see “An Exception to Fitts' Law?”). For example, in addition to describing the aiming-accuracy principle for young adults, the Fitts relationship holds well for children (Hay, 1981; Schellekens, Kalverboer, & Scholten, 1984) and for older adults (Goggin & Meeuwse, 1992; Pohl et al., 1996; Walker et al., 1997; Welford et al., 1969). Although Fitts' law was initially based on movements of the upper limbs, the principle has been found to hold when different effectors are compared, such as the foot, arm, hand, and fingers (Drury & Woolley, 1995; Langolf et al., 1976); when movements are conducted underwater (R. Kerr, 1973, 1978) and in space flight (Fowler, Meehan, & Singhal, 2008); and when the movements required are so small that they must be viewed under magnification (Langolf et al., 1976). Fitts' law even applies when tasks are imagined and the movement is not actually produced (Cerritelli, Maruff, Wilson, & Currie, 2000; Decety & Jeannerod, 1996), and when the difficulty of a Fitts' task is only perceived (Augustyn & Rosenbaum, 2005; Grosjean, Shiffrar, & Knoblich, 2007).

Fitts' law also applies in the context of everyday activities. In Fitts' (1954) original work, two other experiments were reported in which participants either placed discs over pegs or inserted pegs into holes, where  $D$  was the distance between the targets and  $W$  was the amount of *tolerance* between the size of the hole and the diameter of the peg. With ID defined in this way, the Fitts' equation predicted  $T$  very well. Movement-time effects also follow Fitts' law when one compares tasks in which participants point at, reach for, and grasp objects of different sizes

(Bootsma, Marteniuk, MacKenzie, & Zaal, 1994; Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987). As well, Fitts' law describes well the positioning movements of various computer-input devices such as keys (Drury & Hoffmann, 1992; Hoffmann, Tsang, & Mu, 1995), joysticks (Card, English, & Burr, 1978), computer "mice" (Card et al., 1978; MacKenzie & Buxton, 1994; Tränkle & Deutschmann, 1991), and head-pointing devices (Andres & Hartung, 1989; Jagacinski & Monk, 1985). Other ergonomics-related situations also appear to have benefited from the study of Fitts' law, such as the length of screwdrivers and crowbars (Baird, Hoffmann, & Drury, 2002) and alterations in the sizes and distances of monitor icons during computer interactions (Balakrishnan, 2004). The review by Plamondon and Alimi (1997) documents many other demonstrations and applications of Fitts' law.

### *Applications of the Fitts' Task*

The original Fitts' task is a rather strange movement situation, and some have felt that the particular configuration of alternate tapping is not very representative of many real-life tasks (e.g., Schmidt, Zelaznik, & Frank, 1978). Despite its peculiarities, however, the Fitts' task (or slight variations of it) has long been found useful as diagnostic measures in therapeutic situations. For example, a common diagnostic tool used by neurologists in clinical examinations is called the "finger–nose test" (Desrosiers, Hébert, Bravo, & Dutil, 1995). In this test the patient is asked to touch his or her nose, then extend the arm to touch a small target such as the tip of the neurologist's finger, touch the nose, and so on, repeating these alternations as rapidly as possible in a given time frame (e.g., 20 s). The number of successful cycles is counted, and the result is compared to established age-related normative data (Desrosiers et al., 1995). Sometimes this task is used to compare performances of the two upper limbs within an individual who might have neurological damage to one side. This "Fitts-like" task has proven to be a useful, reliable, and valid diagnostic tool (Gagnon, Mathieu, & Desrosiers, 2004).

### *Importance of Fitts' Law*

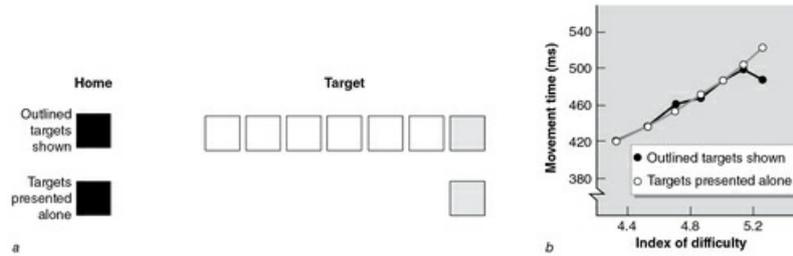
Lastly, one of the most powerful motivations for scientists working toward an explanation is the existence of a well-established principle or *law*—one that has survived the test of time and has been shown to be applicable to a wide variety of situations or people. Fitts' law certainly meets these criteria. Thus, one natural outgrowth of this work was an attempt to understand the movement control processes that produced the particular relations described by Fitts' law. That is, investigators began theorizing about *why* Fitts' law occurs. We have already mentioned viewpoints based on information theory, whereby the ID was taken by Fitts (1954) to be a measure of the amount of information needed to resolve the uncertainty about the movement. However, dissatisfaction with this theoretical perspective led researchers to propose alternative ways of explaining the kinds of speed–accuracy trade-offs that Fitts and others had observed in their data. These theoretical perspectives are dealt with in later sections of this chapter.

### *An Exception to Fitts' Law?*

There are only a very few exceptions to the general principle that increases in the ID result in longer Ts. Adam, Mol, Pratt, and Fischer (2006) had participants make discrete, aimed movements to one of seven target locations on a computer touch screen. Because the targets always remained the same size, changes in ID were produced by changes in the distance from the home position to the target. For each trial, the specific target to which the participant moved was a green square that appeared on the screen after the participant touched the home position. In one set of conditions, the green target square appeared alone ([figure 7.5a](#), line 2). In another condition, the seven possible target locations used were outlined in black and remained on screen at all times. The green target used for any given trial was achieved by coloring one of the target outlines when the participant touched the home position, leaving the other nontargets as unfilled outlines as shown in [figure 7.5a](#) (line 1).



Figure 7.5 (a) An apparent exception to Fitts' law occurred when participants moved from the home position to the target located in the farthest right position in the lower panel (line 1, containing the outlined target boxes), compared to movements made when targets were presented alone (line 2). (b) The exception is seen as a reduction in movement time to the seventh target position compared to the target with a smaller ID to its left (filled circles in the figure).



Adapted from Adams et al. 2006.

The results of the study are illustrated in [figure 7.5b](#). For trials in which the targets were presented alone (without the seven boxes), a linear increase in T accompanied increases in ID, as predicted by Fitts' law. This was true also for the condition with the nontarget boxes; but, peculiarly, only for targets 1 through 6. An exception to Fitts' law was found for the most distant (seventh) target, as the T for this target was *shorter* than that for the previous (sixth) target (which had a *smaller* ID). In a follow-up study, Pratt, Adam, and Fischer (2007) used outlined target contexts of three boxes, rather than seven, but adjusted the target by coloring the leftmost outlined box in one condition, the middle box in another condition, and the rightmost box in a third condition. The results replicated the findings from Adam and colleagues (2006)—regardless of the target arrangement and the specific target IDs used, the rightmost of the outlined targets always violated Fitts' law relative to the adjacent target located to the left.

This exception raises the question about (a) whether Fitts' law needs to be modified, or (b) whether these particular experimental conditions somehow fall outside of the domain of Fitts' law. These findings add an intriguing twist to the nearly ubiquitous finding that T always follows the ID of the task. Apparently, the visual context in which a target is presented had a modifying effect on the movement, perhaps by defining an end boundary that somehow sped the delivery of the limb to the target. There are other relatively complex findings here, such as the fact that the errors on the seventh target ([figure 7.5a](#)) were far larger than on the sixth target, which occurred in both presentation conditions. These results should provide much fodder for discussion and further research about manual aiming and Fitts' law, as such *exceptions* usually do.

## Linear Speed–Accuracy Trade-Off (Schmidt’s Law)

As noted in the previous section, the Fitts’ paradigm involves a unique movement situation that is not typical of all everyday tasks and that produces one specific type of speed–accuracy trade-off. In an alternate approach, the Fitts’ paradigm was changed to examine the speed–accuracy effects in tasks that require a single, aimed movement—requiring mainly *preprogrammed* actions.

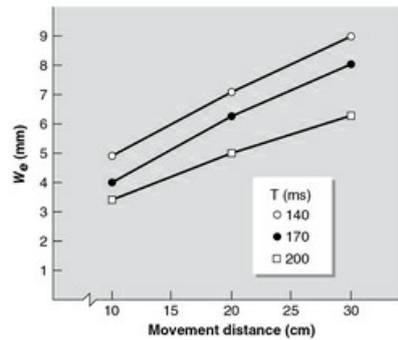
### Discrete, Temporally Constrained Paradigm

The revised paradigm used rapid discrete movements of a stylus from a starting position to a target 10 to 60 cm away (Schmidt et al., 1978; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). But rather than moving as quickly as possible, as in the Fitts and Peterson (1964) experiment, the participants were required to complete the movement in a particular *goal movement time* ( $T$ ) that was specified by the experimenter. As well, the movements were aimed at a thin target line that did not change in width ( $W$ ). Thus, both timing accuracy *and* distance ( $D$ ) accuracy were required of participants. Performance of the goal  $T$  was achieved with augmented feedback after each trial about whether the movement was too fast or slow. Only those movements that conformed to the goal  $T$  (i.e., movements that were within  $\pm 10\%$  of the  $T$  goal) were used for analysis.

One experiment used a factorial combination of three movement distances (10, 20, or 30 cm) and three goal  $T$ s (140, 170, and 200 ms), resulting in nine different combinations of  $D$  and  $T$ , performed by participants in separate sessions. Errors were measured as the within-participant standard deviation (SD) of the movement distance, which defined the “spread” or inconsistency of movements aimed at the target (see chapter 2). In keeping with the Fitts tradition, these errors are termed *effective target width* ( $W_e$ ), which defines the effective size of the “target the participant is using” when moving with a particular  $T$  and  $D$ . Notice also that this paradigm is different from the Fitts’ paradigm in that  $W_e$  is the dependent variable, with  $D$  and  $T$  being the independent variables; in the Fitts’ paradigm,  $T$  is the dependent variable, and  $D$  and  $W$  are the independent variables.

[Figure 7.6](#) shows a plot of  $W_e$  for the various combinations of  $D$  and  $T$ . There was a clear increase in variability as  $D$  increased; the effect was almost linear for the various  $T$ s studied. Also,  $W_e$  increased systematically for any given movement distance as the  $T$  decreased. Both increasing  $D$  with  $T$  fixed, and decreasing  $T$  with  $D$  fixed, imply increases in average velocity (in cm/s). Thus, we can see these data as another example of the principle that increasing movement velocity decreases spatial accuracy (as in Fitts’ law) but for very rapid movements in the case of these movements.

Figure 7.6 Effective target width ( $W_e$ ) in a rapid single-aiming task as a function of the movement time (T) and movement distance. Note in the original Schmidt et al. (1979) paper amplitude (A) was referred to instead of  $D$  for distance.

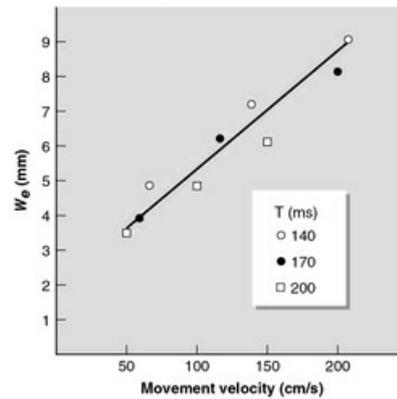


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This speed–accuracy trade-off can be seen somewhat more easily in [figure 7.6](#), where  $W_e$  in [figure 7.6](#) has been plotted as a function of the average velocity, defined as  $D/T$ . Now the relationship between  $W_e$  and  $D/T$  is nearly *linear* across a range of movement velocities, and most of the individual data points fall reasonably close to a line of best fit. Thus, the data in [figure 7.7](#) can be expressed in terms of a linear equation in which

$$W_e = a + b (D / T) \quad (7.3)$$

Figure 7.7 Effective target width ( $W_e$ ) as a function of the average velocity ( $D / T$ ).



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For the data in [figure 7.7](#), the value of  $a$  (the intercept) was 2.12 mm, and the value of  $b$  (the slope) was  $0.033 \text{ mm} \cdot \text{cm}^{-1} \cdot \text{s}^{-1}$ . Notice that for very different distance and movement time combinations, but with the ratio of  $D$  and  $T$  about the same, the  $W_e$  was produced.

These effects have been produced in a number of separate experiments using various tasks—even using eye movements (Abrams, Meyer, & Kornblum, 1989; Patla, Frank, Allard, & Thomas, 1985). This linear speed–accuracy trade-off effect is stable enough for some to name it a law of rapid actions, and in memory of Richard A. Schmidt, we join others in naming this trade-off Schmidt’s Law (e.g., Flach, Guisinger, & Robison, 1996; Jagacinski & Flach, 2003; Keele, 1986; Sanders & McCormick, 1993).

## Relationship to Fitts’ Law

The variables in the discrete aiming paradigm are essentially the same as those in the Fitts’ paradigm (but used slightly differently, as we have seen); and yet the speed–accuracy trade-off is considerably different—*logarithmic* in the Fitts’ paradigm, and *linear* in the temporally constrained paradigm. Try a little algebra and convert the Fitts relation into the Schmidt relation, or vice-versa. It cannot be done. Although the algebraic characteristic of these two relations does not prove that they are capturing independent aspects of movement control, it does suggest that such might be the case. Thus, one can ask the quest *What are the crucial conditions responsible for producing these two different trade-off functions?* Two hypotheses have been suggested, which are related to the key differences between the two paradigms.

### *Movement Brevity or Feedback Hypothesis*

Remember that the linear speed–accuracy trade-off has been found using discrete aiming movement tasks in which  $T$  is very brief—probably less than the amount of time required to detect that an error has been made and to issue a correction (e.g., 200 ms or less in the data from Schmidt et al., 1979, in [figures 7.6](#) and [7.7](#)). One obvious hypothesis is that the logarithmic trade-off occurs for movements that are at least partially governed by *feedback-based corrections* (e.g., the Fitts’ task), whereas the linear trade-off occurs for tasks that are entirely *programmed*. In this view, the two trade-off functions are not in “competition,” but rather are functions that describe different emphases on movement control—open-loop versus closed-loop emphases.

This does *not* mean, however, that Fitts’ law holds for movements with long  $T$ s and that the linear trade-off holds for movements with short  $T$ s. Whereas  $T$  is certainly a factor in determining whether a movement will or will not be preprogrammed, the hypothesis is that  $T$  provides a *lower limit* for feedback control; that is, movements with very short  $T$ s cannot be under closed-loop control. However, movements with long  $T$ s could be under open-loop control provided that the environment is stable, the task is well learned, errors are not too “costly,” and so on. For example, Zelaznik, Shapiro, and McClosky (1981) found that 500 ms movements showed a linear trade-off when

attention was occupied with the performance of a secondary task.

### *Temporal Precision Hypothesis*

Another obvious difference between the paradigms that produce the logarithmic and the linear speed–accuracy trade-offs is the intended goal  $T$ . The single-aiming paradigm uses *controlled*  $T$ s (i.e.,  $T$  goals that are longer than the participants' minimum  $T$ ), whereas in the Fitts' paradigm the  $T$  goal is to be as fast as possible while maintaining a high accuracy rate. Some have suggested that requiring the participant to achieve a particular  $T$  goal, per se, causes the shift to a linear speed–accuracy trade-off (Meyer, Smith, & Wright, 1982; Wright & Meyer, 1983). Some evidence favoring this view has been reported by Zelaznik, Mone, McCabe, and Thaman (1988), who found that a relaxation of the *precision* demands in matching the  $T$  goal diminished the strength of the linear speed–accuracy relationship and increased the strength of the Fitts relation.

What effects might the  $T$  goal have on the motor control processes in these two paradigms? Although the control mechanisms will be the focus of discussion later in this chapter, it is important to note at this point that the discrete-aiming,  $T$  goal paradigm encourages participants to adopt a noncorrected, single-impulse control strategy, whereas the ballistic (minimized  $T$ ) goal requirements of the Fitts' task often result in one or more corrective actions (Jagacinski & Flach, 2003; Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Meyer, Smith, Kornblum, Abrams, & Wright, 1990).

Impressive support for this hypothesis was provided in a clever experiment by Carlton (1994) in which corrective submovements were examined in two movement tasks. Participants produced a 400 ms goal  $T$  in one task (a timed task) and moved as rapidly as possible in the other task (a ballistic task). For each participant, the dispersion of 95% of the aimed movements in the timed task was used to manufacture the target plate for the ballistic task; that is, a within-participant measure of variability in one task ( $W_e$ ) was used to determine the size ( $W$ ) of that participant's target in the other task. With the spatial accuracy demands of each task now closely equated, Carlton found that the ballistic task condition resulted in corrective submovements on 93% of the trials, whereas corrections occurred on less than 20% of trials in the timed task. This difference in the frequency of corrective submovements between the two tasks is even more impressive when one considers that, in the timing task,  $T$  was about 90 ms *longer* than in the ballistic task: If  $T$  were the sole determinant of corrective submovements here, then presumably there should have been more time available for a correction to occur in the timed task.

Carlton's (1994) study also has a behavioral finding. As the width of the target was constructed based on plus or minus two standard deviations in distance ( $4W_e$ ), the Fitts' task, if it is like Schmidt's law, should exhibit a 400 ms value of  $T$ . The fact that  $T$  was about 90 ms less in Fitts' task supports the idea that Fitts' and Schmidt's law are capturing unique aspects of motor control.

Thus, it appears that the feedback and the temporal-precision hypothesis converge on a similar issue regarding the difference between the linear and logarithmic speed–accuracy trade-offs. A linear trade-off appears to occur in movement tasks that encourage a preprogrammed, open-loop control process; a logarithmic trade-off occurs in the performance of tasks that encourage closed-loop, corrective processes. The nature of these control strategies is described in more detail later in this chapter.

## Temporal Speed–Accuracy Trade-Off

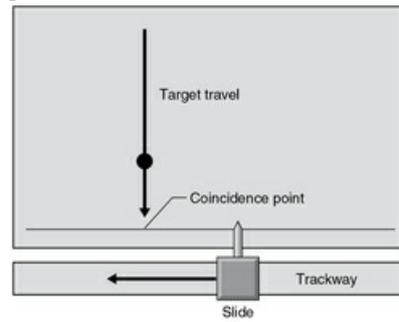
Certainly the view is widespread that when we do things faster, we do them less precisely; and, as we have seen in the previous sections, there is considerable evidence to support it. However, the evidence that we have considered so far describes the trade-off that occurs in reference to *spatial* accuracy. What happens when the focus is on *temporal* accuracy? We deal with these situations next.

### Discrete Anticipation-Timing Tasks

In tasks requiring anticipation and timing, such as hitting a baseball, the individual must monitor the environmental situation (the flight of the ball) and decide when to swing so that the bat arrives at the plate at the same time as the ball. In chapter 3 we mentioned that these tasks require both *receptor anticipation* (of the ball flight) and *effector anticipation* (of one's internal movement processes). Errors in *timing* result if the bat arrives earlier or later than the ball. What is the effect on errors in timing of increasing the speed (decreasing the T) of the limb or bat?

Early research on this topic (Schmidt, 1967, 1969b) required participants to move a slide along a trackway so that an attached pointer would “hit” a target moving rapidly at right angles to the trackway ([figure 7.8](#)), with a follow-through permitted. Accuracy in this task was measured as errors in time—either early or late with respect to the target arrival. Participants produced a movement that was of “maximal” or “moderate” speed, and at each of four movement distances (15, 30, 45, and 60 cm).

Figure 7.8 A coincident-timing task (top view). (A target on a belt moves directly toward the participant, who attempts to move the pointer so that the two “coincide” at the coincidence point.)



Reprinted, by permission, from R.A. Schmidt, 1967, *Motor factors in coincident timing*. Unpublished doctoral dissertation (Urbana, IL: University of Illinois).

In [table 7.1](#), the absolute errors in timing are given as a function of four movement distances (15, 30, 45, and 60 cm) and two movement-speed instructions (to move either at a maximal speed or at a moderate speed). Notice that the absolute error in timing (for any movement distance) was uniformly smaller (20% on the average) for the “maximal” instruction than for the “moderate” instruction. Thus, when the person was performing the task more “violently,” with a smaller  $T$  and larger movement velocity, the timing accuracy in these conditions actually *improved*. Such findings seem to contradict the notion of the speed–accuracy trade-off as discussed previously in this chapter.

**Table 7.1 T, Absolute Error in Timing, and Variable Error in T as a Function of Movement Distance and Instructions in a Timing Task**

Movement distance	MOVEMENT SPEED INSTRUCTIONS					
	MAXIMAL			MODERATE		
	T	AE	T VE	T	AE	T VE
15 cm	76	20	3	139	24	9
30 cm	123	23	7	209	27	13
45 cm	144	25	7	253	30	12
60 cm	206	28	9	274	41	13
Averages	137	24.0	6.5	219	30.5	11.7

AE = absolute error; T VE = variable error of T; all measured in milliseconds.  
Adapted from Schmidt 1967, 1969c.

At least two explanations for these effects are possible. First, when the person moved the handle more rapidly, the movement was initiated when the target was closer to the coincidence point than was the case when the movement was slower. That is, the participant waited longer before initiating the rapid movement. This extra time to view the stimulus may have provided a more accurate receptor anticipation (the estimate of when the target would arrive at the coincidence point), which would permit a more precise estimate of when the person should initiate the movement.

A second explanation is that the rapid movements themselves were more consistent than the slower moves. The variable error (the within-participant SD as discussed in chapter 2) of the Ts (table 7.1) was about 44% smaller for the rapid movements than for the slower ones. Thus, a second feature of fast movements is more *temporal stability* from trial to trial than for slower movements. This can be seen as an effector anticipation advantage: The person can predict with greater accuracy when the limb will arrive at the target if the movement is rapid because the trial-to-trial variability in the movement's travel time is smaller.

## Discrete Movement-Timing Tasks

Newell, Hoshizaki, Carlton, and Halbert (1979) performed a number of experiments on the temporal consistency of movement, and they provided perhaps the best documentation of the effects of T on discrete timing. They used a ballistic-timing task in which the participant moved a slide along a trackway. The participant's primary goal was to produce a specific goal T. Newell and colleagues used a number of Ts (ranging from 100 to 1,000 ms) combined with a number of movement distances (ranging from 0.75 to 15 cm), as can be seen in table 7.2.

	T (MS)					
	100		500		1,000	
Distance (cm)	5	15	5	15	5	15
Velocity (cm/s)	50	150	10	30	5	15
VE <sub>t</sub> (ms)	10.8	9.0	74.6	42.8	125.7	91.2
VE <sub>t</sub> /T (%)	10.8	9.0	14.9	8.6	12.6	9.1

From Newell et al. 1979.

The primary dependent measure of interest was the variable error in timing (VE<sub>t</sub>), defined as the within-participant SD of the T<sub>s</sub> about the participant's own mean, which represents a measure of an individual's inconsistency in timing. As shown in [table 7.2](#), for the 5 cm movements, the inconsistency in movement timing increased markedly as the T increased from 100 to 1,000 ms (VE<sub>t</sub> increased from 10.8 to 125.7 ms). The effect was similar for the 15 cm movements, with VE<sub>t</sub> increasing from 9.0 to 91.2 ms. Thus, it appears that this effect is like that seen in anticipation timing (Schmidt, 1967, 1969b); a shorter T, given the same distance, produces *increased* movement-timing consistency.

An even more interesting feature of these findings is that the timing error is *proportional* to T. In the fourth line of [table 7.2](#) are the VE<sub>t</sub> values divided by the T, multiplied by 100 to convert them to percentage values. If the VE<sub>t</sub> is proportional to T, then the VE<sub>t</sub>/T values will be similar for any T from 100 to 1,000 ms. This did not occur, movements with greater average velocity values had smaller percentage VE values.

This effect of T can perhaps be thought of as one that follows from the generally held view that short intervals of time are “easier” to estimate or produce than are long intervals of time. To illustrate, do this simple experiment. First, using a millisecond timing app or program, and without looking, estimate 1 s (1,000 ms) by pressing the button and releasing it at the appropriate time. Record the actual time for each of 10 trials. Now, do the same task again but use a target interval of 2 s (2,000 ms). You should find that the shorter interval is much “easier” to produce accurately; you should be much closer, on the average, to the target interval with the 1,000 ms task than with the 2,000 ms task. And, if you had calculated VE for your performances, your VE for the 2,000 ms task should be roughly twice that for the 1,000 ms task. The processes responsible for determining the duration of the intervals are variable, and they seem to be variable in direct proportion to the *amount* of time that is to be produced. Because the movements in the experiments of Newell and colleagues (1979) were, in effect, based on processes that take time, it is reasonable that they should have been variable in time in nearly direct proportion to the amount of time that they occupied.

There is considerable evidence that, generally speaking, the VE<sub>t</sub> (or inconsistency) in the production of some interval of time tends to be a nearly constant proportion of the amount of time to be produced, at least within broad limits. For example, Michon (1967) found essentially this effect with rhythmic tapping at different rates; Gottsdanker (1970) found the effect for RT (with participants who had long RTs having greater within-participant VE<sub>t</sub> of their own RTs); and Schmidt and colleagues (1979) found these effects for aiming tasks in which the T<sub>s</sub> were controlled. This well-documented finding is an apparent contradiction to the speed–accuracy principles described previously in this chapter. Here, increased speed (by decreasing the T) produces increases in accuracy in *timing*, whereas earlier we showed that increasing the speed resulted in diminished *spatial* accuracy. The finding that variability in timing is proportional to the duration of the interval to be timed is consistent with a long-held finding in the psychology of perception literature called *Weber's law*.

## Temporal Consistency and Movement Velocity

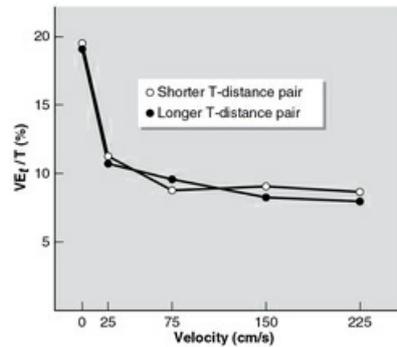
The T is not the only factor that strongly affects the VE<sub>t</sub>—the movement's average velocity (i.e., the movement distance divided by the T, usually in cm/s) has a strong influence as well. Refer again to [table 7.2](#) (Newell et al., 1979) and consider the VE<sub>t</sub> for the various values of movement velocity (second line in the table). Notice that for a given T (e.g., 100 ms), the movement with the smaller movement distance, and hence the lower movement velocity, has a slightly higher VE<sub>t</sub> (10.8 ms for the 5 cm movement, 9.0 ms for the 15 cm movement). This effect

is even stronger for the 500 ms and 1,000 ms movements in the same table; the movement with the higher velocity had a smaller timing error, even when the T was held constant.

To see this effect expressed another way, examine the  $VE_t/T$  (commonly known as the coefficient of variation) values presented on the bottom line of [table 7.2](#). Because the division by T theoretically corrects for the effects of T on the timing error (since these two variables are nearly proportional), any changes in  $VE_t/T$  as a function of movement velocity must be due to something *other than* T. Here, the movements with the longer movement distance (and hence the greater movement velocity) have smaller  $VE_t/T$  values. For the three Ts, these values were about 9% for the 15 cm movements and from 10% to 14% for the 5 cm movements. Increasing movement velocity improved temporal consistency.

Newell, Carlton, Carlton, and Halbert (1980) studied these velocity effects in experiments that were more thorough than those reported in the earlier paper (see Newell, 1980, for a review). Various movement distances (ranging from 1.5 to 67.5 cm) and Ts (ranging from 100 to 600 ms) were used in combination, producing a set of velocity values that ranged from 5 to 225 cm/s. The  $VE_t$  was studied as a function of these variations in velocity; we have converted these data to the  $VE_t/T$  measure here so that they can be compared to the findings in the previous section (see [table 7.2](#)). The 1980 data of Newell and colleagues (experiment 3) are shown in [figure 7.9](#), where the  $VE_t/T$  is plotted against movement velocity. As the velocity increased, the errors in timing decreased markedly at low velocities, and decreased more gradually with further increases in velocity. Similar effects have been seen in experiments involving wider ranges in velocities and distances (Newell, Carlton, Kim, & Chung, 1993; Jasiewicz & Simmons, 1996). This *velocity effect* is yet another example of the temporal speed–accuracy trade-off.

Figure 7.9  $VE_t$  (expressed as  $VE_t / T$ ) as a function of the movement velocity. (Dividing  $VE_t$  by  $T$  theoretically “cancels out” the effect of  $T$  on errors.)



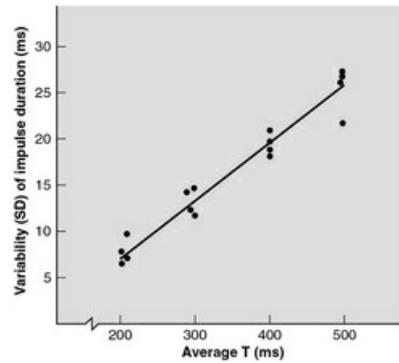
Adapted from Newell et al. 1980.

An interesting application of these findings relates to baseball: As a batter swings “harder” (with a smaller  $T$ , a larger movement distance, or both), the errors in timing should tend to decrease, not increase. Note that this prediction is for errors in *timing* and does not relate to errors in *spatial* accuracy; we consider these issues in more detail later in the chapter.

## Repetitive Movement-Timing Tasks

The finding that movement duration becomes more consistent in time as the  $T$  decreases has been shown in tasks in which the participants make a discrete movement with the intention of achieving a specific goal  $T$ . A similar finding also exists for tasks in which the participants make a repetitive series of timed movements. For example, Schmidt and colleagues (1978, 1979) studied this problem by having participants make rhythmic back-and-forth movements of a lever in time to a metronome. The participant exerted timed forces with a strain gauge on the handle. There were four different goal  $T$ s (200, 300, 400, and 500 ms), and the major concern was the variability in the duration of the force bursts (i.e., impulses) produced by muscular action during these movements. The results of this experiment are illustrated in [figure 7.10](#), where the within-participant variability in impulse duration is plotted against the  $T$  imposed by the metronome. The strong, nearly proportional relation found between these two variables is certainly in keeping with the data presented in the previous section about movement durations as a whole.

Figure 7.10 Variability in impulse duration as a function of the movement time (T).



Reprinted, by permission, from R.A. Schmidt, H.N. Zelaznik, and J.S. Frank, 1978, Sources of inaccuracy in rapid movement. In *Information processing in motor control and learning*, edited by G.E. Stelmach (New York: Academic Press), 197.

### *Synchronization and Continuation Tasks*

The back-and-forth, force-burst task used in the studies by Schmidt and colleagues (1978, 1979) represents a variation of repetitive timing tasks that have been studied for over a century (e.g., Bartlett & Bartlett, 1959; Dunlap, 1910; Stevens, 1886; Woodrow, 1932). There are two fundamental versions of this task. The participant's goal in the *synchronization task* is to produce a motor action (such as a finger movement) resulting in a "tap" that coincides with an external perceptible event (such as the auditory beeps of a metronome). In the *continuation task* (Stevens, 1886), a typical trial begins with a series of synchronization taps; then at some point the experimenter turns off the pacing stimulus (e.g., metronome), and the participant's goal is to continue tapping at the same pace. Both the synchronization task and the continuation task have been used in numerous investigations of human motor performance.

One of the curious findings with the synchronization task is a *negative asynchrony*—that is, participants tend to produce taps about 20 to 40 ms before the synchronization tone appears. Aschersleben's (2002) review of the evidence shows that the asynchrony is larger in musically untrained than in trained participants and that the amount of asynchrony can be reduced with practice and augmented feedback (see chapter 11). The suggestion is that negative asynchronies arise due to a closed-loop process in which feedback from the motor output is compared to the auditory stream from the pacing stimulus. The feedback information requires time to be recognized as a tap. Thus, to perceive simultaneity the tap occurs before the beat so that the central representations of the two auditory consequences are perceived as synchronous. Alternative, viable hypotheses exist, however, and the negative-asynchrony effect continues to stimulate a vibrant research area (e.g., Mates & Aschersleben, 2000; Repp, 2001, 2005).

In some respects the continuation task may be considered a simpler version of timing than the synchronization task, in that there is no objective, pacing stimulus to anticipate. For example, Balasubramaniam, Wing, and Daffertshofer (2004) found that movement trajectories were quite "smooth" when participants produced finger taps in the absence of a pacing signal. In contrast, producing finger taps in time with a metronome, either "on the beat" (synchronizing) or "off the beat" (syncopation), resulted in considerable asymmetry in terms of the kinematics. The downward deflections of the finger to produce a tap, regardless of whether they were made on or off the beat, were produced much faster than upward movements. These asymmetries were associated with timing accuracy, possibly indicating the use of velocity changes as an error correction strategy (Balasubramaniam, 2006).

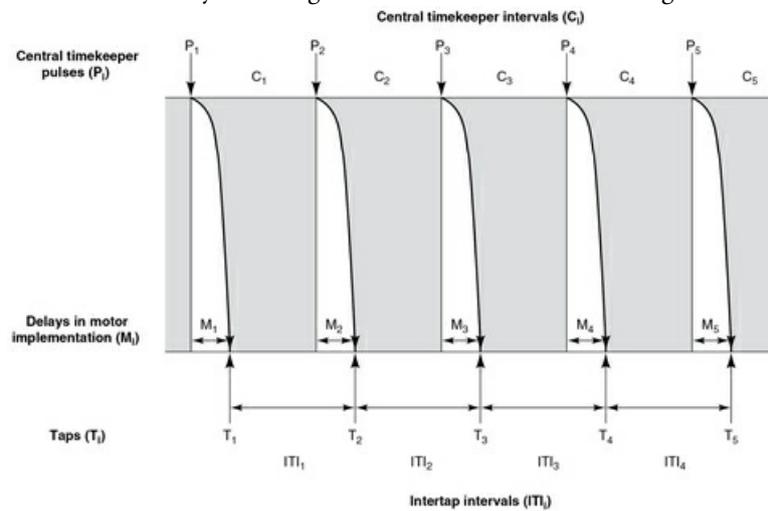
However, in other respects the continuation task is more complex than the synchronization task. In the absence of the pacing stimulus, the participant must establish a central representation of time and adjust performance based on a memory for the pacing rate. Much of the research in the past four decades has been based on an open-loop, hierarchical model of timing performance using the continuation task, which we consider next.

### *Wing-Kristofferson Hierarchical Timing Model*

Recall that in the continuation task, a participant synchronizes a particular movement (e.g., a tap) with a series of paced tones. After about 20 tones have been presented, the metronome is turned off and the participant continues to produce about 30 more taps. Performance of these latter taps is of primary interest. As we have noted several times previously in the chapter, variability in timing is related closely to the  $T$ s of these intertap intervals. As the mean intertap interval decreases, the overall consistency increases. However, something else goes on here as well. In Stevens' (1886) original experiment, a slower intertap interval tended to be followed by one that was faster and vice versa (e.g., see Wing, 1980, for description, and Vorberg & Wing, 1996, [figure 4.2](#)). In other words, the *adjacent* intertap intervals were found to vary inversely with each other (i.e., they demonstrated a negative covariance or correlation), although intervals that were separated by two or more intervening (i.e., not adjacent) intervals were independent of each other (i.e., they had a covariance of zero).

To account for these and other observations in continuation timing, Wing and Kristofferson (1973b) developed an open-loop, hierarchical model of performance, illustrated in [figure 7.11](#). There are two levels in the hierarchy: a *central timekeeper level* and a *motor implementation level*. The model states that, in the absence of a pacing stimulus, a centrally generated “internal clock” sends pulses via the central nervous system that result in the execution of a movement (e.g., a tap). The internal clock—which can be thought of as similar to the timing generated by the motor program (see chapter 6)—is responsible for generating the desired goal durations ( $C_i$ ); the resulting times between successive taps are the intertap intervals ( $ITI_i$ ). Any variability in the rate at which the clock times the pulses (or intervals) will result in  $ITI$  variance that has a central source. There is a delay, however, from the time a central command is issued until a tap is produced by the motor system. In fact, each  $ITI$  is affected by *two* motor implementation delays, because one tap defines the *initiation* of the  $ITI$  ( $M_i$ ) and the next tap defines the *termination* of the  $ITI$  ( $M_{i+1}$ ). Viewed another way, any one motor delay (e.g.,  $M_2$ ) will have an influence on both the preceding interval ( $ITI_1$ ) and the succeeding interval ( $ITI_2$ ). Thus, a short  $M_2$  will tend to shorten the preceding  $ITI$  and lengthen the next  $ITI$ . So, a second source of variation at the motor delay level adds variability to the observed  $ITIs$  that is independent of the clock variability. Wing and Kristofferson developed statistical methods for estimating the value of the total+ variance and the motor delay variance. The Wing-Kristofferson (1973b) model of timing has been one of the most robust and useful models in all of human performance. Therefore, we spend a few paragraphs delving deeply into the model, assumptions, and numerical computations.

Figure 7.11 The Wing-Kristofferson hierarchical model of timing. A high-level, central timekeeper produces pulses (e.g.,  $P_1, P_{i+1}$ , etc.) that generate a time interval ( $C_i$ ). The duration of each observed intertap interval ( $ITI_i$ ) is influenced by the  $C_i$  and the delays in implementing the motor activity that initiate ( $M_i$ ) and terminate ( $M_{i+1}$ ) the ITI. Measures of variability in timing are observed and estimated using statistical techniques.



Adapted from Tutorials in motor behavior, A.M. Wing, pgs. 469-486, *The long and short of timing in response sequences*, edited by G.E. Stelmach and J. Requin, Copyright 1980. By permission of A.M. Wing.

First, you may recall from a statistics course that the variance of a set of scores can be partitioned into components that will add up to the total variance. This assumption is used to compute one of the most popular statistical procedures in kinesiology, the analysis of variance (ANOVA). Another assumption of ANOVA is that the variances are independent. That is, the variance of one component is separate and distinct, and it is unaffected by how another component varies. Wing and Kristofferson used similar assumptions in their model to suppose that we have a perfectly consistent internal clock, triggering each timed event; one might say it is like “clockwork.” Further, the processes that implement the triggering signal are variable, and the variability in the implementation processes is independent of the clock process. Lastly, they assumed that the time-series of implementation durations also is independent.

Next, imagine that the implementation duration  $n - 1$  was long. That will shorten the duration of interval  $n$ , particularly because we expect the implement duration  $n$  to be the mean value (independence assumption of the time series). This expectation is the reason why a long ITI is followed by a short ITI and vice versa. Wing and Kristofferson (1973b) showed that the covariance of the adjacent intervals (called the lag-1 covariance), multiplied by 2, was the measure of the implementation variance. Because we know the total variance through calculation, the clock variance is computed by subtracting the implementation variance from the clock variance.

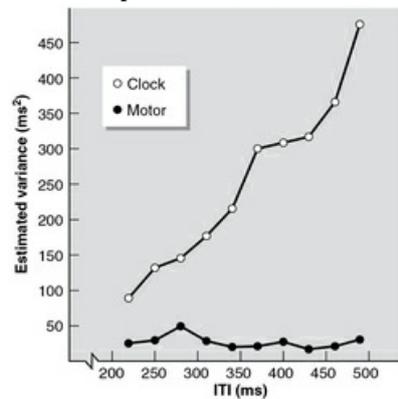
To satisfy the assumption that the tapping time series is produced with open-loop and not closed-loop processes to the data must demonstrate that the lag-2 through lag-5 covariances statistically are equivalent to 0. In other words, there are no adjustments to following intervals based on previous intervals. Finally, the Wing-Kristofferson model does not apply if the lag-1 covariance is positive and if the covariances for lag-2 through lag-5 are non-0.

### *Factors Affecting Clock and Motor Variance*

[Figure 7.12](#) presents data from Wing (1980), in which the variance associated with the duration of the ITI has been decomposed into measures of clock variance and motor implementation variance. As the figure illustrates, the variability due to motor implementation processes contributes very little to the total, and the effect is almost entirely due to variability in central (clock) processes.<sup>2</sup>



Figure 7.12 The effects of the intertap interval (ITI) duration on clock and motor variance.



Adapted from *Tutorials in motor behavior*, A.M. Wing, pgs. 469-486, *The long and short of timing in response sequences*, edited by G.E. Stelmach and J. Requin, Copyright 1980. By permission of A.M. Wing.

Wing (2002) has summarized a large number of studies in which processes affecting clock and motor implementation variances were separated. For example, factors such as the age of the participant (Greene & Williams, 1993) and increased cognitive demands due to a secondary task (Sergent, Hellige, & Cherry, 1993) greatly influenced clock variance but had no effect on motor variance. Compared to unimanual tapping performance, adding a second limb so that both limbs are tapping together in continuation has the effect of reducing the ITI variance, almost all of it due to the reduction in clock variance (Drewing & Aschersleben, 2003; Helmuth & Ivry, 1996). Interestingly, though, if hand tapping is paired with foot tapping, then clock variance is reduced while motor variance actually increases (Ivry, Richardson, & Helmuth, 2002). Additional practice does reduce motor variance, but not clock variance (Drewing & Aschersleben, 2003). If the length of one of the “effectors” is altered in bimanual timing, then only motor variability is affected (Turvey, Schmidt, & Rosenblum, 1989). The Wing-Kristofferson model has also been useful in contrasting the influence of neural disorders on timing in various patient groups. For example, Ivry, Keele, and Diener (1988) found that patients with a lateral lesion in the cerebellum showed increased clock variance whereas another group, with lesions in the medial portion of the cerebellum, showed elevation only in motor variance.

The Wing-Kristofferson model has proven useful in identifying dissociations in motor timing, which is a very important contribution to understanding processes in motor control. Although various alterations to the model have been proposed over the years (e.g., Collier & Ogden, 2004; Vorberg & Wing, 1996), the original Wing-Kristofferson model remains a powerful and important research tool in studies of motor timing.

### *Two Types of Timing?*

Most of the studies discussed in this section have considered timing tasks involving the tapping of a finger in time to a metronome that either is currently present or was present in the recent past (i.e., Stevens’ and Wing-Kristofferson’s synchronization and continuation tasks). Timing has been considered to be *explicit* in these tasks in the sense that the nature of the task and the participant’s internal timing processes represent compatible goals—the “environment” specifies a time goal that the participant tries to match with specifically timed movements. In studies of individual differences in timing ability, Robertson, Zelaznik and colleagues (1999) found that people who are consistent timers for slow tapping rates (e.g., 800 ms per tap) are also consistent timers for fast rates (e.g., 400 ms per tap). That is, the within-trial variability in tapping is similar among individuals for the two tasks, resulting in high correlations between people—timing appears to be a type of *general ability*. In contrast to this tapping timing task is a circle-drawing timing task (e.g., Robertson et al., 1999), in which participants produce circles continuously with a defined completion cycle time (e.g., 400 or 800 ms for each revolution). Again, high interindividual correlations exist for the variances in producing timed circles at different cycling rates. However, there is *no correlation* between timed taps and timed circles, suggesting that these two tasks represent different fundamental timing processes. This suggestion is supported by studies involving patients with cerebellar damage, who revealed deficits in performing tapping timing tasks but not circle timing tasks (Spencer, Zelaznik,

Diedrichsen, & Ivry, 2003). These and related findings support a dissociation of processes involving these two types of timing tasks (e.g., Studenka & Zelaznik, 2008; Torre & Balasubramaniam, 2009; Zelaznik et al., 2005).

Robertson and Zelaznik (Robertson et al., 1999) attempted to apply the Wing-Kristofferson model of timing to timing in tapping as well as circle drawing tasks. We observed that for tapping the Wing-Kristofferson model worked quite well, and the model could not be applied to circle drawing timing. Robertson et al. (1999) inferred that this observation further supported the idea that timing in tapping and in circle drawing uses different timing processes (see Zelaznik, Spencer & Ivry, 2008).

## Central Contributions to the Spatial Speed–Accuracy Trade-Off

Up to this point, we have discussed the spatial speed accuracy trade-off and the trade-off between timing and the timed interval. Some theoretical issues related to timing were presented in the last section, and others will be discussed in more detail in chapter 8. In this section, we concentrate on the spatial trade-off. Two general perspectives have dominated much of the thinking; these perspectives correspond in general to the topics discussed in chapters 5 and 6. With regard to the generation of an impulse to propel a limb toward a target, one perspective has been to consider the importance of *central* contributions. The other perspective has been to examine how *corrective* processes contribute to the speed–accuracy trade-off. In the following sections we discuss the major ideas that have been suggested within these general theoretical approaches.

Keele (1981, 1986) suggested that central processing of rapid aiming movements can be classified under two broad categories. In one category, the thinking is that central commands specify the *distance* that must be traveled to reach a target. Distance programming is assumed by models of impulse variability, whereby the agonist and antagonist muscles produce bursts of force (open loop) that propel a limb a specific goal distance. The other general class of models assumes a programming of commands that specifies a target's *location*. Location programming is assumed by a class of models that specify equilibrium–tension ratios between agonist and antagonist muscle groups.

### Impulse-Variability Theory

A number of the principles related to the linear speed–accuracy trade-off form the basis for impulse-variability models of movement control. Two principles are of critical importance: (a) The variability in the *duration* of a group of muscular contractions is directly related to the mean duration; and (b) the variability in *force* applied in a group of attempts is an increasing function of the mean force. The reason these principles have such importance is that they define variability in the two dimensions of the *impulse*—the primary determinant of what the limb will do when muscles attached to it are activated. The notion of the impulse, that is, the forces produced over time, was discussed in chapter 6 (section on the impulse-timing hypothesis). If as we have argued earlier, the impulse is a critical determiner of movement, and variability in impulses is a critical determiner of the variability in movement, then an analysis of the variability of the components of the impulse (variability in force and variability in duration) should allow considerable insight into the sources of spatial errors in movement control—at least in relatively quick actions where feedback processes do not play a major role. Schmidt and colleagues provided the early modeling of these phenomena (Schmidt et al., 1978, 1979), and a revision and correction of the same idea were provided by Meyer and colleagues (Meyer et al., 1982).

#### *Force-Variability Principles*

In this section we consider factors that produce variability in the amount of force generated by the activation of the motor program. This is an important issue for understanding the processes underlying skillful behavior. All that the muscles can do to bones is to exert a pulling force on them, with this application being adjustable in terms of amount of force or in terms of the temporal onset and duration of that force. Complex patterns of force produced *during* a particular contraction are presumably also under the control of the motor system. If the activation sent to the muscles is preprogrammed, then any factors causing the amount of force to deviate from the intended amount of force will cause the movement to deviate from its intended path or fail to meet its goal. Put simply, *muscular forces produce movements, and variability in muscular forces produces variability in movements.*

Schmidt and colleagues (1978, 1979) began a series of studies on the relationship between forces involved in quick, preprogrammed movements and their within-participant variability, and these findings are described next. In relation to slower movements, there has been some interest in these questions for over a century (e.g., Fullerton & Cattell, 1892; see Newell, Carlton, & Hancock, 1984, for a review), although the theoretical orientations of

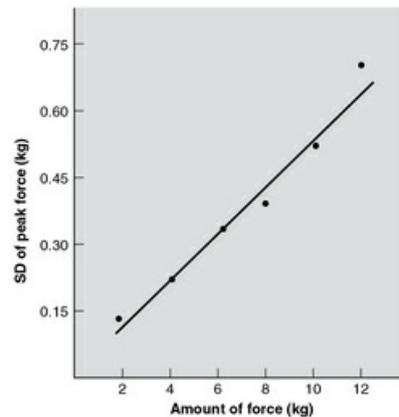
this earlier work were considerably different. The initial issue addressed in the studies by Schmidt and colleagues concerned the relationship between the amount of force produced and the resulting within-participant variability in that force. For example, why did an aiming movement with twice the amplitude (T constant) produce approximately twice the error in hitting a target (e.g., Schmidt, et al., 1979; Woodworth, 1899)? According to the generalized motor program (GMP) idea (see chapter 6), in order to produce a movement of twice the amplitude, the program would remain the same, but the overall force parameter would be increased so that the limb would travel twice the distance in the same T. Could it be that when the forces in the limb are increased so that the limb can travel farther, the variability in this force is increased as well, making the output of the movement more variable? This was the hypothesis.

### Moderate Force Levels

The participant's task was to produce quick "shots" of force against an immovable handle. Attached to the handle was a strain gauge that measured the amount of force applied; this information was sent to an oscilloscope screen so that the participant could see the force levels. A zero-force level was indicated at the bottom of the screen, and increasing force applied to the handle would move the dot upward. Participants attempted to produce ballistic "shots" of force that would peak exactly at a target location on the screen, the goal being to produce the same peak force on each trial. The peak force and the within-participant variability (SD) of the peak forces were measured; participants were asked to produce different amounts of force during separate series of trials.

In [figure 7.13](#), the SD in peak force is plotted as a function of the amount of force the participants were asked to produce. A clear linear relationship between force and its variability can be seen. In a number of other experiments, force and force variability were found to be linearly related in situations in which the forces were much smaller than indicated in [figure 7.13](#) (40 g elbow flexion measured at the wrist) and also when they were as large as 65% of the participant's maximum (Newell & Carlton, 1985; Schmidt et al., 1978, 1979; Sherwood & Schmidt, 1980).

Figure 7.13 Variability in peak static force as a function of the amount of force to be produced.



Reprinted, by permission, from R.A. Schmidt, H.N. Zelaznik, and J.S. Frank, 1978, *Sources of inaccuracy in rapid movement*. *Information processing in motor control and learning*, edited by G.E. Stelmach, (Elsevier Science), 197.

These results were from static (isometric) contractions, though, and it was not clear that such relationships would occur in actual isotonic *movements*, in which the muscle shortens as it is producing force against the bone. Sherwood and Schmidt (1980) examined this issue in an experiment in which forces were recorded during a simple ballistic-timing movement. Again, a linear relationship between force and force variability was found, suggesting that this principle had a strong role in movements. These data certainly supported the speculation that, as the amount of force was increased (in order, for example, to move farther in the same T), the variability in force would increase in nearly direct proportion, leading to increased variability in the movement's spatial outcome—in this case, in hitting a target accurately.

### Near-Maximal Force Levels

Will the linear relationship between force and force variability continue to hold as the forces are increased even further? This is an important question, as many of the skills performed by athletes have very high force requirements, such as those for the forces in the quadriceps muscles generated during a football punt for distance. With such large forces, one might expect that there would be no “room” for variability near the performer's maximum. If the participant actually did produce the theoretical maximum on every trial, there would be no variability (because the SD of a set of constant values is zero). Thus, as the maximum force is approached, one could imagine a point of maximum force variability (perhaps near the middle of the range in force capability) and a gradual decline in force variability (i.e., more consistency) as the forces are increased further. With this reasoning, an inverted-U function should exist between force variability and force across the total range of human force capability.

Another experiment by Sherwood and Schmidt (1980) presents data in which the forces were increased to very near the participant's maximum. The data show the variability in peak force as a function of the level of force produced, as before. But in this case a maximum point occurred in force variability, with a strong tendency for decreasing force variability as the forces were increased further. The peak force variability occurred, on the average, at about 65% of maximum force for these participants; the largest force examined was about 92% of maximum.

### Inverted-U or Negatively Accelerating Functions?

Some controversy has developed with regard to the inverted-U function. Newell and Carlton (1985, 1988; Carlton & Newell, 1988; Newell et al., 1984) have criticized the procedures used to obtain this inverted-U result on the grounds that the *time* to peak force was not controlled in these experiments. They showed that larger peak forces tend to be associated with a longer time to achieve peak force, and they argued that this should have the effect of producing an artificial inverted U at high force levels. In a subsequent experiment in which the time to

peak force was held strictly constant, Sherwood, Schmidt, and Walter (1988) showed that the inverted-U function was no longer as pronounced. Thus, perhaps rather than an inverted-U function, the relation between force and force variability follows a curvilinear, *negatively accelerated* function. Beyond about 65% of maximum force, force variability tends to increase at a decreasing rate, leveling off somewhere near the maximum force capabilities (or perhaps decreasing very slightly—Sherwood et al., 1988). Theoretical modeling of force summation characteristics by Ulrich and Wing (1991) suggests that both the inverted-U *and* the negatively accelerated functions may be correct in certain situations. In the original Schmidt et al. (1979) work two experiments used the discrete aiming task. In the second of these two experiments, participants attempted to move 30 cm with a goal T of 140 ms. This task clearly was the participant's maximum velocity. An inverted-U speed–accuracy function was not observed. Thus, it is still an open question whether maximum force (velocity) movements show a reduction or slight reduction in spatial variability.

### *Modeling the Initial Impulse*

It is easy to understand the general idea of impulse-variability principles if one considers only the initial impulse for acceleration in a rapid movement. A good example is the ballistic-timing task, in which the participant moves a slide along a trackway, past a switch at the end, and attempts to achieve a goal T (initial movement until arrival at the switch). Here the participant is accelerating for the entire (measured) movement, so the movement trajectory is governed solely by the initial impulse for positive acceleration. When the experimenter changes either the movement distance or the goal T, the person's movement is assumed to be handled by changes in the parameters of the GMP for this rapid action (see chapter 6). Let us examine the effect of variables like movement distance and movement time—critical variables in the speed–accuracy trade-off—on the nature of impulse variability in this task.<sup>3</sup>

#### Effect of Movement Distance

Consider what happens to the impulse as the person moves twice as far in the same T. In this case the movement-duration parameter of the GMP is fixed, so the duration of the impulse is constant. However, the overall force parameter must be doubled so that the force produced will be twice as large as for the shorter movement. From the earlier section on force variability, we know that as the amount of force is doubled, the variability is approximately doubled as well. Therefore, with a doubled force but a constant duration, the impulse will have twice the variability, with all of the increase in variability occurring because of the changes in the amplitude of the impulse. The overall result is that the impulse variability is linearly related to the movement distance:

$$\text{Impulse variability} = k_1 (D) \quad (7.4)$$

where  $k_1$  is an empirical constant, and  $D$  is the movement distance (the intercept is zero because proportionality is assumed; see the section on empirical equations in chapter 2).

#### Effect of Movement Time

Next, consider what happens to the impulse as the T is halved with a constant movement distance. From the notion of the GMP, we know that the overall duration parameter will be halved as well, so that all of the impulses in the action will be half their original duration. We know that the variability in the duration of an interval is directly proportional to its duration, so halving the duration of the impulse should reduce its variability *in time* by half also. Generally, the temporal variability of an impulse is linearly related to T:

$$\text{Temporal variability} = k_2 (T) \quad (7.5)$$

where  $k_2$  is a proportionality constant (again, the intercept is zero). This is interesting (and somewhat counterintuitive) because the variability of one component (temporal) of the impulse becomes *more* consistent as

the T is shortened, while the variability of another component (force) becomes *less* consistent at the same time.

But along with this shortening of impulse duration as the T is halved, the impulse must increase in amplitude (force), so that the increased velocity needed for the shorter T can be achieved. From physics we know that for a movement with twice the velocity (i.e., half the T), the area of the impulse must be twice as large. But the duration is half as long, so the amplitude must be four times as large (i.e., four times the amplitude together with half the duration yields twice the area). Then, because of force-variability principles, the force variability is increased by a factor of four as well, so that halving the T produces a fourfold increase in the *force* component of impulse variability. More generally, the force component of impulse variability is inversely related to the squared T, or

$$\text{Force variability} = k_3 (1 / T^2) \quad (7.6)$$

We see that the overall impulse variability is related both (a) directly to the T in the temporal dimension and (b) directly to  $1/T^2$  in the force dimension. Combining these two effects of impulse variability (equations 7.5 and 7.6) produces the generalization that

$$\text{Impulse variability} = k_4 (T / T^2) = k_4 (1 / T) \quad (7.7)$$

That is, total impulse variability is proportional to  $1/T$ .

### Distance and Movement Time

When we combine the effects of *D* and the effects of T from equations 7.4 and 7.7, we obtain the relation that

$$\text{Impulse variability} = k (D / T) \quad (7.8)$$

where the total variability in an impulse for accelerating a limb is directly related to the distance and inversely related to the duration. Because the velocity of a movement after an impulse is directly proportional to the size (area) of the impulse, and because the variability in the impulse leads directly to variability in velocity, this relation implies that the variability in the velocity of a movement when an impulse has stopped acting on it will be directly proportional to  $D/T$  as well. This is a key feature in impulse-variability modeling, and many other interesting predictions emerge from it.

### *Impulse-Variability Principles in Movement Control*

The original impulse-variability theory (Schmidt et al., 1978, 1979), which concerned the effects of various movement variables on initial-impulse variability, seems to account relatively well for the behavior of *single* impulses in a number of rapid movement tasks (see Schmidt, Sherwood, Zelaznik, & Leikind, 1985, for a review). As a result, the model accounts fairly well for accuracy in tasks in which only a single impulse is acting, such as the ballistic-timing tasks described at the beginning of this section.

### Errors in Ballistic Timing

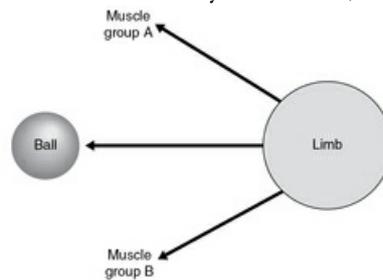
For ballistic-timing tasks, we have already mentioned that the  $VE_t$  has been shown to be nearly proportional to the T (tables 7.1 and 7.2, figure 7.9). The model also accounts for spatial errors—the error in *position* at the moment that the goal T has elapsed, or  $W_e$ . In this case the model predicts that  $W_e$  should be independent of T, and several experiments show this to be essentially so (e.g., Schmidt, 1994; Schmidt et al., 1979, 1985). Therefore, changing the T affects mainly timing errors in this timing task, not spatial errors. The principle is just the opposite when *D* is manipulated in this task. Here, increasing *D* causes nearly proportional increases in spatial errors but causes almost no effect in the timing errors.<sup>4</sup> This seemingly curious set of findings is derivable from the model,

and is related to the tight connection between space and time in such situations involving tasks in which time is the dependent variable (see Newell, 1980; Newell et al., 1984).

### Spatial Errors in Very Rapid Movements

Some applications of impulse-variability notions can be seen in a task like hitting a baseball, where the limb seems to be driven by a single impulse, with no deceleration until after the bat passes over the plate and the ball is struck. Here, in addition to being temporally accurate, the batter must be spatially accurate so that the swing will not miss the ball. We can think of such a movement as shown in [figure 7.14](#), where the limb (or limb plus bat) is moving horizontally toward a ball. Assume that the limb is controlled by two muscle groups, A and B, each of which pulls obliquely on it, their combined action being to move the limb toward the ball. What will be the effect on spatial accuracy of increasing the mass of the bat, with T constant?

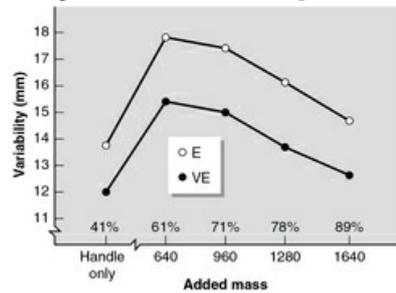
Figure 7.14 The limb conceptualized as a mass moved by two forces (muscles) operating in different directions.



If muscle groups A and B are contracting with less than 65% of maximum force, then increasing the mass of the bat will require increased force output in each of them, and the force variability will increase in both muscle groups at the same time (figure 7.14). This should result in progressively larger variations in the direction of bat travel and in progressively lower probability that the bat will hit the ball. But what if the forces in the two muscle groups are larger, perhaps greater than 65% of maximum? Here, with increased mass of the bat, there would be a decrease (or at least a much smaller increase) in the force variability as the forces are increased, resulting in *increased* consistency of bat travel as the mass is increased.

Schmidt and Sherwood (1982) conducted an experiment that seems to show just that. Participants made horizontal forward arm swings to attempt to hit a target, with a T that was to be as close to 200 ms as possible. Figure 7.15 shows the spatial accuracy in hitting the target as a function of the mass added to the handle, measured as VE and total variability (E). As mass was added to the unloaded handle, there was first an increase in spatial errors; but the function soon peaked, so that the errors decreased with further increases in mass. Thus, there was an inverted-U relation between spatial accuracy and mass for this task, with the peak at approximately the mass that resulted in about 60% to 70% of maximum force. This corresponds surprisingly well with the peak in the force/force-variability function.

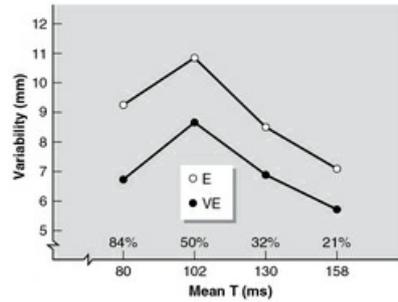
Figure 7.15 The effect of added mass on the spatial accuracy of a 200 ms arm swing movement. The values above the  $x$ -axis are the percentages of maximum force produced with that added mass.



Reprinted, by permission, from R.A. Schmidt and D.E. Sherwood, 1982, "An inverted-U relation between spatial error and force requirements in rapid limb movements: Further evidence for the impulse-variability model," *Journal of Experimental Psychology: Human Perception and Performance* 8: 165. Copyright © 1982 by the American Psychological Association.

A similar experiment was conducted with variations in  $T$ , this time with the mass held constant. If decreased  $T$  results in increases in force beyond about 65% of maximum, then we should find that making the movement faster results in increased accuracy, not less as would be expected from the speed-accuracy trade-off effect. [Figure 7.16](#) illustrates the results. As the average  $T$  decreased from 158 ms to about 102 ms, there was a progressive increase in the spatial errors, as one would expect. But when the  $T$  was reduced further to 80 ms, requiring approximately 84% of maximum force, there was a decrease in the spatial errors, with the function showing a peak error somewhere near 50% of maximum contraction (102 ms  $T$ ). Again, this is compatible with the peak in the force/force-variability function seen in [figure 7.15](#). It is interesting to note that when the movement was very rapid and required 84% of maximum force, the amount of error was nearly the same as that in a very slow (130 ms) movement.

Figure 7.16 The effect of movement time (T) on the spatial accuracy in a horizontal arm swing movement. The values above the x-axis are the percentages of maximum force produced with that movement time.



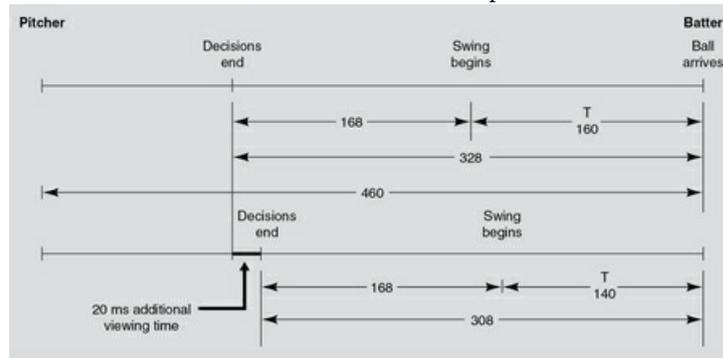
Reprinted, by permission, from R.A. Schmidt and D.E. Sherwood, 1982, "An inverted-U relation between spatial error and force requirements in rapid limb movements: Further evidence for the impulse-variability model." *Journal of Experimental Psychology: Human Perception and Performance* 8: 165. Copyright © 1982 by the American Psychological Association.

Both of these results provide exceptions to the speed–accuracy trade-off ideas presented earlier, as increasing speed (or increasing mass) resulted in *increased* accuracy when the movements were very violent. This supports indirectly the impulse-variability model, in which the variability in forces is expected to be a major determiner of the spatial accuracy in these rapid actions. There are also interesting practical implications. Perhaps telling a baseball player to swing slowly to “make contact” would actually result in less spatial accuracy than giving an instruction to swing “hard” (we develop this idea more fully next).

### Principles of Motor Control Applied to Baseball Batting

We now attempt to use a number of the principles discussed in this section to understand a complex skill like batting a pitched baseball. Let us review some basic facts about hitting a baseball. In [figure 7.17](#) are data from a number of studies referred to earlier, as well as from Hubbard and Seng (1954). It takes about 460 ms for a ball (moving at 89 mph) to travel from the pitcher to the plate. The T of the bat (the time from the first movement of the bat until it reached the plate) was about 160 ms; this is equivalent to about 21 ft (6.4 m) of ball travel.

Figure 7.17 A time line showing the critical events in hitting a pitched baseball. (The top example has a 160 ms movement time [T], and the bottom example has a 140 ms T.)



If the batter were to reduce the T of the swing by 20 ms, from 160 ms to 140 ms and made contact with the ball, the ball travels farther and faster, which is usually beneficial in baseball. But, what effect does speeding up the swing have in terms of accuracy?

First, the batter can view the ball for 20 ms longer. More importantly, those 20 ms occur during the time that the ball is as close as possible to the batter before the ultimate decision has to be made to trigger the action. In this way, the batter should be able to make more accurate predictions about the spatial relation of the ball to the batter when it arrives in the hitting zone, and therefore more effective choices regarding the swing.

Second, swinging faster improves effector anticipation. Here, this interval begins at the point marked “Decisions end” and ends when the bat reaches the plate. When the T is 160 ms, this interval is 328 ms, and when the T is 140 ms, it is 308 ms. Because the accuracy in timing an interval is diminished as the interval length increases, more accurate effector anticipation occurs when the swing is 140 ms versus 160 ms and less variability in the time of swing initiation should result. A third advantage of swinging more rapidly is that the movement itself is more temporally consistent as the T is shorter (Newell et al., 1979, 1980; Schmidt et al., 1979).

The combination of increased consistency in the time of swing initiation and in the duration of the swing itself should lead to increased consistency in the time at which the bat arrives at the plate. In the laboratory task mentioned previously, Schmidt (1969c) found that the temporal accuracy in meeting the ball was greater when the T was shorter (see [table 7.1](#)). If the level of muscle contraction in the bat swing is above about 65% of the batter’s maximum, then increased swing speed, or increased bat mass with a constant swing speed, should produce increases in the spatial accuracy of the swing. This is so because with increased levels of contraction there is increased consistency in force production, which results in increased consistency in where the limbs go during the action. These kinds of effects have been shown for laboratory tasks (Schmidt & Sherwood, 1982), as well as in sport-related tasks (Zernicke & Roberts, 1978).

### *Limitations of the Impulse-Variability Theory*

One limitation of impulse-variability theory is that it does not predict movement accuracy in discrete aiming tasks in which a *number* of impulses are presumably combined to produce a complete action (e.g., see [figure 7.6](#)). So, the impulse-variability model falls considerably short of the goal of explaining speed–accuracy phenomena in general. A modification of the theory, using similar assumptions about GMPs, force and time variability, and so on, was provided by Meyer and colleagues (1982). This view does represent an improvement in certain ways, but it suffers from a number of other problems that seem to argue against its adequacy as an account of speed–accuracy effects (see Schmidt et al., 1985; Zelaznik, Schmidt, & Gielen, 1986). Specifically, the Meyer et al. (1982) account requires that acceleration profiles in aimed-hand movements exhibit a particular form; the acceleration profile is temporally “stretched” or “compressed,” keeping the overall shape of the acceleration trajectory unchanged. Zelaznik et al. (1986) demonstrated that this time *rescalability* property was not observed in these discrete hand movements.

Overall, the impulse-variability theory accounts reasonably well for certain types of ballistic actions that do not require feedback. Thus, the theory provides an important description of some of the centrally generated errors that result in a linear speed–accuracy trade-off. Later in this chapter we describe a more recent model of Fitts-type tasks by Meyer and colleagues (1988, 1990) that describes how impulse-variability principles are involved in both the initial and corrective portions of aiming movements.

## Equilibrium-Point Theories

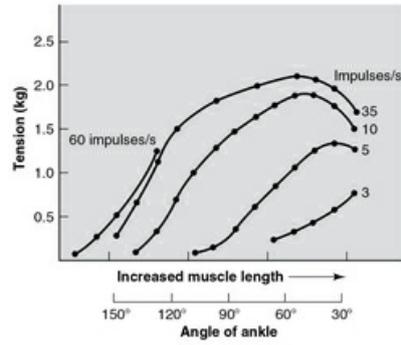
Alternatives to theories suggesting that movement distances are controlled on the basis of programmed impulses are theories suggesting that the *movement end point* is programmed and that muscle and mechanical properties determine the trajectory. The relation of these theories to speed–accuracy trade-offs per se has not been fully investigated (Latash, 1993; Latash & Gutman, 1993). However, these ideas represent a major theoretical advance regarding the way limb positioning movements are controlled by the central nervous system, so it is important to consider them here.

### *Length–Tension Diagram*

Muscles, and tendons that connect muscles to bones, have a certain amount of compliance, or *springiness*. In an older view of muscle (e.g., Huxley, 1969), the notion was that the *contractile component* of muscle was responsible for the production of forces and that a *series elastic component* (in the muscular connective tissue and in the tendons) provided elasticity. Although the concept has been known for more than a century (Weber, 1846; see Partridge, 1983), what has been emphasized more recently is that the contractile portion of muscle has elasticity as well, such that the entire muscle–tendon unit is analogous to a “complicated spring.” This concept has influenced thinking about what muscles do when they move bones in skilled actions (see Partridge & Benton, 1981, for a review).

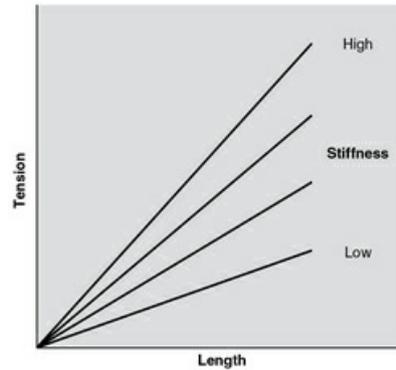
One way to study the properties of muscles is to describe them in terms of a length–tension curve—that is, the relation between a muscle’s length and the tension that it is capable of producing at that length under a given level of contraction. If a muscle is excised from the animal, the length of the muscle can be predetermined; the nerve is stimulated artificially so that the level of activation to the muscle can be controlled, and the resulting tension is measured. Such a procedure can produce a family of *length–tension diagrams*, with one curve for each of the levels of contraction that the experimenter uses. Some of these curves from Rack and Westbury (1969) are shown in [figure 7.18](#), in which five levels of activation were used (defined in terms of the number of impulses of electrical stimulus given per second). Notice that at all levels, a generally increasing relationship was found between the length of the muscle and the tension it developed. This relationship is roughly what we would expect if the muscle were a spring attached to a lever (the bone). A fundamental mechanical principle about springs—Hooke’s law—is that the tension produced is directly proportional to the amount the spring is stretched (i.e., proportional to the spring’s length). [Figure 7.19](#) is a hypothetical length–tension diagram for springs. The four curves represent four different springs, each with a different *stiffness*. Stiffness is the force required to lengthen the spring by one unit (i.e., the change in tension divided by the resulting change in length), represented as the slope of the length–tension curve.

Figure 7.18 Tension produced by muscle as a function of the level of activation (impulses per second) and the length of the muscle.



Reprinted, by permission, from P.M.H. Rack and D.R. Westbury, 1969, "The effects of length and stimulus rate on tension in the isometric cat soleus muscle," *Journal of Physiology* 204: 443-460.

Figure 7.19 Idealized length–tension curves as would be produced from four springs, each with a different stiffness.

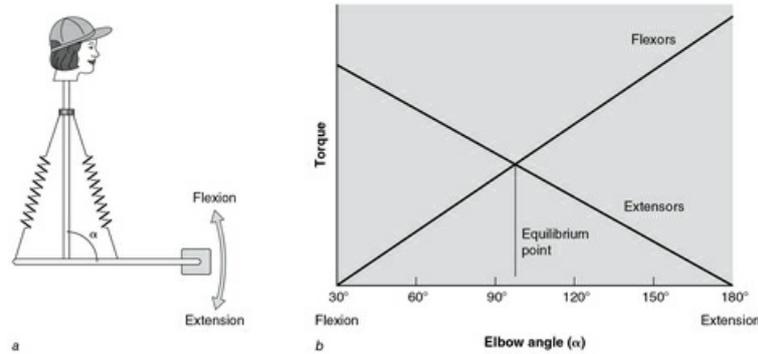


### *Mass–Spring Mechanisms*

The realization by Asatryan and Feldman (1965; Feldman, 1966a, 1966b)<sup>5</sup> that muscles could behave something like complex springs has revealed a possible mechanism for movement control known as *mass–spring* control. Consider a lever, pivoted near one end, with two springs attached on either side. This setup is shown in [figure 7.20a](#). Think of the lever as the bone in the forearm; the pivot is the elbow joint, and the two springs are the groups of muscles that span the joint—the flexors and the extensors.

In [figure 7.20b](#) are the hypothetical length–tension curves for these two springs, assuming a constant level of motor activation. Consider what happens when some external force applied to the “hand” extends the elbow. First consider the curve labeled “Flexors” in [figure 7.20b](#). Here, as the elbow angle is increased from 30° to 180° (i.e., the elbow is extended), a progressively increased tension is produced in the flexors because they are being lengthened (stretched). Also, the curve labeled “Extensors” represents the tension in the extensor muscles. As the elbow extends, the tension in the extensors decreases because the length of the extensors decreases, and the tensions they produce are related to their lengths.

Figure 7.20 The mass–spring or equilibrium-point model. (a) Muscles seen as springs; (b) the length–tension diagrams for the flexors and extensors plotted for different elbow angles, with the intersection being the equilibrium point where the tensions (more properly, torques) in the two muscle groups are equal and opposite.

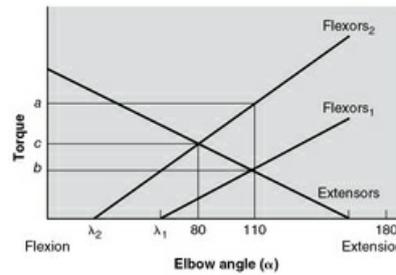


What happens when this force moving the “hand” is suddenly removed? For a given amount of stiffness in the springs, the lever would move to (“spring to”) an *equilibrium position* (or *equilibrium point*) in its range, finally stabilizing at a point where it would be held by the opposing actions of the two springs. The equilibrium point is represented by the elbow angle in which the tension (or, more properly, torque at the elbow) from the flexor group is equal and opposite to the tension from the extensor group. In the diagram, the two tensions are equal at only one elbow angle: the elbow angle at which the two length–tension diagrams cross each other, at about 95°. When the system is perturbed, the mass–spring system will tend to move the limb back to the equilibrium point, regardless of the amount or direction of the original deflection. This view helps to explain how limbs can be stabilized in one position, as in the maintenance of posture (see also [figure 5.15](#)).

### *Equilibrium-Point Principles ( $\alpha$ and $\lambda$ Models)*

The mass–spring view perhaps explains some simple things about how we can hold a limb in one place and how the limb is stabilized after an external perturbation. But how can it explain *movement*? Closely related models have been proposed by Feldman (1966a, 1966b, 1986) and Polit and Bizzi (1978, 1979), which differ in the ways the processes are thought to work. In the  $\lambda$  model (Feldman), illustrated in [figure 7.21](#), assume that the limb is initially at a particular equilibrium position (110°) defined by the two length–tension functions for flexors and extensors (what Feldman called the *invariant characteristic*). When the flexor group is activated, there is a shift from one length–tension function to another (from Flexors<sub>1</sub> to Flexors<sub>2</sub> in the figure), which occurs because of two distinctly different changes. First, the function is shifted to the left through a change in the *threshold length* (which Feldman labeled  $l$ ). This is the muscle length at which the length–tension curve crosses the zero-tension axis (here shifted leftward from  $\lambda_1$  to  $\lambda_2$ ); it is the muscle length at which the reflex activities just begin to cause the muscle to contract, with tension increasing progressively as the muscle is lengthened further. Second, the *stiffness* of the muscle is increased as well—seen as the steeper slope of the length–tension function for Flexors<sub>2</sub> as compared to Flexors<sub>1</sub>.

Figure 7.21 Length–tension diagrams for the extensors and flexors for various elbow angles at times 1 and 2. (The equilibrium point is shifted from 110° to 80° by increased activation in the flexors to produce a new length–tension relation.)



These shifts in the length–tension function result in a change in the equilibrium point from 110° to 80°. But the limb is still at 110°, and not in equilibrium, because the flexors are exerting  $a$  units of torque, whereas the extensors are exerting  $b$  units; the difference in torque ( $a - b$ ) begins to move the limb into flexion. This movement continues until the limb is in equilibrium again, this time at the new equilibrium point of 80°, where the two muscle groups are producing torques that are again equal and opposite ( $c$  units). The analogous process can also occur in the extensor group, or probably in both groups at the same time in most normal movements. So, through appropriate selection of the activation to the muscle groups spanning a joint, and hence a new equilibrium point, the joint can be moved to any position within its anatomical range. The viewpoint has been referred to as an *equilibrium-point model* because the limb moves to the mechanically defined equilibrium point.

At this point, the Polit-Bizzi and Feldman models become slightly different. According to the  $\alpha$  model (Polit & Bizzi, 1978, 1979), the mechanical characteristics of the muscles enable the limbs to move to the new equilibrium position without any feedback (see the next section for evidence). On the other hand, the  $\lambda$  model (Feldman, 1966a, 1966b, 1986; Feldman & Levin, 1995; Latash, 1993) holds that the feedback from the spindle activities is an essential part of the process, perhaps to ensure that the muscle maintains approximately constant stiffness as Nichols and Houk (1976) suggested. In any case, no feedback to either higher centers or the stages of information processing is needed to move accurately; errors are not detected and corrected as in a closed-loop system. Another difference concerns what the motor system is thought to control. In the  $\alpha$  model, the motor system activates only the alpha motor neurons to change the length–tension function; the muscle spindles and the gamma system are uninvolved. In the  $\lambda$  model, the alpha and gamma systems are controlled together, with the muscle spindles being involved in the control of stiffness.

The controversy surrounding the ability of the  $\alpha$  and the  $\lambda$  models to explain certain features of limb control has existed for many years and continues to draw diverse opinions. Numerous commentaries have been published, and a number of references represent a good start for the interested reader wishing to gain an appreciation of the differing opinions that exist on the issue (see Bizzi, Hogan, Mussa-Ivaldi, & Giszter, 1992; Balasubramaniam & Turvey, 2005; Berkinblit, Feldman, & Fukson, 1986; Feldman & Latash, 2005; Feldman & Levin, 1995; Feldman, Ostry, Levin, Gribble, & Mitnitski, 1998; Gottlieb, 1998, 2000; Gottlieb, Corcos, & Agarwal, 1989; Jaric & Latash, 2000; Latash, 1993). For our purposes, however, the equilibrium-point models provide an important contrast to the impulse-timing model of movement control discussed earlier in this chapter. In that model, the critical determiner of the limb’s action and trajectory was the amount of force programmed and the *timing* and *duration* of this force. With the equilibrium-point model, the muscle activation is simply changed to a new level, and no pre-established timing of the onsets and offsets of the muscular impulses is involved.

Finally, an important distinction is that, in the equilibrium-point theory, the motor system does not have to “know” where the limb is starting from in order to move it to a new location. Computation of the necessary force levels implies that the central nervous system can do physics computations. However, as [figures 7.20](#) and [7.21](#) illustrate, the equilibrium point can be achieved mechanically regardless of the starting position. Thus, the equilibrium-point models are computationally simpler than the impulse-timing view because only two levels of activation are specified to the muscles. With the impulse-timing view, the system must know where the limb is at the beginning of the movement and then must specify the appropriate durations and intensities of the muscular

impulses. Joints cannot adopt an infinite level of precision. Therefore, Sakitt (1980) has posited that a look-up table of stiffness ratios can serve to set equilibrium points for joint position.

### *Evidence for Equilibrium-Point Control*

Scientists have long known that muscles act like “complicated springs,” but the Russian physiologist Feldman (1966a, 1966b; Asatryan & Feldman, 1965) was probably the first to describe relationships between position and torque in human movements, and to propose how mechanical properties might be used in movement control (see footnote 5). Feldman’s work was not widely known in the West until it was popularized by Turvey (1977). At about the same time, Polit and Bizzi’s (1978, 1979) work in the United States with deafferented monkeys independently supported similar ideas, and some of this evidence is given next.

### Experiments With Deafferented Monkeys

Polit and Bizzi used monkeys with deafferented forelimbs that were trained to point the hand and an attached lever to a target light, via elbow joint flexion and extension. With the hand actions, the monkeys could not, of course, feel the limb move, and they could not see the limb either, as the movements were made in the absence of visual information about limb and hand position. The major dependent variable was the terminal location of the movement, and Polit and Bizzi studied these moves when the limb was perturbed prior to or during the movement. For example, when the stimulus light was turned on and the animal looked at it, the experimenters would unexpectedly shift the initial limb position. Sometimes a mass would be applied to the lever unexpectedly, or a brief pulse of force was applied that restrained or aided the movement temporarily.

Polit and Bizzi (1978) produced several results. First, the monkeys appeared to be equally accurate regardless of whether they performed before or after deafferentation surgery. Second—and critical for a mass-spring view of motor control—a torque was applied to the forearm so that when the monkey attempted to initiate movement to a new target, no movement occurred. After the muscle response, measured as electromyographic (EMG) activity ceased, the torque was released. Surprisingly, the forearm moved to point toward the intended target. How did the limb move, in spite of no EMG activity? The EMG activity “set” a new equilibrium point by changing muscular mechanical properties, thus the muscle was compelled to achieve the new equilibrium point. This astounding result turned many scientists to embrace the mass-spring model.

These findings raise some interesting questions. First, the monkeys tended to move directly to the target regardless of the mass that was applied to the limb and regardless of shifts in initial location. All this was accomplished without feedback about limb position to the spinal cord. The hypothesis that the monkey “felt” the change in position, or that reflex processes were involved, cannot explain these findings.

The results do not lend support for an impulse-timing hypothesis. According to this view, the monkey first determines where the limb is, and the movement is then controlled by the GMP to produce the required impulses. In other words, the monkey must “solve” Newton’s classical distance equation. If the initial position is shifted, under the impulse-timing view the animal would have to take this into account, because the program (if unaltered) would cause under- or overshooting of the target. Yet, the deafferented animal could not detect this shift and moved directly to the target. Second, when the monkey’s limb was shifted *past* the target position before the movement, the limb moved “backward” toward the target. The impulse-timing hypothesis has the limb moved by a contraction of the agonist first, then of the antagonist, with this order of contraction being specified by the motor program. If so, then the initial movement should have been *away from* the target, not “backward” toward it.

### Experiments With Humans

The studies just described generated skepticism for a number of reasons. First, it is not certain that these processes found in animals also operate in humans. Second, it is never perfectly clear that deafferentation keeps all sensory

movement information from reaching the brain, as bone-conducted vibrations from the movement can be sensed by parts of the body that are not deafferented. Finally, and perhaps most importantly, the monkeys may have adopted an equilibrium-point mode of control simply because Polit and Bizzi deprived them of all their usual movement mechanisms. Do these experiments have relevance for human movement control? Probably, as seen in various experiments with humans.

In experiments with humans, Schmidt (1980; Schmidt & McGown, 1980) had participants produce rapid elbow flexion movements of a lever to a target. Occasionally, the load on the lever was unpredictably changed before the movement, and the participant moved with the changed load conditions. In the first of these experiments, the lever movement was horizontal, and the lever mechanism itself would support the weight. The experimenters were interested in the constant errors (CEs) in achieving the target on the “normal trials” (with the expected weight) and on the “switch trials,” for which the weight was either added or subtracted unexpectedly.

From [table 7.3](#) (top), when the mass was suddenly increased, the movement end point (the CE) statistically, was unaffected. The same was true in the mass-subtracted portion of the experiment. However, the Ts shifted considerably, being far longer when the mass was suddenly added and far shorter when the mass was suddenly subtracted. These results are consistent with the equilibrium-point view, as the movements arrived at the target even when the inertial characteristics of the lever were unexpectedly changed, with only the rate of approach to the target position being affected by the load.

Horizontal: mass varied		Normal trials	Switch trials
Mass added	CE	+6.36°	+6.81°
	T	187 ms	278 ms
Mass subtracted	CE	+5.78°	+6.28°
	T	214 ms	180 ms
Vertical: mass varied		Normal trials	Switch trials
Mass added	CE	+15.82°	+10.40°
	T	202 ms	243 ms
Mass subtracted	CE	+7.83°	+15.79°
	T	196 ms	155 ms

A second experiment had the lever movements in the *vertical* plane rather than in the horizontal plane. The equilibrium-point model, in this case, predicts that the movement end point should now be affected by the changed weight since the added weight will bias the equilibrium point downward because of gravity; a weight subtracted unexpectedly will tend to shift the equilibrium point upward. Thus, the prediction is that the limb will undershoot the target when the weight is added and overshoot it when the weight is subtracted, which is different from the prediction of no change in the horizontal-movement experiment where gravity is not involved.

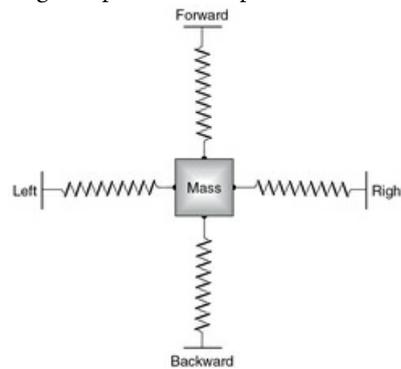
When the weight was added, from [table 7.3](#) we see that the movement in the switch trials was about 5° shorter than in the normal trials. When the weight was subtracted, the limb movement was approximately 8° longer than in the normal trials. Large shifts in T also occurred, with the added weight slowing the movement and the subtracted weight speeding it. The prediction of an impulse-timing view would be that the limb would come to a stop in the correct time. Interestingly, a reflexive closed-loop model would predict that the movement should achieve its desired end point here, because the limb system would simply move to the position that it “recognizes” to be correct, and added weight should have no effect on the terminal location of the limb—so closed-loop models are contradicted as well.

### *Extensions of the Equilibrium-Point Models*

Berkinblit and colleagues (1986) proposed a very interesting model for sequential actions on the basis of the wiping reflex in the spinal frog. They argue that this action is really a *series* of approximately seven discrete positions. The action is achieved by specifying a sequence of equilibrium positions, and each of these positions is achieved exactly as in the equilibrium-point model. This model requires something like a central program to control when each of the separate equilibrium points is specified, so the model tends to be a compromise between the equilibrium-point models and the motor program models (see Feldman & Levin, 1995; see also Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, & Engelbrecht, 1995, for a similar application).

Another application of the equilibrium-point model was described by Hollerbach (1978, 1981), who attempted to simulate handwriting through the use of various mechanical principles. He conceptualized the muscles that move the fingers as springs that move the finger up (toward the top of the page placed horizontally), down, left, and right, as shown in [figure 7.22](#). One important point about the models of Rosenbaum and colleagues and Hollerbach is that treating the muscles as “complicated springs” allows an explanation of how a trajectory is produced with a minimum of complexity in the motor programming.

Figure 7.22 A mass–spring model for handwriting. (The forward–backward and right–left spring pairs oscillate to produce writing-like patterns of a pencil attached to the mass.)



Reprinted, by permission, from J.M. Hollerbach, 1978, *A study of human motor control through analysis and synthesis of handwriting*. Unpublished doctoral dissertation (Cambridge, MA: Massachusetts Institute of Technology).

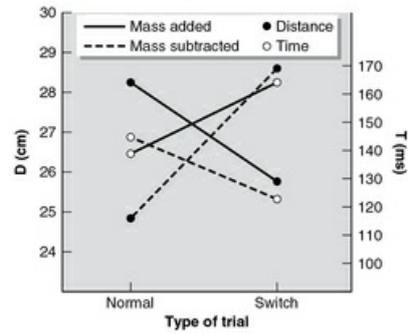
### *Limitations of the Equilibrium-Point Models*

Most of the support for the equilibrium-point model comes from only one kind of movement—simple, unidirectional positioning tasks (but see Feldman & Levin, 2009, for recent theoretical developments). To what extent is this kind of mechanism involved in movements that use more than one direction of a limb or in movements that involve more than one limb and that must be coordinated?

Schmidt and McGown (cited in Schmidt, 1980) and Schmidt, McGown, Quinn, and Hawkins (1986) investigated this problem with various kinds of movements. One study used the same kind of apparatus and experimental design as just described (see [table 7.3](#)) for the single-direction moves, but the horizontal movements now involved a reversal in direction. The participant moved in flexion, reversed the move, and extended the elbow past the starting position so that the time from the beginning until the time the starting point was again reached was 300 ms. Mass was unexpectedly added or subtracted from the lever exactly as before. Of interest was where and when the movement reversal occurred under the normal and switch conditions. Was the reversal point determined by equilibrium-point control, so that it would be unbiased in location with added load?

The major results are shown in [figure 7.23](#). The reversal point was shorter when the mass was added and longer when the mass was subtracted unexpectedly. Thus, the equilibrium-point model does not seem to account for the results (on reversal position) when the action requires a reversal that must be timed. The impulse-timing model explains these results easily: The motor program “told” the agonist when to turn off, and the movement with added weight could not go as far in this fixed amount of time, so the movement’s reversal fell short of its goal.

Figure 7.23 Results of switching mass in aimed discrete movements.



Adapted from Schmidt 1980.

It is fairly well accepted that the equilibrium-point model is the best account of how a joint achieves its *terminal* position. But there is considerable doubt that this model can account for the events that occur at the very beginning of the movement. Other evidence suggests that the initial trajectories are generated by processes somewhat more complicated than this (Atkeson & Hollerbach, 1985; Hollerbach & Flash, 1982). Also, equilibrium-point models cannot account for the results of Wadman, Denier van der Gon, Geuze, and Mol (1979), in whose experiment the unexpected blocking of the limb resulted in an unaffected agonist–antagonist–agonist EMG pattern (see [figure 6.5](#)). It also cannot account for Polit and Bizzi's (1979) experiments in which the monkey pointed at an unseen target by moving the elbow joint: If the *shoulder* joint was moved before the action, the overall pointing direction was grossly incorrect. Overall, neither the equilibrium-point model nor the impulse-timing model is capable of accounting for *all* of the findings.

## Correction Models of the Speed–Accuracy Trade-Off

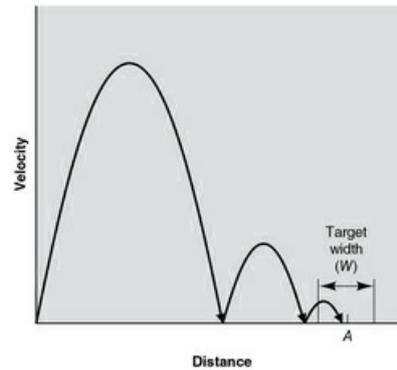
To this point in our discussions about the theoretical basis for rapidly aimed movements, we have ignored the problem of how errors are corrected. However, from previous discussions we know that errors (variability) in centrally generated signals are bound to occur. The motor system is inherently “noisy,” leading to variability in the generation of impulses or joint positions. Thus, theories describing how these error corrections occur have been important for a more complete understanding of the speed–accuracy trade-off.

### Crossman-Goodeve Model

At the 1963 meeting of the Experimental Psychology Society in England, Crossman and Goodeve presented a feedback-based explanation of Fitts’ law. They suggested that Fitts’ law could be derived mathematically, on the basis of feedback control in movement (with a number of assumptions), without the need to resort to ideas about information theory as Fitts (1954) had done. This derivation with its associated argument was described in a more accessible form by Keele (1968) and was reprinted in its entirety in 1983.

Crossman and Goodeve (1963/1983) assumed that movement toward a target is made up of two kinds of processes—much as Woodworth (1899) had proposed—except that the ballistic, distance-covering phase and the feedback-controlled “homing-in” phase were thought to operate in *rapid alternation* during a movement to the target. This mode of control is termed *intermittent* (or *iterative*); hence, their idea has often been termed the iterative-correction model. The model, illustrated in [figure 7.24](#), is based on the idea that a ballistic, distance-covering phase would operate for a *fixed* period of time, moving the limb a certain distance toward the target. This initial phase would have a spatial inaccuracy proportional to the distance that had been moved during that time. Then, feedback processes would evaluate the size and direction of the error and initiate a second ballistic movement that would serve as a correction. This second movement would also have an error proportional to its (much shorter) distance; its error would then be evaluated, another correction would be initiated, and so on until the movement reached the target. Thus, the model is based on rapid alternation between ballistic movement processes and feedback-based corrective processes during the action. The  $T$ , which is the dependent variable in the Fitts’ equation, was thought to be based on the *number* of these corrective processes that had to be made to achieve the target.

Figure 7.24 Crossman and Goodeve's (1963/1983) iterative-correction model of aiming.



Adapted, by permission, from D.E. Meyer et al., 1988, "Optimality in human motor performance: Ideal control of rapid aimed movements," *Psychological Review* 95: 343. Copyright © 1988 by the American Psychological Association.

Keele (1968) used Crossman and Goodeve's basic idea and added to it the assumptions that the time between corrections was fixed at 190 ms (Keele & Posner, 1968; see chapter 5) and that the error in each movement was about one-seventh of the total distance moved in each correction. Keele argued that each correction was processed in the stages of information processing, requiring attention, and that aimed movements were made up of a series of such corrections leading to the target. With use of these assumptions, the Crossman-Goodeve model was shown to lead to Fitts' law. Furthermore, there was a good quantitative fit to some of the experimental data (Keele, 1981).

One major drawback to the Crossman-Goodeve model of discrete aimed movements is related to the speed with which humans can process visual feedback. This was a major theme of chapter 5, and it is one of the most fundamental reasons for believing that very rapid movements must be planned in advance. Another problem relates to the psychological refractory period: Even though it might be possible to make one such correction in 190 ms, it is doubtful that the second and third corrections could also be made this quickly (review discussion of psychological refractory period effects in chapter 4). These and other criticisms of the Crossman-Goodeve theory have been discussed in more detail in several reviews (Schmidt et al., 1978, 1979; Meyer et al., 1982, 1988).

Perhaps the most persuasive argument against the Crossman-Goodeve theory was based on kinematic records of participants' movement trajectories (Langolf et al., 1976). Transitions between one ballistic segment and the next could be seen as sudden changes in the position or velocity of the limb. Generally, most of the movements studied had one correction (a very few had two), although some had no visible corrections at all, even with  $T_s$  of 700 ms. These findings failed to support the hypothesis that a correction occurs every 190 ms.

A side issue here is that Fitts' law, and the speed-accuracy trade-off in general, had usually relied on closed-loop control processes for explanation (e.g., the Crossman-Goodeve view). However, note that one contribution of the impulse-variability theory (Schmidt et al., 1979) is that it provided evidence of speed-accuracy trade-off even when the movements were far too short in time to be explained by feedback-based processes.

Finally, a crucial experiment provided strong evidence against the Crossman and Goodeve model for Fitts' law. Wallace and Newell (1983) extinguished the lights at the moment of movement initiation in a Fitts discrete task. The room lights turned on coincident with the completion of each movement. Thus, only concurrent visual feedback was removed. However, counter to the implication of the Crossman and Goodeve model, Fitts' law was obeyed for movements executed without concurrent visual feedback. Thus, although visually based corrections could not be produced, Fitts' law was still observed. This crucial finding is used as evidence that the Crossman and Goodeve model is in need of serious revision. Meyer and colleagues (1988) provided a revised theory for Fitts' law, which is described next.

## Optimized-Submovement Models

The failure of the Crossman-Goodeve theory to handle these and other data was addressed by Meyer and colleagues (1988, 1990) in what they termed the *optimized-submovement* model. Meyer and colleagues began with the idea that the initial segment of an aiming movement was handled by principles of impulse variability as described earlier in this chapter. In particular, the performer attempts to land in the center of the target with a minimal movement time. This initial submovement is governed by impulse-variability principles so that movement at too great a speed will produce too much error. With practice the performer learns to move at such a speed (“just fast enough”) to control for impulse variability and to allow for initiating a submovement correction if needed. This speed of aiming for the center while being ready for one submovement correction leads to the prediction that

$$T = \sqrt{D / W}$$

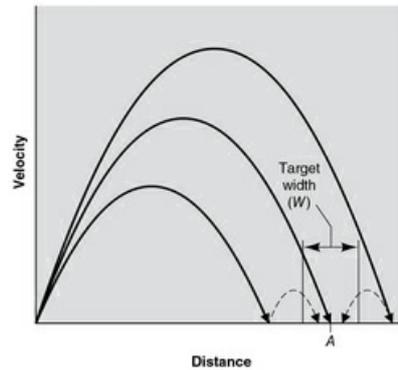
(7.9)

Because the square root of  $D/W$  and the  $\text{Log}(D/W)$  are correlated close to 1.0 at ID values less than 8, Fitts’ law is a good approximation of the square root relation. Thus, the Meyer et al. (1988) theory is similar to the hypothesis that Woodworth proposed in 1899, but it is made more concrete and experimentally testable by adding assumptions concerning how many such corrections should be expected, and where and under what conditions they should be found in a movement as a function of various movement variables.

#### *Dual-Submovement Model*

In most aiming tasks, the processes involved in bringing the limb to the target can be described by two situations that are illustrated in [figure 7.25](#). The first situation (middle curve in [figure 7.25](#)) occurs when the initial action (termed the *primary submovement*) requires no correction. The other situation occurs when the initial impulse either undershoots or overshoots the target, requiring a corrective impulse (or *secondary submovement*), shown as the dashed lines. Total T in an aiming task is considered to reflect a strategy whereby a participant attempts to trade off speed for accuracy by *optimizing* the duration of both the initial impulse and, if necessary, the correction. Thus, movement accuracy is achieved in a minimum T by optimizing the control of the submovement(s)—a nice combination of some of the important open-loop and closed-loop processes discussed in this chapter.

Figure 7.25 The optimized-submovement correction model.



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### *Multiple-Submovement Model*

In general, the dual-submovement model fits the experimental data quite well (Meyer et al., 1988). However, Meyer and colleagues also found that corrections occurred more frequently than predicted under some combinations of target amplitude and width. In a revised version of the model, Meyer and colleagues (1990) made additional assumptions to account for the fact that more than one corrective impulse could be made during an aimed movement. This multiple-submovement model was supported by a reanalysis of data from Meyer and colleagues (1988) using a different kinematic analysis protocol (see also Jagacinski & Flach, 2003, chapter 8). This reanalysis confirmed that about 80% of all aimed movements were composed of two or three submovements (i.e., one or two corrections; 43% and 37%, respectively).

### *How Is a Correction Identified and Measured?*

Although Meyer and colleagues' (1988, 1990) models provide a balanced, *hybrid* approach to the issue of open- and closed-loop processes, experimental examination of their predictions places a critical emphasis on the quantitative analysis of corrective submovements. As we have seen before, motor output processes are rather noisy, and often it is not clear how evaluations of kinematic data (e.g., position, velocity, acceleration, or jerk) can discriminate between corrections and motor noise. Various techniques have been used to objectify kinematic data, but it is beyond the scope of the present discussion to describe these analytical techniques (for theoretical discussions underlying these techniques, see Khan et al., 2006, for a review and the following references: Carlton, 1979; Chua & Elliott, 1993; Langolf et al., 1976; Meyer et al., 1988; Pratt & Abrams, 1996).

## Summary

Three types of speed–accuracy trade-offs were described in this chapter. The earliest formal mathematical statement of this relationship was proposed over 50 years ago by Paul M. Fitts, called *Fitts' law* in his honor. It says that, in reciprocal movements, the average T is linearly related to the  $\text{Log}_2$  of the ratio of the movement amplitude and the target width. This principle holds for a wide variety of movement situations and types of participants and is considered one of the cornerstones of motor control.

Force and force variability are strongly related to each other, with the relationship being essentially linear until forces of about 65% of the participant's maximum are achieved. The force variability levels off or even decreases with further increases in force toward the participant's maximum. The laws about T variability and force variability have been combined into various *impulse-variability* models for movement accuracy: The prediction is that the variability of a movement's initial impulse is linearly related to the ratio of the movement distance ( $D$ ) and T ( $D/T$ ), which is average velocity.

An analysis of laws of movement timing shows that, as the T is decreased, an increase occurs in movement-timing consistency. This occurs in addition to the effect of movement velocity, whereby movement-timing consistency is also increased as velocity is increased. These two effects combined imply that increasing the speed of movements in timing tasks leads to increased temporal consistency, contrary to ideas about the spatial speed–accuracy trade-off. Timing consistency has also been examined in repetitive movement tasks. A model of timing in which variability is due to independent, central, and peripheral sources has been a useful research tool.

Many aiming movements are influenced by central (programmed) mechanisms, closed-loop, corrective actions (both reflexive and intentional), or both. Impulse-variability principles describe how programmed impulses affect the trajectory of a rapid aimed limb movement. A different view is suggested by the *equilibrium-point* model, which holds that the limb moves to a position defined by an equilibrium point between the forces (torques) from the opposing muscles spanning a joint, and that the movement to this position is dependent on the mechanical, spring-like characteristics of the muscles. Such a model is different from an impulse-timing mechanism whereby the amounts of force, as well as the times over which they are applied, are controlled by the motor program.

Early explanations for Fitts' law were based on *intermittent-control* models, in which the commands for action were produced alternately with the analysis of feedback to determine movement corrections. Several lines of evidence, however, suggest that the intermittent-control model is incorrect. More acceptable views indicate that the timing of an open-loop, distance-covering phase and later correction(s) is *optimized* in some way in order to idealize the inconsistency in the distance-covering phase as the forces applied to the limb are increased.

### Student Assignments

1. Prepare to answer the following questions during class discussion:
  - a. Calculate the Fitts index of difficulty for the following sport tasks: throwing a strike in baseball, scoring a basket from the free-throw line, successfully scoring a field goal from 35 yd in American football, scoring a penalty kick in soccer (assuming no goalkeeper), holing a putt in golf from 30 ft, and scoring a bull's-eye in darts. (As appropriate, use regulation distances and target sizes to calculate your answers.)
  - b. Discuss the open-loop and closed-loop processes involved in using a computer mouse to open a desktop icon.
  - c. Describe the playing of a musical instrument using the concepts of spatial and temporal speed–accuracy trade-offs.
2. Find a research article that investigates or discusses the role of Fitts' law in ergonomics and human factors.

### Notes

<sup>1</sup> The  $\text{Log}_2$  of a number is the power to which the base 2 must be raised in order to reach that number; in other words,  $2^5 = 32$ , thus  $\text{Log}_2(32) = 5$ . To compute:  $\text{Log}_2(N) = \text{Ln}(N) / \text{Ln}(2)$ , Ln is the natural log. Please note that any base will work.

<sup>2</sup> The observant reader will notice that the measures of variability in [figure 7.12](#) are an order of magnitude higher than those seen in [figure 7.10](#). This occurs because *variance* is the dependent measure in [figure 7.12](#), whereas *standard deviation* is presented in [figure 7.10](#). Since the variance is equal to the squared value of the standard deviation, the results presented in [figure 7.12](#) agree remarkably well with the values in [figure 7.10](#).

<sup>3</sup> The analysis of impulses described here is simplified considerably in order to give an overview of impulse-variability modeling. Space here does not permit a discussion of the numerous assumptions underlying the analyses of impulse variability. For a more complete treatment, see Schmidt and colleagues (1978, 1979, 1985).

<sup>4</sup> These effects are not precisely as predicted by the model, however. For example, changing  $D$  does change  $VE_t$  slightly, and changing  $T$  does change  $W_e$  slightly, in both cases probably because of the effects of velocity discussed earlier (see [figure 7.9](#); Newell, Carlton, & Kim, 1994; Newell et al., 1979, 1980).

<sup>5</sup> Feldman (2009) and Larash (2008a) provide historical reflections on the origins of the Asatryan and Feldman (1965) formulation. Related (though generally unacknowledged) views were presented earlier by Wachholder and Altenburger (1927; see Sternad, 2002) and by Crossman and Goodeve (1963/1983). Perhaps these were generally unknown because Wachholder and Altenburger wrote in German and the Crossman-Goodeve model was presented at a conference and not widely circulated. These ideas were not readily available until many years later.

# Chapter 8

## Coordination

In some instances, we seem to be able to produce coordinated actions easily, almost trivially. We engage in countless activities in which our limbs perform different actions at the same time, seemingly without any interference at all (e.g., using a knife and fork; playing piano; walking and chewing gum). In tasks such as throwing and kicking, our upper and lower limbs perform very different functions and movements, all without difficulty.

Yet in other instances, there is substantial interference between the effectors when we try to perform some actions. Well-known cases of interference include the task of patting your head while rubbing your stomach. Both hands seem to “want” to do the same thing, either to rub or to pat, but not to do the different actions as required. Another example comes from Peters (1977), who found that not a single participant, out of 100 who were tested, could recite a nursery rhyme with proper timing while concurrently tapping a different rhythm. Summers, Todd, and Kim (1993) provide further evidence about difficulties in tapping different rhythms with the two hands (producing so-called *polyrhythms*, discussed in more detail later in this chapter). These and many other observations suggest the existence of interlimb coordination processes that facilitate biologically important activities, such as locomotion, but that tend to impede more arbitrary skills, which may be culturally important (piano playing, throwing) or unimportant (rubbing and patting the head and stomach).

In this book we define coordination based on the work of Newell (1985, 1986): *Coordination* involves the constraints that exist among multiple moving effectors such that variables being coordinated obey allegiance to a simple function. For example, Soechting and Lacquaniti (1981) discovered that when making a point-to-point movement with a limb, there a linear relation exists between elbow angular velocity and shoulder angular velocity; thus the elbow and shoulder are coordinated. One popular method for discovering these simple rules involves determining the task characteristics that either prevent or lead to coordinative behavior.

We have recognized for several decades now that a major source of interference in interlimb coordination is related to the *temporal* structure of the actions being coordinated (see Heuer, 1996; Klapp, 1979, 1981, for reviews). Actions with the same temporal organization are easily coordinated, with a tight temporal relationship between the limbs, whereas activities with different temporal organizations are not easily produced, if they can be produced at all. There is clearly more to coordination than this, however, as will be seen in the variety of tasks and means by which researchers have attempted to study the fundamental problems of coordination. One important factor in coordination is the duration of the movements being controlled. As we have noted in many of the chapters presented so far, the control processes in discrete skills seem to be very different (in terms of fundamental activities involved) from those underlying continuous skills. This, among other things, has created a vigorous (usually healthy) debate between a group of scientists who think of movement control in terms of self-organizing systems versus a group that thinks in terms of motor program concepts. Indeed, Keele (1998; see “Steve Keele” in chapter 1) held the view that this gulf between competing scientific “camps” “is due less to competing conceptualizations of the *same* phenomena than to the *kinds* of phenomena with which different groups of investigators are concerned” (p. 403, emphases added). Keele was referring to the tendency of (a) the self-organizing systems group to study continuous, often rhythmical, skills of (usually) long duration, where processes involving feedback and adjustment for environmental changes can be studied most easily; and (b) the more cognitively-based motor program group to study discrete skills of (usually) short duration, where planning and motor programming seem to be critically important and feedback-based adjustments do not.

In chapter 2, we distinguished between discrete and continuous tasks in terms of their beginning and end points. Discrete tasks, such as turning on a light switch or swinging a golf club, have definitive start and end points. In contrast, the start and end of continuous tasks, such as running and driving, are rather arbitrary or context dependent. Discrete tasks are usually (but not always) performed quite rapidly, and considerable theoretical importance is placed on the motor program in preplanning and organizing the body’s movements (see chapter 6).

In contrast, the role of premovement planning is less important for continuous movements; and other factors such as feedback, error detection, and error correction take on more important roles in the ongoing regulation of control, chiefly because of the additional time allowed for them to occur. Thus, in keeping with the view of motor control—where discrete and continuous skills are performed fundamentally differently—we have organized this chapter by considering the coordination of discrete and continuous tasks in separate sections. Hogan and Sternad (2007) propose that the distinction between rhythmic versus discrete tasks captures a fundamental taxonomy for motor skills.

Thus, the understanding of coordination seems to represent different challenges for discrete and continuous tasks. However, keep in mind that the problems encountered in coordinating movements in discrete and continuous tasks share many similarities. The most prominent of these is the *degrees of freedom* problem (Bernstein, 1967): Given that there are more independently moving parts of the body than seemingly can be controlled individually, how is an individual able to perform actions that coordinate these parts so effectively? The study of coordination in both discrete and continuous tasks points to some fundamental, yet distinct, principles regarding how the degrees of freedom problem is solved.

## Discrete Tasks

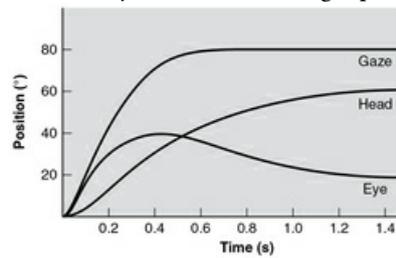
The focus of discussion in chapter 7 was on the principles by which limb movements, primarily aimed hand movements, achieved a target with minimum time and maximum accuracy. Although the motor skills that led to the generation of these principles involved relatively “simple” movements, such as repetitive tapping, in reality these movements are far from simple. The following sections also describe relatively “simple” movements, but here the focus instead is on the kinds of organization that must underlie the simultaneous control of the different effectors—that is, how are the various effectors constrained to act together (reduce degrees of freedom) in order to achieve task goals.

### Eye–Head–Hand Coordination

In chapters 5 and 7 we presented evidence that many tasks involving aiming, including reaching and grasping actions, rely on visual feedback in order to maximize movement end-point accuracy. Visual feedback information is most precise for this kind of task when the eyes can fixate on the target or object for a significant length of time prior to manual contact (e.g., Abrams, Meyer, & Kornblum, 1990). When a target occurs unpredictably, the localization of the target or object to be contacted must be fixated as rapidly as possible in order to provide sufficient time for *processing* the visual information. How is coordination of the eyes, head, and hand achieved in this situation?

Early work with monkeys revealed the existence of a tight relationship between the head and eyes (Bizzi, Kalil, & Tagliasco, 1971). [Figure 8.1](#) illustrates a typical trial in which a monkey turns to look at an unexpected target that has appeared in the periphery of the visual field. From a starting position in which the monkey’s eyes and head are pointed straight ahead, the tracings reveal that, after a brief reaction-time (RT) period, the eyes initially make a rapid *saccade* to fixate the target on the fovea. Movements of the head are initiated at the same time as those of the eyes but are much slower. As the head moves in the direction of the target, the eyes rotate in a direction *opposite* to the movement of the head. The timing of the opposing motions of the eyes and head is tightly coordinated, so that the fovea remains fixated on the target throughout the head movement. The existence of this coordination between the eyes and head has been known for a long time and is called the *vestibulo-ocular reflex (VOR)*. In the case of rapid looking, the saccade facilitates a quick identification of the unexpected visual signal. The counter rotation of the eyes maintains the fixation of the target while the head is turning.

Figure 8.1 Rotation of the eyes and head during rapid looking at a target.



Based on S. Saeb, C. Weber, and J. Triesch, 2011, "Learning the optimal control of coordinated eye and head movement," *PLOS Computational Biology* 7(11): 1-12. This is an open-access article distributed under the terms of the Creative Commons Attribution License 4.0.

A similar relationship between the eyes, head, and hand appears to exist when an intentional manual response is made to a stimulus. Biguer, Jeannerod, and Prablanc (1982) found that the onset of eye movements occurs almost simultaneously with initiation activity of electromyographic (EMG) signals in the arm and neck. This temporal coordination in the *initiation* of eye, head, and limb movements is quite flexible, however, as performance differences arise when instructions do not constrain movement strategies (Abrams et al., 1990; Stahl, 2001) or when instructions emphasize either movement speed or accuracy (Carnahan, 1992; Carnahan & Marteniuk, 1991). In addition to the temporal relationship of eye, head, and limb movements, there is also a *spatial* facilitation when these degrees of freedom interact. Manual aiming is more accurate when the head is free to move than when head position is fixed (Biguer, Prablanc, & Jeannerod, 1984; Vercher, Magenes, Prablanc, & Gauthier, 1994). It remains unclear, whether the improved accuracy is due to facilitation from the allowed movement of the head or a decrement due to the immobilization of the head.

The timing of limb movements is also well coordinated with eye movements during the *termination* of movement toward a target. Using an eye-tracking system (see chapter 2), Helsen, Starkses, and Buekers (1997) found, perhaps not too surprisingly, that an eye saccade always reached and fixated on or near the target before the hand reached the target. Of some surprise, though, was the finding of an invariant relative timing of the saccade and the manual response: Regardless of the amplitude of the movement or the absolute movement time taken to reach the target, the saccade brought the eye onto the target at 50% of the total movement time (see also Starkses, Helsen, & Elliott, 2002). Recall from chapter 6 that evidence of invariant relative timing supported the arguments for a generalized motor program (GMP). A similar argument could explain Helsen and colleagues' findings, such that a GMP coordinates the relative timing of eye and hand movement. In the next section, we show how GMP theory has been developed to explain other types of coordinated discrete actions.

## Units of Action

Discrete skills—especially rapid ones—seem to be controlled by a pattern of neuromuscular activity that is largely organized in advance. Of course, this is the essential feature of the theory of motor programs described in chapter 6. While many have debated the relative merits of central versus peripheral contributions to motor control, it seems incontrovertible that at least some fundamental features of the action are specified in advance.

The principles of speed and accuracy discussed in chapter 7 involved actions in which the primary goal was to move an effector from one location to another. Pushing the keys on a telephone and using a keyboard are examples of this type of action. However, there are other, related actions that have a more complex organization, involving serial or parallel (or both) coordination of different muscles and limbs. For example, a computer mouse enables the user to move a cursor to a target, at which time a button click (or double click) initiates the icon's function. Here, one action must be completed *before* another action can be performed. If we consider an action that is somewhat longer in duration and greater in complexity, however, such as serving a tennis ball or shifting gears in a car, it is difficult to claim that such longer sequences are controlled completely by single programs. Nevertheless, it is possible that such actions are composed of a string of programs (each lasting part of a second or more).

Each of these programs might be thought of as a *unit of action*—a "piece" of motor behavior that can be utilized

repeatedly in various actions, producing essentially the same movements (but scaled to the environment) each time. For example, we might think of shifting gears in a car from second to third gear as being composed of three units: (1) gas up/clutch down, (2) shift lever up-over-up, and (3) gas down/clutch up. (A skilled racecar driver such as Richard A. Schmidt might have performed this task as one unit.) And a given unit could be observed in other actions; a clutch-down/gas-up unit could be involved in both a gear change from first to second and a gear change from second to third, while another unit (shift-lever movements) would be different in the two actions. In the next section, we present one possible way to identify such units of behavior, based on GMP concepts.

### *Identifying Units of Action*

The underlying idea for identifying units of action is based on the notion of GMPs, discussed in chapter 6 and in the previous section. To review (see also chapter 6), the GMP is a program with invariant (a) sequencing of muscles, (b) relative timing, and (c) relative forces among the contractions. Superficial features such as overall movement duration and movement size are controlled by parameters that scale (linearly, in this simple view) the surface expression of the GMP's output, yet allow it to retain its invariant structure or pattern.

An invariance in relative timing means that the correlations (within participant, across trials) in the times of various temporal events (called landmarks) in an action should be high. To turn the argument around, if an invariance in relative timing happens to be found for a sequence of behavior (i.e., the correlations among landmarks happen to be very close to 1.0), such evidence would be consistent with the hypothesis that a GMP produced that behavior. Keep in mind that a correlation of 1.0 does not mean proportionality in the movement durations; instead, it is a strictly linear relation.

Now, consider a longer movement. Suppose that temporal occurrences of the first several landmarks in the movement intercorrelate highly, but that the time of a later landmark does not correlate with any of them. One interpretation is that the first set of landmarks was governed by a GMP (because relative timing was approximately invariant there) but that the later set of landmarks was not (because the invariance was no longer present). It could be the other way around too; the group of highly related landmarks could be located at the end of the movement, perhaps with all these landmarks being unrelated to a landmark at the start.

This evidence provides the essential idea for identifying motor programs within a sequence, which we call a unit. A unit is a sequence of behavior with essentially invariant relative timing; that is, it has high correlations in the times of component landmarks. When later landmarks of the action no longer share this invariance (i.e., they do not correlate with landmarks in the earlier portions), it indicates that the first unit has ended or that some sort of boundary exists between it and the next unit.

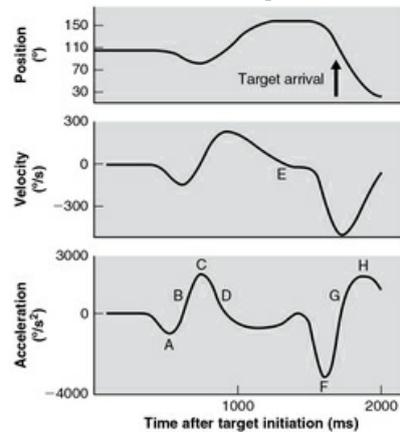
### *Methods in Unit Identification*

Schneider and Schmidt (1995; also Young & Schmidt, 1990, 1991) required participants to learn a coincident-timing task in which the timed motion of a right-handheld lever was to coincide with the arrival of a virtual moving object (as in baseball or tennis). After the virtual object began moving, the participant made a small preparatory movement to the right, followed by a backswing to the left, and finished with a striking movement back to the right (a kind of “backhand” action, with a follow-through), with the goal of “hitting” the virtual object with the lever during the second rightward movement.

Kinematic analyses of each trial were used to determine the timing of eight “landmarks” within each trial. These kinematic landmarks (shown as points A, B, C, . . . , H in [figure 8.2](#)) were defined as maxima, minima, or zero crossings taken from the position-, velocity-, and acceleration-time records (see chapter 2 for kinematic methods). Within-participant correlations were computed over trials for all of the possible pairs of landmark times. The critical comparisons involved both forward and backward methods of computing the intercorrelations. The forward computation involved the correlation of the first landmark with the second, first with the third, and so on (A-B, A-C, A-D, . . . , A-H). The backward method examined the correlations between the last landmark (H) and all possible earlier landmarks (A-H, B-H, C-H, etc.).



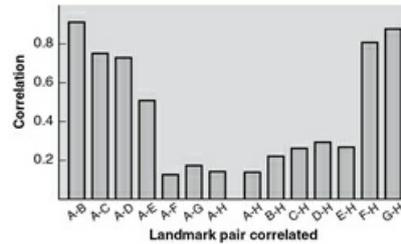
Figure 8.2 Kinematic landmarks (A, B, C, . . . , H) taken from the position, velocity, and acceleration profiles of an action are used to search for specific units of action.



Reprinted, by permission, from D.M. Schneider and R.A. Schmidt, 1995, "Units of action in motor control: Role of response complexity and target speed," *Human Performance* 8: 27-39.

If the entire action is governed by a single unit, then all of the correlations (using both the forward and backward methods) should be relatively high, as all intervals would be scaled proportionally in time. The correlations are shown in [figure 8.3](#). On the left, the correlations from the forward method are high for the landmark pairs A-B, A-C, and A-D but are low for the later combinations with A. Using the backward method, the correlations illustrated at the right side of [figure 8.3](#) show that landmark H is highly related to landmarks F and G but is not related to any of the earlier landmarks. These data suggest that this action has two identifiable units of action, one containing landmarks A-D, and the other containing landmarks F-H, with a boundary between them (between landmarks D and F).

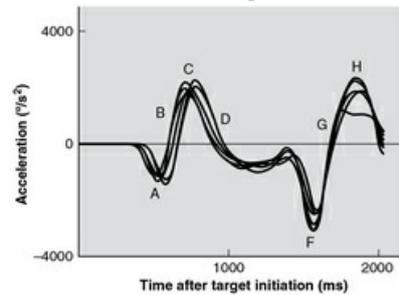
Figure 8.3 Correlations of the time of the first landmark (A) with the times of the later landmarks (left side); correlations of the time of the last landmark (H) with the times of the earlier landmarks (right side).



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The functioning of these units can perhaps be seen more easily in the acceleration–time traces in [figure 8.4](#), where these traces for six movements are overlaid. Notice that the traces are all of the same general form (but adjusted with respect to each other in time) for the first portions of the action (A-D, up to about 1,000 ms); the same is true for those in the last part of the action (F-H). However, the traces lose their common form at about 1,000 to 1,400 ms, with the traces crossing over each other. This period of time, according to the analysis, is the transition between units. At this time, the participant has completed the first action (the initial backswing) and is preparing to time the initiation of the forward swing to strike the moving object. Notice also that the first unit (A through D) actually contains two preparatory movements (right then left; [figure 8.4](#)), indicating that this one unit organizes at least two submovements and involves a change in direction. These general methods have been used in several real-world tasks; for example, researchers in one study analyzed the unit structure involved in lighting a butane cigarette lighter, identifying three sequential elements (Schmidt, Wood, Young, & Kelkar, 1996).

Figure 8.4 Visualizing units of action; unit 1 (ABCD) and unit 2 (FGH) are separated by nonsystematic crossovers after point D.

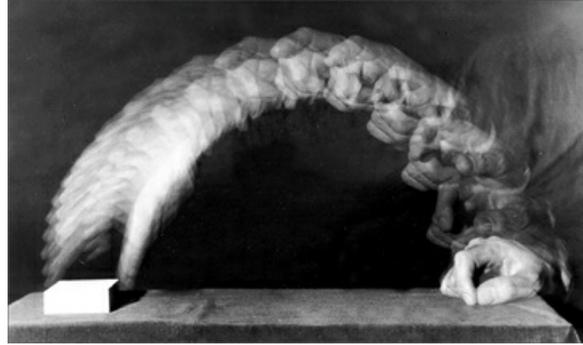


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## Reaching and Grasping

Another type of unimanual coordination has been studied in situations when limb transport ends in *grasping* an object. The composite photograph in [figure 8.5](#) illustrates how the reach and grasp are coordinated in time and space. The functional *aperture* (separation of the thumb and fingers) of the grasping hand opens during the reach toward the object. Although the hand *could* wait and open once it reached the target, this would likely be an inefficient strategy in terms of economy of effort and time. Typically, the hand reaches its maximum aperture well before object contact, at a peak size that is larger than the width of the target, and then the aperture is fine-tuned to the object's size just prior to contact.

Figure 8.5 Composite photograph of the reach and grasp action.



Reprinted from M.A. Goodale and P. Servos, 1996, Visual control of prehension. In *Advances in motor control and learning*, edited by H.N. Zelaznik (Champaign, IL: Human Kinetics), 87. By permission of M.A. Goodale.

Does this example reflect two separate and independent actions of motor control, as implied by the phrase “reaching and (then) grasping,” or is the entire action controlled as one motor program, which seems to be implied by the coordinated relationship between the limb and hand in [figure 8.5](#)? This question is at the heart of the research controversy concerning how reaching and grasping are controlled and has motivated two very different theoretical positions about movement planning, one based on temporal relationships and another that concerns spatial relationships involved in acquiring an object.

### *Temporal Planning in Reaching and Grasping*

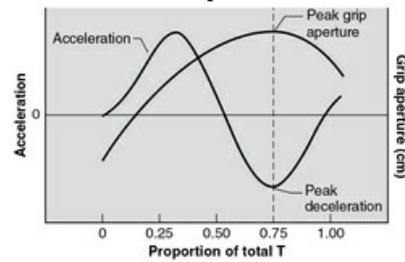
Jeannerod (1981, 1984) extended the concepts that began with Woodworth (1899) to theorize about the coordination of reaching and grasping. Recall from chapter 5 that Woodworth proposed a two-component model of manual aiming. A ballistic component brought the pencil near the target, and a closed-loop process provided fine adjustments to guide the pencil onto the target. According to Jeannerod, reaching and grasping are organized into the same fundamental components: a *transport* component and a *grip-formation* component. The composite photograph of reaching to grasp an object in [figure 8.5](#) appears to illustrate that the transport component moves the hand into the general vicinity of the target space so that the object may be grasped. The grip-formation component is responsible for preparing the hand to capture the object, and the person’s intention regarding what will be done with the object determines how the grip is formed (Jeannerod, 1996; see Castiello, 2005, for a review).<sup>1</sup>

Jeannerod (1981, 1984) and Arbib (1981; Fagg & Arbib, 1998) developed these ideas further by providing a neurologically plausible rationale for dissociating the transport and grip components. By this view, separate visuomotor channels in the central nervous system (CNS) are responsible for limb transport and grip formation. Jeannerod proposed that each channel independently processes different information in movement planning. From a viewer-centered perspective, an object’s *extrinsic* properties (e.g., its distance from the body, its location in space, or both) are used to plan the details of limb transport (e.g., the spatial coordinates of the wrist). Grip formation is determined from the object-centered perspective—the object’s *intrinsic* properties (e.g., size, shape, texture) being used to determine the specific details of hand shaping. Coordination of the reach and grasp was hypothesized to follow a *temporal* patterning—where the timing of various kinematic landmarks is scaled proportionally.

By *independent* processing, Jeannerod meant that changes in one type of visual information (i.e., an intrinsic or an extrinsic property) would affect one movement component but not the other. In support of the theory, reaching for objects at various distances from the starting location (extrinsic information) was found to affect the kinematics of the transport component only but not the grip-formation component (e.g., Jeannerod, 1981; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991; see also Jakobson & Goodale, 1991). Coordination of the two components was found to be invariant. The occurrence of maximum aperture size was synchronized in time with the peak deceleration of the wrist, regardless of the distance. An idealized trial representing the kinematics as reported by Jeannerod is illustrated in [figure 8.6](#). As shown in the figure, the time to peak grip aperture coincided

with the point of peak deceleration of the wrist, at approximately 75% of the overall movement time (T) (Jeannerod, 1981).

Figure 8.6 Illustration of relation between wrist transport kinematics and grip aperture size—idealized trial.



Based on Jeannerod 1981, 1984.

Not all studies have supported the temporal-coordination view of reaching and grasping, however, and the evidence for and against this view is mixed and complex (e.g., Bootsma, Marteniuk, MacKenzie, & Zaal, 1994; Marteniuk, Leavitt, MacKenzie, & Athenes, 1990). As noted by Wing, Turton, and Fraser (1986), research is not necessary to show that arm movements and hand shaping can be performed independently, as each action *can* be done in the absence of the other. When the two are performed together, though, the evidence suggests that reaching and grasping are not independently controlled actions. A common research method that demonstrates this phenomenon involves a perturbation during the action, such as an unexpected change in the location of the object (Gentilucci, Chieffi, Scarpa, & Castiello, 1992; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991), in the size of the object (Castiello, Bennett, & Stelmach, 1993; Paulignan, Jeannerod, MacKenzie, & Marteniuk, 1991), in the spatial orientation of the object (Desmurget et al., 1996), or via a mechanical perturbation of the moving limb itself (Haggard & Wing, 1995). The magnitude of effects observed in these studies was influenced most when a change in the type of grip was required (Paulignan & Jeannerod, 1996). In general, these studies demonstrate that any sudden change in either the perceptual or effector attributes of the action will result in a reorganization of both the reach and grasp components: The coordinated component parts of the action are not reorganized independently (see Goodale & Servos, 1996; Jeannerod & Marteniuk, 1992; Paulignan & Jeannerod, 1996, for further discussion). In sum, this evidence does not provide strong support for a temporal view of coordination in the planning of reaching and grasping actions.

### *Spatial Planning in Reaching and Grasping*

An alternative view of movement planning considers reaching and grasping not as separate components of an action but instead as a coordinated aiming movement. From chapter 7 we know that spatial variability increases if the same movement distance is completed in progressively shorter Ts (Schmidt, Zelaznik, & Frank, 1978; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). A similar effect appears to apply in reaching for objects. In a study by Wing and colleagues (1986), participants attempted to grasp an object by reaching for it as rapidly as possible, or reaching for it at a comfortable speed, with or without vision. Under full-vision conditions, the size of the grasp aperture widened as movement duration decreased (735 ms to 376 ms). Further widening of the aperture occurred when the movements were made with the eyes closed. These findings suggested that participants compensated for anticipated increased spatial variability in limb transport by increasing the size of the grasp, thereby maintaining a constant success rate by adjusting the tolerance for spatial error as needed (see also Wallace & Weeks, 1988; Wallace, Weeks, & Kelso, 1990).

In contrast to a temporal-components view of reaching and grasping, as we discussed previously, Wing (Wing & Fraser, 1983; Wing et al., 1986) suggested that a reach-and-grasp action requires aiming the *thumb* at the object, then shaping the fingers as appropriate to acquire the object. Smeets and Brenner (1999; Smeets, Brenner, & Biegstraaten, 2002; Smeets, Brenner, & Martin, 2009) extended Wing's idea to suggest that both the thumb and the finger(s) are aimed at specific locations on the object. Importantly, a change in either the position of the object (an extrinsic property in Jeannerod's scheme) or the size of the object (an intrinsic property) is compensated for by simply changing the targeted position for the thumb and finger(s).

A related view by Rosenbaum, Meulenbroek, Vaughan, and Jansen (2001) also considers reaching and grasping as a complex target-aiming task (see also Rosenbaum, Loukopolous, Meulenbroek, Vaughan, & Engelbrecht, 1995;

Rosenbaum, 2009). In their model, a reach-and-grasp action occurs by means of a selection process in which various potential *goal postures* (a forward model of the position adopted by the hand and arm when the object has been grasped, see chapters 5 and 6) are compared with the current posture of the hand and arm. The best candidate posture for the action is then selected, based on a process in which certain movement constraints must be met during the action (e.g., the resulting movement will avoid collisions, and effort is to be economized). Models of the resultant kinematics of this motion-planning view appear to agree quite well with existing data and, together with the Smeets and Brenner theory, provide exciting and potentially significant advances in our understanding of how reaching and grasping are coordinated.

## Bimanual Coordination

Using the two hands together is often studied as the archetypal coordination task. Sometimes the hands perform similar actions (e.g., lifting a baby from the crib; steering a car), and sometimes the two actions are different (e.g., holding a bottle with one hand and twisting the cap with the other; using a fork with one hand to stabilize a piece of food while using a knife to cut it with the other hand). How the control of one hand interacts with the control of the other hand while both are moving at the *same time* represents a fundamental problem for scientists who study movement coordination.

### *Bimanual Fitts' Paradigm*

The movement distance and size of the target to which a limb is aimed are strong determiners of  $T$ —a relationship identified most commonly with Fitts' law (see chapter 7). However, this law was based on experiments in which only one limb was moving. What happens to  $T$  when two limbs are moved? And more importantly, what happens to  $T$  when index of difficulty (ID) assigned to the two limbs is different? These questions were addressed in experiments by Robinson and Kavinsky (1976) and more thoroughly by Kelso, Southard, and Goodman (1979). Participants in the study by Kelso and colleagues made bimanual aiming movements in which each limb moved to a separate target as rapidly as possible. Two target IDs were used: In an “easy” task, the participant moved a short distance to a large target (ID = 0.8), and in a “difficult” task, the participant moved a long distance to a small target (ID = 3.7).

Kelso and colleagues (1979) found that the answer to the question of having both hands moving depended on which task was examined. The effect of distance and target width held true for the limb assigned to the high-ID task. This target was reached in about the same  $T$  (average of 147 ms) regardless of whether the limb moved (a) alone (i.e., “unimanually”); (b) together (“bimanually”) with the other limb, which was also moving to a high-ID task; or (c) bimanually but with the other limb moving to a low-ID task. However, distance and target width did not always predict  $T$  for the limb moving to a low-ID task. The  $T$  for this limb *changed* depending on the task conditions: (a) The  $T$  was 98 ms when performed unimanually; (b) the  $T$  increased slightly (to 105 ms) when the limb was paired with a limb that also moved to a low-ID task; and (c)  $T$  increased much more (to 130 ms) when the limb was paired with a limb moving to the high-ID task. In summary, incongruent bimanual-task ID conditions influenced the  $T$  for a limb assigned to an “easy” task but did not influence  $T$  for a limb assigned to a “difficult” task.

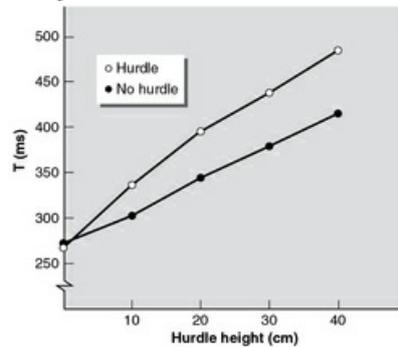
A more global way of thinking about the Kelso et al. (1979) results is that the two hands are constrained to act as a single unit. In other words, only one coordination function can be active at one time. Although there were no physical reasons why the limbs could not be controlled independently, the natural state is that the limbs are coordinated as a unit. Schmidt and Marteniuk (unpublished 1978; reported in Schmidt et al., 1979) required participants to move each hand to attempt to hit a target in a temporally constrained task, with a  $T$  goal of 200 ms. Over trials, the correlation between movement distance as well as between movement time was computed. For  $T$ , the correlation between hands, across trials was about .80; however, the correlation for  $D$  was .10. Thus, the hands shared a constraint in terms of movement duration but not for movement distance.

The Kelso et al. (1979) findings were replicated by Fowler, Duck, Mosher, and Mathieson (1991), who used

procedures identical to those of Kelso and colleagues (1979, experiment 3) but added another aiming condition in which the task had an even larger ID (of 5.2). However, in both of these studies, it is important to note that the incongruent bimanual Ts for the low-ID task (130 ms in Kelso et al., 1979) remained conspicuously *smaller* than the Ts for the high-ID task (147 ms in Kelso et al., 1979; see also Corcos, 1984; Marteniuk, MacKenzie, & Baba, 1984). Thus, it is probably more appropriate to conclude that the limb that moved to the more “difficult” task exerted a *strong determining influence* on the other limb (Riek, Tresilian, Mon-Williams, Coppard, & Carson, 2003). Probably, differences in T between experiments result from the strategic changes in the participants who performed in the separate experiments. For example, changes in accuracy rates across experiments will affect T differences. There is not a clear solution to this problem, as the phenomenon is to examine how T in individual hands accommodates the most difficult hand ID. Thus, although there are clear violations of perfect accommodation, the more important result is that the two limbs cannot be moved independently. The task pairing has a large effect on the hands.

This conclusion is supported by the results of a variant of this rapid bimanual-task paradigm. Participants moved both hands simultaneously to the same distance and to the same-sized target, but with a cardboard *hurdle* placed between the home position and the target for one of the limbs only, so that one limb was forced to move with a higher trajectory than the other to acquire the target (Goodman, Kobayashi, & Kelso, 1983; Kelso, Putnam, & Goodman, 1983). In the study by Goodman and colleagues, the height of the hurdle for one limb was systematically varied from 0 cm (no hurdle) to 40 cm, while the other limb always moved without a hurdle. The T findings are presented in [figure 8.7](#). As expected, the T of the limb going over the hurdle increased markedly with increased height of the hurdle. However, the limb that had *no hurdle* also revealed an increase in its T as a function of the hurdle height that the *other limb* was assigned to clear, showing the tendency for the two hands to produce a similar pattern. Once again, it is important to note that the increased T of the no-hurdle limb was not identical to the increased T of the limb that had to clear a hurdle; rather, the T of the two limbs was influenced similarly by the hurdle. The size of the difference in T of the limbs with and without a hurdle increased with hurdle height, as can be seen by comparing the slopes of the filled and open circle functions in [figure 8.7](#). In the Goodman and Kelso studies (Goodman et al., 1983; Kelso et al., 1983), the effect on the no-hurdle limb was also seen in the kinematic analyses of the movement trajectories. The trajectory required in order for the limb to clear the hurdle was accompanied by a similar *tendency* in the no-hurdle limb (although the effect was not a mirror-image mapping of the two limbs). The bimanual aiming task demands influenced the control of the two limbs in terms of both space and time.

Figure 8.7 Movement time (T) for two limbs. The two limbs are moving simultaneously toward targets of equal difficulty, but only one limb (open circles) must go over a hurdle that varies in height. But, T for the other limb, which does not go over a hurdle, also increases (filled circles).



Adapted from Goodman, Kobayashi, and Kelso 1983.

A much stronger temporal constraint appears to occur with use of a bimanual reaching and grasping task. Participants in studies by Jackson, Jackson, and Kritikos (1999) reached both hands forward to grasp small wooden dowels. In one experiment, the two dowels were the same size but could be placed either at the same distance from the home position (congruent bimanual task) or at different distances (incongruent bimanual task). In another experiment, the dowels were located at the same distance but were either the same size or different sizes. Regardless of the experimental manipulations, the effect on the temporal outcomes was dramatic. When the limbs were required to reach and grasp dowels in the incongruent conditions, all of the temporal measures of the reach-and-grasp actions were nearly identical for both limbs and were very different compared to the Ts in each task performed unimanually. Although more research needs to be done with this paradigm (see also Jackson, German, & Peacock, 2002), it appears that temporal coupling of the limbs is stronger when a reach-and-grasp action is the goal than in the bimanual Fitts' aiming task. Why there is a difference in these effects for reaching and grasping versus the Fitts' task is not clear at this point.

### *Spatial Coordination*

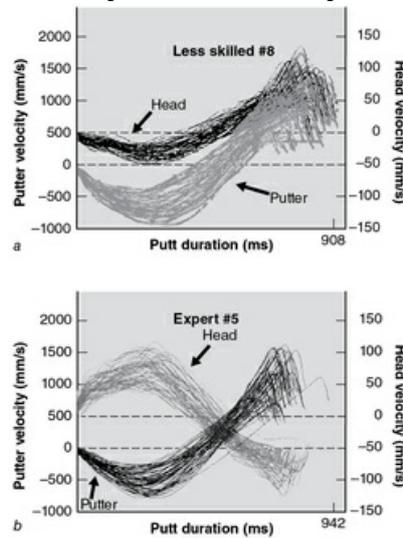
Spatial coordination can be observed when two or more body parts are assigned to perform different actions, or arise as the result of a common goal (see "Head-Arm Coordination in Golf Putting"). These effects have been studied in a number of experimental paradigms. Instead of varying target widths (as in the Fitts' task), Marteniuk and colleagues (1984) asked their participants to move as rapidly as possible and as closely as possible to a small target point, and measured the effective target width ( $W_e$  in Schmidt et al., 1979; see chapter 7). Marteniuk and colleagues found that one limb tended to overshoot a short target when the other limb moved to a far target. They also observed a small tendency for a limb to undershoot a far target when paired with a limb moving to a short target. Experiments by Sherwood (1991, 1994) suggest that these spatial *assimilation* effects occurred because the *force output* of the limb moving the lesser distance was *biased* by the greater force output required to move the other limb a farther distance.

In all these tasks, the goal was to produce the same action in the two limbs but with different amounts of distance or slightly different trajectories. The timing of the major force pulses or reversals in direction was nearly identical in the two limbs. In terms of motor programming views, the two limbs could have been controlled by the same GMP but with different parameters assigned to each of the limbs. These results suggest an interlimb interference, not at the level of the GMP, but rather in terms of the assigned parameters. One question that arises is whether such assimilation would occur when the tasks require different GMPs.

## Head-Arm Coordination in Golf Putting

Coordinating the motions of the arms and head is commonly emphasized in the act of putting in golf, and most experts recommend that the head be kept completely motionless while the arms swing like a pendulum during the putting stroke (e.g., Nicklaus & Bowden, 1974, p. 238; Woods, 2001, p. 37). However, recent research suggests that this recommendation is violated not only by less skilled golfers but also by expert putters (Lee et al., 2008a, 2008b). [Figure 8.8](#) illustrates the simultaneous velocity profiles of the putter (held by both arms) and the head during the backswing and downstroke of the golf putt (lasting about 1 s in duration). The typical less skilled golfer moved both the head and the putter away from the direction of the putt during the backstroke, and then moved both the head and putter toward the direction of the putt during the downstroke. All the pairs of velocity profiles from the 60 trials in the experiment for one participant are overlaid in [figure 8.8a](#), revealing a head–arm (putter) coordination pattern that was repeated almost identically on each trial. This tight coupling of the head and arms in the *same direction* during the putt resulted in high positive correlations (+0.78; correlations computed within each trial).

Figure 8.8 Velocity profiles of head and putter (arm) movements for (a) a typical less skilled golfer and (b) an expert golfer. Each figure contains 60 pairs of traces, corresponding to each trial in the experiment.



Reprinted, by permission, from T.D. Lee et al., 2008b, “Do expert golfers really keep their heads still while putting?” *Annual Review of Golf Coaching* 2: 135-143.

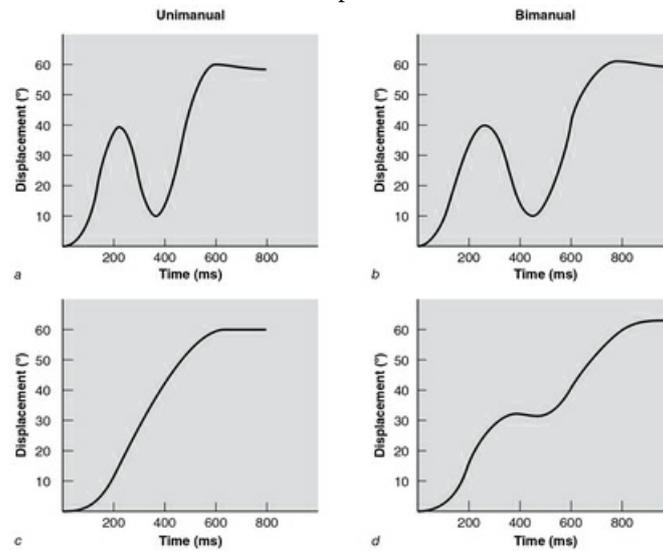
A typical set of trials performed by the expert golfers is illustrated in [figure 8.8b](#). Once again, the pairs of velocity profiles are nearly identical from the 60 trials in the experiment for this golfer. However, the major difference, compared to the less skilled golfer, was that the expert golfers moved their head in a direction that was opposite to the motion of the arms during the putt. Experts moved their heads toward the direction of the putt as the backswing moved away from the ball. Then, at the same time the putter reversed its direction, the head reversed its direction too. This tight coupling of the head and arms in the *opposite direction* during the putt resulted in high *negative* ( $-0.70$ ) correlations of the velocity profiles.

These findings have a number of important implications regarding coordination of degrees of freedom in putting. One implication is that golfers of varying skill level reduce the complexity of the putt by tightly coordinating the motions of the arms and head to act as a GMP. Coordinating the interdependence of the two limbs to act as a single unit of action—both for the less skilled and the expert golfers—is consistent with the evidence that a single GMP governs the coordination of these degrees of freedom (for details see the research of Heuer, Schmidt, & Ghodsian, 1995, discussed later in the chapter). Another implication of these findings is that, during the motor learning process (presumably with practice and augmented feedback), the GMP for the putt undergoes a fundamental change from a same-direction to an opposite-direction coupling of the head and arms. However, it does *not* appear that the skilled golfer keeps the head completely still during the putt, despite how it might seem.

Swinnen, Walter, and colleagues examined interference in tasks that required the upper limbs to perform two completely different patterns at the same time (e.g., Swinnen, Walter, & Shapiro, 1988; Walter & Swinnen, 1990)—that is, in tasks for which a given program controlling the right arm could not have been merely scaled to produce the required action in the left arm. Walter and Swinnen (1990) had participants produce an 800 ms movement with two reversals in direction with one arm and a unidirectional movement in the other arm. When these actions were done separately, the typical position–time records resembled the traces shown in [figure 8.9, a](#) and *c*. But when the participants produced the two actions simultaneously, evidence of the pattern of the arm performing the complex movement could be detected in the action of the arm doing the simple movement, although the amount of interference was not sufficient to make the arms produce identical movements ([figure 8.9, b](#) and *d*). The patterns of forces in the two arms occurred at essentially the same time, as if the pattern of

contractions in the complex-movement arm were somehow “overflowing” to the simpler arm action. Furthermore, the interference appeared to be greater when the left arm performed the complex task and the right arm produced the simple task; adding a load to the complex-movement arm tended to increase this bias, and practice reduced the interference (see Walter, Swinnen, & Franz, 1993, for a review).

Figure 8.9 Bimanual coordination effects for limbs with different displacement–time goals; two-reversal task (*a and b*), unidirectional movement (*c and d*), unimanual performance (*a and c*), bimanual performance (*b and d*).



Adapted from *Brain and Cognition*, Vol. 14, C.B. Walter and S.P. Swinnen, “Asymmetric interlimb interference during the performance of a dynamic bimanual task,” pgs.185-200, Copyright 1990, with permission from Elsevier.

These authors have discussed their results in terms of what they call structural and metrical *coupling* of the two limbs, with practice serving to uncouple, or *dissociate*, the actions of the arms (e.g., Swinnen, 1992; Walter & Swinnen, 1992). How this uncoupling occurs, though, is not entirely clear. One possibility is that independent control of each limb is acquired through the development of separate motor programs. This seems unlikely for a number of reasons, most important of which is the evidence presented in chapter 4 that the CNS appears incapable of programming and initiating two different actions at *exactly* the same time. Another possibility is that some different form of *interdependence* emerges that allows the limbs to do slightly different things at the same time.

Heuer, Schmidt, and Ghodsian (1995; Schmidt, Heuer, Ghodsian, & Young, 1998) studied movement performances in a situation where the two arms produced deliberately different rapid, discrete patterns. The seated participants moved two horizontal levers with elbow flexion–extension movements to produce specific space–time patterns for each limb. The right arm produced a flexion–extension–flexion pattern through about 70°, while the left arm simultaneously produced a flexion–extension pattern through about 60°, with Ts ranging from 400 to 600 ms. Participants had considerable difficulty at first, but after several hundred trials, they were able to produce the actions very easily.

From the acceleration–time traces, Schmidt and colleagues (1998) defined 12 landmarks, essentially as had been done in the analysis of units described earlier (see [figure 8.2](#)). The within-participant (across trials) correlations of all possible pairs of landmarks were then computed (see [figure 8.3](#)). The correlations for the landmarks within each arm were generally very high, averaging 0.91 (right) and 0.94 (left), especially when the actions were done as quickly as possible (Schmidt et al., 1998). The relatively high correlations for all the landmarks suggested that each arm produced a pattern controlled as a single unit, as discussed earlier.

The interesting point for coordination, however, concerns the correlations of the landmarks *between* the arms. These correlations were also generally very high, especially when the actions were very rapid, and were nearly the same as those for the individual arms (mean = 0.91). These findings supported the view that the coordination between the two arms was controlled as a single unit (i.e., by a single GMP controlling both hands at the same time, as discussed earlier in this chapter), even though the two limbs produced completely different spatial–temporal patterns. In fact, supporting this single-GMP view, participants became able to speed up or slow down this entire bimanual pattern on command, changing the left- and right-arm speeds together. But, when instructed to produce the arm movements at different speeds (e.g., speed the right arm and slow the left), participants found this variant nearly impossible to do (Schmidt et al., 1998). These data imply that the right and left arms were

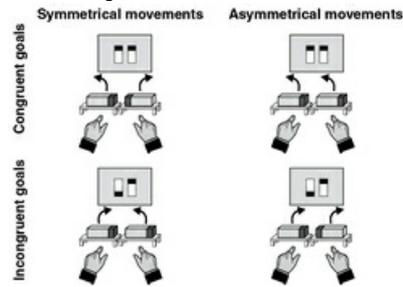
being scaled together in time so that relative timing (both within and between arms) was essentially invariant. In other experiments, where the movements were done even more quickly, the landmarks between the two arms were even more strongly coordinated. Therefore, on the basis of the logic of units of action presented earlier, the separate actions produced by the right and left arms were part of the *same* GMP. This result shows *increased* coupling between the limbs with practice—not decoupling as argued by Swinnen (1992; Walter & Swinnen, 1992), discussed earlier. This finding also provides a basis for the idea that complex, multilimb actions—in which all of the limbs are doing different things, as in pole-vaulting, or the golf-putting example given earlier—can probably be controlled by a single, learned GMP. Apparently, when two limbs do different things at the same time, this does not necessarily mean that they are operating independently.<sup>2</sup>

### *End-State Coordination*

Recall from chapter 3 that, in some situations, we choose rather awkward initial limb postures in order to maximize biomechanical efficiency (or “end-state comfort”) at movement completion (Rosenbaum, 2009; Rosenbaum et al., 1990). In these cases, selecting a movement plan to satisfy a specific (end) goal appears to be a natural and spontaneous process. So, how would *two* limbs be coordinated if each had a specific but incompatible end goal? Would the end-state comfort effect be traded off in order to achieve a well-coordinated movement? Surprisingly, individuals do not prefer one coordination pattern to another—they tend to choose the pattern most likely to satisfy a goal that maximizes end comfort for both limbs, as described next.

Kunde and Weigelt (2005) had participants perform the tasks illustrated in [figure 8.10](#), involving the raising of two blocks from a horizontal to a vertical orientation. These actions could be performed with either symmetrical or asymmetrical hand movements, resulting in end goals that were either congruent or incongruent with respect to object orientation ([figure 8.10](#)). The main finding was that participants showed no preference for symmetric over asymmetric hand movements. Rather, the achievement of congruent goals with both hands resulted in responses performed with faster RTs and Ts and fewer errors than incongruent goals, regardless of *how* the actions were performed. Other experiments, in which participants were allowed to choose the orientation of the hands, revealed that even an uncomfortable coordination pattern was preferred if it maximized end-state comfort (Fischman, Stodden, & Lehman, 2003; Hughes & Franz, 2008; Janssen, Beuting, Meulenbroek, & Steenbergen, 2009; Weigelt, Kunde, & Prinz, 2006). These findings are similar to the results seen in unimanual tasks (Rosenbaum, 2009).

Figure 8.10 Participants performed bimanual movements to raise two blocks, with colored ends, from horizontal to vertical positions. Congruent goals were defined as raising the two colored ends to the same vertical position. Incongruent goals required one colored end to be on top and the other on the bottom of the vertical position. Symmetrical movements involved hand actions in which both raised blocks were turned inward or outward. Asymmetrical movements required both hands to move in the same direction.



Reprinted, by permission, from W. Kunde and M. Weigelt, 2005, "Goal congruency in bimanual object manipulation," *Journal of Experimental Psychology: Human Perception and Performance* 31: 145-156. Copyright © 2005 by the American Psychological Association.

These findings suggest that the nature of the coordination pattern appears to be subservient to the desired end result. In the case of end-state comfort effects, biomechanical efficiency at movement completion appears to take precedence over how the limbs move there.

## Continuous Tasks

A recurring issue throughout this book is the difference between discrete and continuous skills in how motor control is achieved. Although some commonalities exist, major differences abound as well (e.g., role of feedback and motor programs). In this section, we will see that many researchers who study coordination in continuous tasks take a fundamentally different view regarding the process of movement control than researchers who study discrete tasks. “Costs and Benefits of Coordinating Two Limbs” presents two little experiments for you to try, which represent examples of some fundamental processes when continuous movements of two or more limbs are performed simultaneously. These phenomena have interested scientists for over a century but have been the topic of intense experimental scrutiny only in recent years.

### Early Research

Bimanual coordination of continuous tasks in humans has interested researchers for many years (see “R.S. Woodworth on Coordination”). For example, right-handed participants in Langfeld’s (1915) experiment tapped one finger as rapidly as possible for 30 s—either the index or middle finger of the right or left hand. Between-finger differences on the same hand were small, but between-hand differences were large: Average Ts for the right-hand taps were 181 ms compared with 222 ms for the left hand. This is not too surprising; asymmetries in performance are frequently found when left- and right-hand performances of right-handed people are compared (e.g., Elliott & Roy, 1996; Sainburg, 2005). However, on some trials, participants tapped with one finger on each hand such that the two taps were made *simultaneously* and as fast as possible. When participants tapped with the same finger on both hands (e.g., the right and left index finger at the same time) the average T was 208 ms, which represents a 27 ms *decrement* for the right finger (compared to 181 ms in unimanual tapping) but a 14 ms *facilitation* for the left hand (compared to 222 ms). Langfeld (1915) thus showed that, in the process of becoming coordinated, the temporal, “independent behavior” of the two hands changed dramatically. The timing of the two hands became much more interdependent, resulting in a facilitation in performance for the finger on the nondominant hand and a decrement for the finger on the dominant hand.

The struggle between the tendency of one oscillating limb to maintain an independent motor behavior (termed *maintenance tendency* by von Holst [1937/1973]) and the tendency of its behavior to become coupled with another oscillating limb (which von Holst called the *magnet effect*) captures a critical feature of temporal coordination in continuous skills (see Gallistel, 1980). As we will see in the next sections, these strong natural tendencies play an important role in the coordination of continuous actions.

### R.S. Woodworth on Coordination

#### Research capsule

Much of the current work on coordination has its roots in monographs that were not available in English until quite some time after their original publication. Some of these works were eventually translated and had a very influential effect on English readers when they were published (e.g., Bernstein, 1967; von Holst, 1937/1973). In other cases, contemporary researchers have made us aware of important untranslated works (e.g., Heuer, 1996; Latash & Zatsiorsky, 2001; Worringham, 1992). Another source of 19th-century work on coordination—a brief review published in French by Woodworth (1903)—had not, to our knowledge, been translated into English prior to the third edition of this book. A comparison of the following quoted passage to some of the “modern” work on coordination reveals some remarkable early insights regarding spatial and temporal coordination, which became a dormant issue in research for quite some time.

"It is common knowledge that one can execute with ease simultaneous, corresponding movements with the right and left hand. One must, however, make an effort so that they correspond; if one moves the right hand in mid-air, tracing any shape, one must devote attention to the left hand simply for it to move, for it will trace the symmetrical corresponding shape. The connection is more between the innervation of corresponding muscles on both sides of the body.

"Munsterberg proved that there was another relationship between movements of both sides. When an arm is balanced in front, the other must naturally balance itself, not in front, but behind; there are also other cases in which symmetrical movements on both sides must naturally alternate with one another. It is not less true that it is easy to execute simultaneous movements that correspond on each side.

"Ostermann found that this ease appeared only in bilateral symmetrical movements. If we tried to make simultaneous movement, symmetrical in relation to a horizontal plane, the attempt would result in inexactness and confusion. The attempt had not been "natural" and was executed without confidence, whereas bilateral symmetrical movements were executed with ease and confidence and some achieved exactness.

"Bloch discovered that in order for the symmetrical movements to be executed with ease and precision, both arms have to move at the same time. If one moves an arm toward a certain point, the effort that one will make to place the other arm to the corresponding point will result in inexact movement." (Woodworth, 1903, pp. 97-98)

## Gait Transitions

Watch people as they hurry to catch a bus. They usually choose one of two gaits to get to the bus: a fast walking gait or a running gait. Each gait has distinct relative timing and biomechanical characteristics. Within a certain range of speeds, either gait will get the job done. What process determines the gait that will be used? As it turns out, this question is not a trivial one; and the answer has provided considerable evidence to support an important view of motor control.

### *Animal Research*

In chapter 6 we discussed the mesencephalic preparation in cats. Walking could be initiated in these spinalized cats on a treadmill; the provided stimulation was not rhythmical and in time with the walking patterns, though. One important finding was that increases in the speed of the treadmill induced changes from a walk to a trot, and occasionally to a gallop. Although the animal could not feel its legs while in locomotion, these specific gait patterns, and more importantly, the *qualitative* (or "nonlinear") change from one gait pattern to another, still occurred on occasion.

## Costs and Benefits of Coordinating Two Limbs

Two quick and easy little experiments will demonstrate how moving a second limb along with one that is already moving can have both positive and negative consequences, depending on the task. In the first experiment, using a blackboard and chalk, try to write your name with your nondominant hand at usual speed but backward (i.e., producing a mirror image of your name). You will probably find that this is very difficult to do and that the pattern is barely legible. Now do the same task again, but this time, do it simultaneously with the dominant hand writing normally, so that the hands are writing in opposite

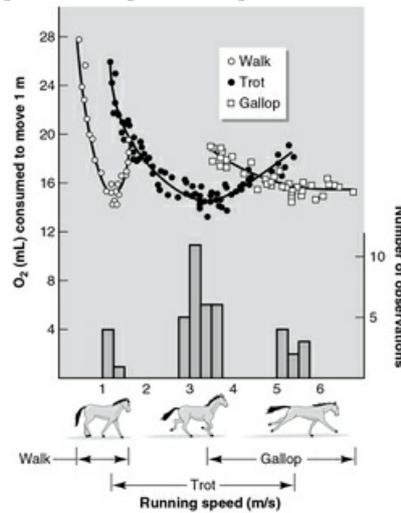
directions. You should find that the pattern of the nondominant hand is much smoother and that the two patterns are roughly similar (but mirror images of each other). More importantly, as you perform the two-handed task, notice how the two limbs seem to be “locked together” (or “coupled”). Even though the nondominant handwriting is somewhat more uncontrolled than the dominant, a characteristic pattern still emerges—the same loops, straight parts, and so on.

Sit in a chair to do the second experiment. Begin by making clockwise circles on the floor with your right foot. Then, while continuing to make circles, draw the number “6” in the air with your right hand. What happened to your foot’s movement? In all likelihood, your foot no longer continued to make circles. Now, try this experiment again, combining the right-handed 6s with your left foot making the circles; then again with your left hand making the circles. Now try all three again by making the circles in the counterclockwise direction. Was the circle drawing easier to maintain in any of these six experimental conditions?

In performing these two experiments, notice how the two limbs tend to *want* to be locked together, as if you had lost some control of them and they were being controlled by some other influence. In the handwriting experiment, this tendency has a facilitating effect—the performance of the nondominant limb improves relative to the unimanual (control) condition. In the circle-drawing experiment, this same tendency has a detrimental effect—the performance of the circle declines relative to the control condition. As suggested by the differences in performance in the six circle-drawing conditions, though, the tendencies to couple the limb movements depend largely on the tasks and the effectors that are involved in performing them.

Gait patterns and the transition between gait patterns in animals with four or more limbs are fascinating to compare across species (e.g., Alexander, 2003, chapter 7). Of particular interest here is the process by which an animal selects a particular speed within each gait, and the process that determines *when* the animal will change gaits. A leading hypothesis is that gait selection and the decision to change gaits are both based on a principle of *minimal energy costs* (Alexander, 2003). Consider the analysis of horse gaits in [figure 8.11](#) (Hoyt & Taylor, 1981). The histograms in the bottom half of [figure 8.11](#) illustrate the frequency of gaits that a horse selected spontaneously when the treadmill speed was changed. These histograms represent a subset of the total range of speeds that the horse *could* select within each gait. Taking this analysis further, Hoyt and Taylor measured the energy cost (defined in terms of oxygen consumption) of horses that were trained to walk, trot, and gallop at a range of speeds on a treadmill (speed now being determined by the experimenter). The data in the top half of [figure 8.11](#) suggest that the energy costs of walking and trotting were rather high at both extremes of the speed ranges within each gait. Moreover, the maximum energy efficiency, defined at the minimum points on the walk and trot curves, corresponded rather well with the speeds that the horses selected spontaneously when locomoting at different speeds. Hoyt and Taylor (1981) suggested that energy efficiency might represent a basis used by an animal for the selection of specific speeds within a gait, and that energy *inefficiency* serves as the *catalyst*, or *trigger*, to change gaits.

Figure 8.11 Oxygen consumption at various speeds in the walk, trot, and gallop gaits of a horse. The histograms just above the  $x$ -axis represent the preferred speeds that the horse selects in each gait.



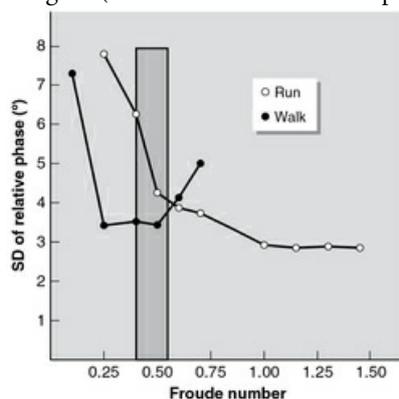
Reprinted from *Nature* Vol. 292, D.F. Hoyt and C.R. Taylor, 1981, "Gait and the energetics of locomotion in horses," pgs. 239-240, Copyright 1981. By permission of D.F. Hoyt.

### Human Research

Humans typically use only two gaits, walking and running. The transition between these two gaits occurs between 2.0 and 2.2 m/s (about 4.5 and 4.9 mph), but this can change depending on a number of factors, such as whether the person is accelerating (a walk-to-run transition) or decelerating (run to walk) (Diedrich & Warren, 1995), the rate of acceleration (Van Caekenberghe, Segers, De Smet, Aerts, & De Clercq, 2010), and cognitive load (Daniels & Newell, 2003). On the basis of the energy-trigger view from the animal research just presented, one hypothesis would suggest that inefficiency in metabolic costs might be a leading catalyst for this transition. Support for this view would be strong if oxygen consumption levels were drastically different between performances at the pre- and postgait transition speeds. An experiment to test this prediction, however, showed no such drastic change, even when load conditions were added to increase overall energy expenditure (Raynor, Yi, Abernethy, & Jong, 2002).

An alternative view of the trigger process suggests that the gait pattern begins to lose *stability* at speeds beyond the normal transition point (Diedrich & Warren, 1995, 1998a, 1998b). In these experiments, Diedrich and Warren examined the variability in the ankle-hip and ankle-knee segments in terms of within-limb relative phase as participants walked and ran at speeds that were greater and less than those in the normal transition region. Results from one of these studies are illustrated in [figure 8.12](#). Here the normal transition range appears as the shaded region of the graph, and measures of the SD of relative phase for the ankle-knee segment are plotted for both walking and running at various speeds. (The measure on the  $x$ -axis, the so-called Froude number, represents speed normalized for leg length.<sup>3</sup>) The results are clear: For the relative phase in both segments measured, walking became more variable (less stable) at speeds *higher* than the normal transition point, and running became more variable at speeds *lower* than the normal transition point (Diedrich & Warren, 1995; see also Kao, Ringenbach, & Martin, 2003). Note, however, that these data do not provide clear evidence that pattern instability is necessarily *the trigger* for a gait transition, just that improved stability is concomitant with a gait transition.

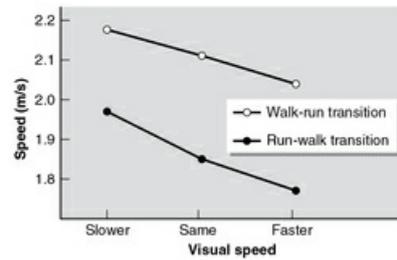
Figure 8.12 The variability in ankle–knee relative phasing in walking and running at speeds that were greater and less than the normal transition region (Froude number refers to speed normalized for leg length).



Adapted, by permission, from F.J. Diedrich and W.H. Warren, Jr., 1995, "Why change gaits? Dynamics of the walk-run transition," *Journal of Experimental Psychology: Human Perception and Performance* 21: 183-202. Copyright © 1995 by the American Psychological Association.

Neither the energetic nor the stability hypothesis appears to explain the findings of the role of *vision* on gait transitions, however. In a recent study by Mohler, Thompson, Creem-Regehr, Pick, and Warren (2007), participants walked on a treadmill that provided an "endless hallway" virtual environment. Walk-to-run and run-to-walk gait transitions were stimulated by increasing or decreasing the treadmill speed periodically over the duration of the trial (which is typical of this research protocol). However, the additional manipulation used by Mohler and associates (2007) was to covary the visual feedback provided by the virtual environment. In a control condition, the virtual visual feedback was matched to the visual array that the participant would have received in a normal environment for that biomechanical speed (1:1 correspondence, or 1.0 gain). In two other conditions, the virtual visual feedback was halved (1:2 correspondence, or 0.5 gain) or doubled (2:1 correspondence or 2.0 gain) relative to the actual gait speed. Thus, a slower visual feedback condition resulted in the sensation that gait was slower than was actually the case (and conversely for the faster visual feedback condition). The results of the study are illustrated in [figure 8.13](#). Regardless of the gait transition (walk-run or run-walk), providing the *visual sensation* of a slower gait resulted in a transition that occurred at a faster speed than in the control condition. Conversely, the faster visual feedback condition resulted in gait transitions at speeds less than normal.

Figure 8.13 Effects of actual gait speed and apparent (visual) speed on the point of walk–run and run–walk gait transitions.



Mohler and colleagues’ findings provide difficulties for both the energetic and stability gait-transition hypotheses. Since the only manipulation in the study was *virtual* visual feedback (i.e., the treadmill speeds were consistent in all visual conditions), there were no biomechanical or physiological reasons for changes in the gait-transition speeds. Therefore, these findings suggest that gait transitions, and perhaps coordination more generally, are based on multisensory information sources.

## Temporal Coordination

A considerable research emphasis that has emerged in the past two to three decades is devoted to bimanual coordination of the upper limbs. Some of the initial work was motivated by a desire to understand transitions from one pattern to another more fully; a task involving the continuous cycling of two fingers provided a paradigm to study phase transitions between any two limbs (Kelso, 1995). However, the study of temporal coordination, in general, went far beyond these initial motivations and now represents a complex area of research investigation in itself. In this section we provide an overview of the research issues, paradigms, and theoretical orientations that have emerged in the study of temporal coordination. Much more in-depth treatments of this literature are widely available (Kelso, 1995; Kelso & Engström, 2005; Swinnen, 2002; Turvey & Fonseca, 2009).

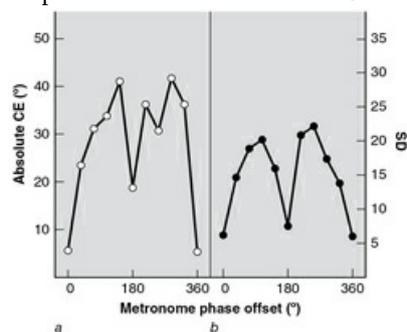
### *Bimanual Timing Patterns*

Try this simple experiment (cf. Kelso, 1984). Hold your hands in front of you with the index fingers pointing straight ahead, and make a series of “pinches” by touching the finger to the thumb. Do this with both hands such that you are making one “pinch” about every second with each hand. When we ask students in our classes to do this simple task, with no further instructions, almost everyone does it the same way—the pinches are coordinated such that the fingers and thumbs on both hands are making contact at about the same time. This tendency to produce a recognizable *timing pattern* can be quantified by measuring the relative phase of the between-hand timing (as described in chapter 2). In this case, the “pinch” of the one hand occurs at about the same time within its cycle as does the pinch of the other hand, relative to its cycle. (The difference in phase angles of the two limbs within each of their respective cycles provides a quantitative measure of coordination, called “relative phase”; see chapter 2 and [figure 2.12](#) for more details). Moreover, the maximum opening between the finger and thumb (which occurs about halfway through the cycle) also occurs at about the same time for each hand. The timing relation of these (and other) kinematic landmarks within each cycle for the two hands result in a mean relative phase of 0°. The standard deviation of individual scores used to calculate the mean provides a measure of the *stability* of the pattern, which is usually very stable for this task (i.e., the SD of these phase angles is typically about 5°–10° around the mean value). The pattern is commonly described as moving *in-phase*, or in *symmetry* (see chapter 2). For this task, the in-phase coordination mode is the *preferred*, or most frequently adopted pattern.

Now, holding your hands and moving at about the same speed as before, try performing a different pattern. Make pinching movements with both hands such that the pinches alternate on the two hands. You will probably find that this is also quite easy to do. Since the closing of the pinch for one hand occurs while the other pinch is about halfway through its cycle (i.e., when it is at maximum aperture), the relative phase of this pattern has a mean of 180°. This pattern is commonly known as moving in *anti-phase*, or in *asymmetry*.

Numerous investigators have studied in-phase ( $0^\circ$  mean relative phase), anti-phase ( $180^\circ$ ), and timing patterns with phase relations in between (e.g.,  $60^\circ$ ,  $90^\circ$ ,  $150^\circ$ ); the results illustrated in [figure 8.14](#) are typical (Yamanishi, Kawato, & Suzuki, 1980). In this study, participants tapped their left and right fingers in time with left and right visual metronomes that were set to “beat” at various phase offsets. Measures of relative-phase accuracy and variability are presented in [figure 8.14](#).<sup>4</sup> The in-phase patterns ( $0^\circ$  and  $360^\circ$  on the  $x$ -axis) and anti-phase pattern ( $180^\circ$ ) were performed with much greater accuracy ([figure 8.14a](#)) and with more stability (lower SDs in [figure 8.14b](#)) than for any of the other phase relations. In addition, there was a slight tendency for the in-phase pattern to be performed with more stability than the anti-phase pattern. The performances of these two timing patterns illustrate natural and stable coordination modes for oscillatory bimanual movements and have been replicated in experiments using finger-oscillation tasks (e.g., Kelso, 1984), finger tapping (e.g., Tuller & Kelso, 1989), wrist rotations (e.g., Cohen, 1971; Lee, Blandin, & Proteau, 1996), swinging pendulums (Schmidt, Shaw, & Turvey, 1993; Turvey, Rosenblum, Schmidt, & Kugler, 1986), and other similar movement coordination tasks. This work has been reviewed by Kelso (1995) and Swinnen (2002; Swinnen & Wenderoth, 2004).

Figure 8.14 (a) Absolute constant error (|CE|) and (b) standard deviation (SD) of relative phase for limbs moving at phase offsets between 0° and 360°.



Based on Yamanishi, Kawato, and Suzuki 1980.

## Unintended Phase Transitions

Here is another little experiment. Perform the in-phase, pinching pattern as before, starting at a comfortable timing frequency (e.g., 1 beat/s). Now, gradually speed up the pinching frequency until eventually you are moving as fast as possible. Then repeat the experiment, this time starting with the anti-phase pattern. As seen before (Yamanishi et al., 1980; see [figure 8.14](#)), both timing patterns were performed close to their intended goal and with small variability at low oscillation frequencies. This stable and accurate performance continued for the in-phase pattern as oscillation frequency increased. However, the influence of frequency on the anti-phase pattern was rather startling: At about 2.25 Hz, the timing pattern began to *switch* from anti-phase to in-phase coordination mode. The anti-phase pattern actually began to become more variable at about 1.75 Hz, suggesting that the loss in stability somehow precipitated the switch. Participants in Kelso’s experiment had been instructed not to resist these pattern switches, so once the original anti-phase pattern had become an in-phase pattern at higher speeds, the new mean relative phase remained close to 0° with low variability. This basic set of findings has been replicated many times, using different effector pairs (see Lee et al., 1996, for a review).

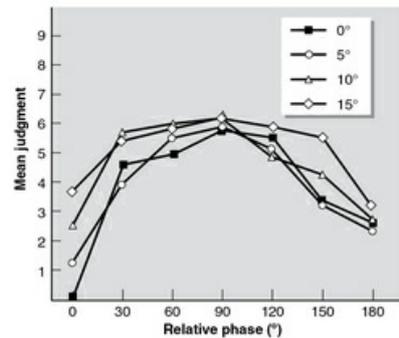
Although there are some similarities in the transitions between patterns of bimanual coordination and the gait transitions discussed earlier, there are just about as many differences. For example, a stable in-phase pattern can be performed at all speeds, whereas a stable anti-phase pattern can be performed only at low oscillation frequencies. As well, when changing gaits as the speed increases we do not change from anti-phase to in-phase—that is, we don’t start hopping). However, there are many intriguing similarities too. The most important of these is the loss of stability that precedes a phase transition from anti-phase to in-phase. This result is quite similar to the loss in stability that precedes a gait transition at nonpreferred speeds (Diedrich & Warren, 1995). And, in a way, similar to what is seen with gait transitions (discussed previously; Mohler et al., 2007; see [figure 8.13](#)), the performance of these timing patterns is highly susceptible to visual feedback influences (Mechsner, Kerzel, Knoblich, & Prinz, 2001).

## Self-Organization Theory

Haken, Kelso, and Bunz (1985) presented an influential model of the results reported in [figure 8.15](#) that has had profound effects on motor control research (see Jeka & Kelso, 1989; Kelso, 1995, 2008; Kelso & Engström, 2005; Wallace, 1996, for more details). This model of two coupled oscillators (commonly referred to now as the HKB model) was grounded in the science of dynamics—literally, how physical systems change states over time. Five important effects depicted in [figure 8.15](#) laid the groundwork for the HKB model. (1) Both the in-phase and anti-phase patterns are performed well at low movement frequencies. The system is said to be *bistable*—there are two stable coordination regimes. (2) At maximal speeds, only the in-phase pattern remains stable; the anti-phase is destabilized and switches to in-phase. Thus, the system underwent a *phase transition* from a bistable to a monostable coordination regime. (3) The process of change for the initially anti-phase pattern is abrupt and

qualitative—the change involved a *nonlinear* transition, called a *bifurcation*. (4) The phase transition was instigated by an outside agency (changes in the pacing frequency in this case), called a *control parameter*.<sup>5</sup> (5) The nonlinear phase shift was precipitated by a destabilization of the anti-phase pattern during a *critical period*.

Figure 8.15 Judgments of perceived variability for two objects in motion with different mean relative phases (denoted on the  $x$ -axis) and levels of variability (corresponding to the symbols in the key). Mean judgment was scored on a Likert scale, where 0 represented no variability and 10 represented maximal variability.



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The general purpose of the HKB model was to conceptualize these movement coordination findings (and other, related findings) as a self-organizing system, as in the way the physics of chemical actions might be modeled. By *self-organization*, Haken and colleagues assumed that the degrees of freedom involved in movement were governed by patterns (called "collectives") that were subject to destabilization and transitions. Compared to more cognitively based models or theories of motor control, the key feature of self-organization was a decentralization of the burden of how coordination is achieved. According to this view, the system organizes its degrees of freedom through preferences that undergo transitions as an interaction with the environment within which it performs. The role of cognition is diminished, especially as compared to that in contemporary motor control models. In other words, self-organization is like an orchestra playing without a conductor (Kelso & Engström, 2005). A better way to conceptualize self-organization is to imagine an orchestra playing without a *score* to guide them; it is unrealistic to expect organized music to result. Or imagine children playing a sport without an adult coach to teach them; the task seems impossible. However, many organized, coordinated activities such as flock of birds flying, fireflies synchronizing their lights, and termites building structures neither have a score nor a master builder or conductor but are based upon adherence to simple rules produce organized behavior (Strogatz, 2003).

One critical feature that sets the HKB model (and theoretical approach) apart from many other theories is the role of *variability* in motor control. Recall the discussion of the laws of speed and accuracy in chapter 7. Increases in variability were associated with declines in the efficiency of the motor control system. In the HKB model, variability is viewed as a characteristic of the current state of the system; that is, instability gives rise to change (Kelso, 1992), and change leads to a more stable state.

The HKB model has had an enormous impact on coordination research, and in the ensuing years hundreds of studies were published in which participants performed continuous, cyclical tasks. Some of the studies described in the next sections were motivated as direct tests of the HKB model, and other studies were performed as a result of the research that it spawned in the ensuing decades. However, a vast majority of this research has carried on the theoretical tradition to understand coordination as a self-organizing process. The HKB model is part of a larger movement, known as dynamical systems, which is discussed later in the chapter.

## Spatial Orientation and Timing Patterns

Swinnen (2002) concluded that interlimb coordination preferences can be summarized into two general categories: an *egocentric* preference, in which synchrony of the timing of two limbs is toward and away from the center of any plane of motion (e.g., toward the middle of the chest for upper limb movements in front of the body), and a *directional* preference, in which synchrony of the timing of two limbs is in the same direction along any plane of motion. For bimanual tasks performed in front of the body (e.g., tapping, finger wiggling, and our pinching examples), the egocentric preference (in-phase) dominates over the directional preference (anti-phase).

However, a directional preference exists when one is moving an arm and a leg in the up–down direction. But research by Swinnen and his colleagues has demonstrated quite clearly that the relative dominance of these preferences is participant to spatial interactions (Bogaerts & Swinnen, 2001; Serrien, Bogaerts, Suy, & Swinnen, 1999; Swinnen, Jardin, Meulenbroek, Dounskaia, & Hofkens-van den Brandt, 1997; Swinnen et al., 1998).

For example, in one study (Swinnen et al., 1998), participants moved their right and left limbs in various combinations either along the  $x$ -axis (left-right, in front of the body) or in the  $y$ -axis direction (toward and away from the body). In this study, “in-phase” and “anti-phase” were defined in terms of an egocentric referent. Regardless of the spatial trajectory of the limbs, in-phase movements arrived at the egocentrically closest point at the same time and at the point farthest from egocenter at the same time; for anti-phase coordination, one limb arrived at the closest egocentric point at the same time that the other limb arrived at the farthest point from egocenter. As before, when both limbs were moving along the  $x$ -axis, in a *parallel* ( $180^\circ$ ) spatial orientation, the egocentric preference (in-phase) dominated performance. However, when one limb moved along the  $x$ -axis and the other along the  $y$ -axis, in an *orthogonal* ( $90^\circ$ ) spatial orientation, the normal stability of these patterns was reversed—anti-phase was more stable than in-phase.

These effects were extended by Lee, Almeida, and Chua (2002) and Welsh, Almeida, and Lee (2005), who used both the parallel and orthogonal spatial orientations as had Swinnen and colleagues (1998); they also included obtuse angles of spatial orientation (such as one limb moving along the  $x$ -axis and the other at a  $120^\circ$  or  $150^\circ$  spatial orientation to the  $x$ -axis). When performance was assessed in a high-oscillation frequency condition, the stability of the patterns showed a clear trend. The shift in dominance between the egocentric (in-phase) and directional (anti-phase) preferences was mediated by the spatial orientation of the limbs. Findings such as these (see also Amazeen, Amazeen, & Turvey, 1998; Carson, Riek, Smethurst, Párraga, & Byblow, 2000; Salesse, Oullier, & Tempardo, 2005)—in which the motor system finds new stable solutions when changed environmental conditions have caused instabilities in the current pattern—have prompted some to suggest modifications to the HKB model (Fuchs & Jirsa, 2000; Newell, Liu, & Mayer-Kress, 2008; Peper, Ridderikhoff, Daffertshofer, & Beek, 2004).

## Intention and Attention

In the Kelso studies described previously, the metronome pacing frequency served as a control parameter to inject energy into the system (by forcing it to move faster or slower); these changes resulted in different effects depending on whether the pattern was stable (in-phase) or unstable (anti-phase). As we mentioned before, the role of cognition in self-organization theory is minimized. But, according to the theory, *intentions* do have a specific role—to stabilize or destabilize a movement pattern in much the same way oscillation frequency and spatial orientation did as described in the previous sections.

To illustrate the role of intentions, let’s go back to our bimanual pinching experiment one more time. Start by coordinating your pinching movements in the anti-phase pattern at a relatively slow pace (say, 1 beat/s). At some point, try to switch to an in-phase pattern as quickly as possible. You probably had little difficulty in doing so. Now, trying doing the opposite—try to switch as rapidly as possible from the in-phase pattern to the anti-phase pattern. Experiments of this kind typically show that it takes longer to switch completely from the in-phase mode to the anti-phase mode than vice versa (e.g., Byblow, Lewis, Stinear, Austin, & Lynch, 2000; Carson, Byblow, Abernethy, & Summers, 1996; Kelso, Scholz, & Schöner, 1988; Scholz & Kelso, 1990; Serrien & Swinnen, 1999). Similar differences between the two bimanual coordination modes are seen when a mechanical device is introduced that *perturbs* coordination: The in-phase pattern restabilizes more quickly following a perturbation than the anti-phase pattern (Scholz, Kelso, & Schöner, 1987).

These findings have been interpreted within self-organization theory as being consistent with the unintended phase transitions discussed earlier. The *intention* to switch coordination patterns creates a destabilization of the current pattern, and that destabilization now facilitates the transition to a new pattern. Since the in-phase pattern is a stronger, more stable mode of coordination, intentionally destabilizing this pattern is more “difficult” and

takes more time than destabilizing the anti-phase pattern.

The role of intention also highlights a peculiarity associated with some of the research on self-organized coordination. In the early studies by Kelso (1984; Kelso et al., 1986), in which patterns of motion were performed at specified oscillation frequencies, participants were instructed to let the hands “do what came naturally,” and to not intervene intentionally if a pattern destabilized. From one perspective, this instruction is perfect for the study of self-organization—letting the system relax into a pattern that is best suited or “natural” for the given frequency. From another perspective, however, one could argue that the nonlinear phase transition from anti-phase to in-phase occurred because the participants’ *task* had changed—that is, they were no longer intending to perform the original pattern. If the goal of the task was to perform the anti-phase pattern *as well as possible*, then it is peculiar to use an instructional procedure that allows the task goal to change midway through a trial. Indeed, results of studies in which participants were instructed to try to *maintain* the goal pattern at all times were quite different: There was an overall linear increase in pattern variability but not a permanent switch to a stable new pattern (Lee, 2004; Lee et al., 1996; Smethurst & Carson, 2003).

The role of intention in bimanual coordination has also been examined in the more traditional sense of attention, as in experiments on mental workload, which was discussed at length in chapter 4. One group of investigators has conducted studies in which in-phase and anti-phase patterns were performed together with a secondary, probe RT task (see chapter 4) (see Monno, Temprado, Zanone, & Laurent, 2002; Temprado, 2004, for reviews). As might be expected given the foregoing discussion, the performance of an in-phase bimanual pattern was relatively immune to the effects of a secondary task. In contrast, an anti-phase pattern was rather markedly destabilized if priority in the “division” of attention was given to the secondary task. However, performance of an anti-phase task became *more* stable if increased cognitive effort was induced through moderate levels of anxiety (Court, Bennett, Williams, & Davids, 2005). Thus, the effects of attention (in terms of divided attention) converge well with the role of intentions discussed earlier—attention can serve to perturb a stable system and to maintain either a stable or a destabilized coordination pattern. Inattention has no effect on a highly stable pattern but gives rise to destabilization and pattern switching for less stable states (see Lee, 2004; Pellecchia, Shockley, & Turvey, 2005; and Shockley & Turvey, 2006, for further discussion on the roles of attention and intention in bimanual coordination).

## Perception and Bimanual Timing

One of the important advances in self-organization theory has to do with the critical role played by *information*, which is analogous to its role in other theoretical accounts of motor control. Specifically, information is considered to have a strong influence in coordination stability, arising from intrinsic-feedback sources as well as perception of the environment. In this section we review evidence suggesting that perceptual information is used to stabilize coordination as well as perturb it.

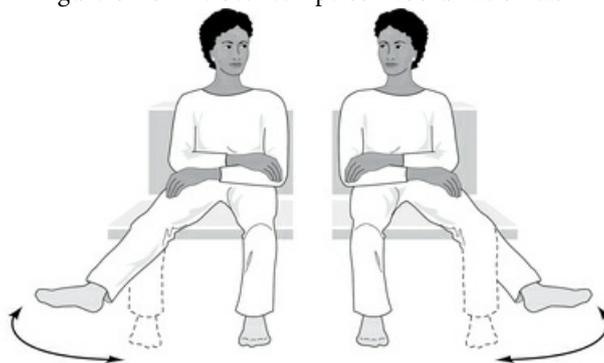
As we have discussed often in the previous sections, simple bimanual coordination patterns differ in stability—in-phase patterns are more stable than anti-phase patterns, which in turn are more stable than all other phase relations (e.g., Yamanishi et al., 1980). Perhaps not surprisingly, researchers have found that a similar relation exists if one merely *perceives* the phase relation of two objects in motion. For example, participants in a study by Zaai, Bingham, and Schmidt (2000) watched two spheres oscillate on a computer screen, like two illuminated “balls” at the bottom of pendulums oscillating in a darkened room. On each trial the balls could oscillate with a mean relative phasing between 0° and 180°, with a variability ranging from 0° (perfectly stable) to 20° (highly unstable). So, for example, a 180° relative-phase pattern with 0° of variability would resemble the windshield wipers of many cars—moving in a perfectly locked asymmetric coordination mode. In contrast, a pattern with 20° of variability would show considerable random fluctuations in which the pattern deviated from perfect asymmetry, but overall would have a *mean* relative phase of 180°. Following an extensive training period with these stimuli, the participant was simply to judge the pattern’s mean relative phase (using a 0-10 Likert scale, with 0 denoting symmetry and 10 asymmetry) or the pattern’s phase variability (0 = no variability and 10 = highest variability).

Judgments of mean relative phase were accurate for all participants—they could identify patterns accurately in symmetrical and asymmetrical motion as well as the relative phase of objects with relative phases between  $0^\circ$  and  $180^\circ$ . However, as illustrated in [figure 8.15](#), perceptual judgments of variability were relatively inaccurate, with some exceptions. For objects moving in-phase (corresponding to  $0^\circ$  on the  $x$ -axis in the figure), participants could accurately judge when the pattern was performed with maximal stability (filled square symbols)—as evidenced by the near-zero score, indicating a judgment of no variability. And, participants perceived added instability quite accurately, too, with correspondingly increased levels of judged variability. In contrast, the anti-phase pattern (corresponding to  $180^\circ$  on the  $x$ -axis in the figure) was judged to have a moderate level of variability (values around two or three units), regardless of how much actual variability was present. Even so, the anti-phase pattern was perceived to be more stable than all of the other phase relations examined in the experiment; in general, the anti-phase pattern received lower judgments of perceived variability (see Wilson & Bingham, 2008, for a review of this research).

One implication of the findings of Zaal and colleagues is that the ability to *perceive* relative phase accurately may contribute significantly to one's ability to *perform* coordinated movements accurately. This implication is supported by results from a study using a related research strategy in which participants attempted to coordinate movements of one limb with an external object, using perceptual judgments as the basis for stabilizing coordination. Participants in an experiment by Wimmers, Beek, and van Wieringen (1992) coordinated left and right movements of a lever with a visual metronome that oscillated horizontally across a monitor. The findings revealed many of the same self-organizing properties that had been observed in studies of bimanual coordination discussed earlier (e.g., Kelso, 1984; Kelso et al., 1986).

Very similar effects have been observed when a participant coordinated his or her movements with another person rather than with an inanimate object. For instance, Schmidt, Carello, and Turvey (1990) asked participants to swing one leg in temporal coordination with another person, who was also swinging one leg ([figure 8.16](#)). The mutual goal between the two participants resembled the (within participant) bimanual finger-wiggling task used by Kelso (1984). The findings were similar; the anti-phase pattern was more variable and difficult to maintain at high movement frequencies than the in-phase pattern (Amazeen, Schmidt, & Turvey, 1995; Schmidt, Carello, & Turvey, 1990; Temprado & Laurent, 2004). The importance of these findings is that a similar set of effects emerged when these movements were coordinated, even though each *individual* movement was controlled by a separate nervous system. (We will have more to say about such *social coordination* later in this chapter.)

Figure 8.16 The between-person coordination task.



Reprinted, by permission, from R.C. Schmidt, C. Carello, and M.T. Turvey, 1990, "Phase transitions and critical fluctuations in the visual coordination of rhythmic movements between people," *Journal of Experimental Psychology: Human Perception and Performance* 16: 229. Copyright © 1990 by the American Psychological Association.

The importance of perception in coordination was probably revealed most spectacularly in experiments by Mechsner and colleagues (Mechsner, 2004; Mechsner et al., 2001; Mechsner & Knoblich, 2004). These researchers conducted bimanual timing experiments in which visual feedback of their upper limbs was manipulated. For example, in one experiment, participants moved two hand-wheels either in-phase or anti-phase. Instead of viewing these movements directly, the participants viewed "flags" moving in patterns that were either compatible with the direction of their movements or in opposition to the actual movement patterns. That is, sometimes how they *saw their limbs apparently move* was the mirror image of how the limbs were actually moving. Mechsner and colleagues (2001) obtained a startling result: The actually produced anti-phase pattern that was *perceived* to be in-phase was always the more stable pattern. Mechsner's findings, together with the information presented earlier about the role of perception (see also Franz, Zelaznik, Swinnen, & Walter, 2001; Semjen & Ivry, 2001; Wilson, Bingham, & Craig, 2003), highlight the key role of visual information in stabilizing and destabilizing coordination patterns.

### *Upper and Lower Limb Coordination*

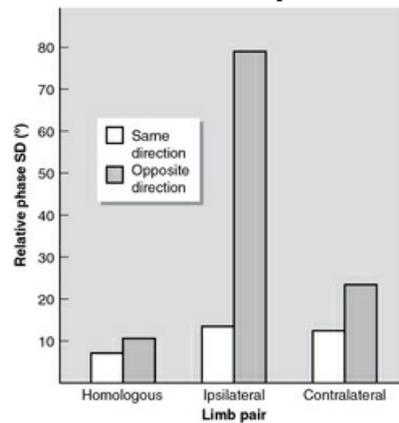
Common activities such as driving, sewing, and playing musical instruments (e.g., the piano and drums) require that we coordinate the timing of our hands and arms with foot and leg movements. In many of these coordinated actions, the dominant pattern of movement is a *directional preference* (both limbs move in the same direction), not the egocentric preference (limbs move toward and away from the center of a plane of motion) that has been observed for many bimanual coordination patterns (Swinnen, 2002). Many of these findings were shown in early experiments by Baldissera and colleagues (1982, 1991; Baldissera, Cavallari, & Tesio, 1994; see also Carson, Goodman, Kelso, & Elliott, 1995). For example, participants in Baldissera and colleagues' (1982) study were asked to coordinate ankle movements in the upward direction (dorsal flexion) or downward direction (plantar flexion) with specific combinations of wrist movements. When the forearm was fixed in the *supine* position (palm of the hand facing up), movements that were coordinated in the *same direction* (i.e., plantar flexion with wrist extension and dorsal flexion with wrist flexion) were more stable than actions coordinated in the opposite direction. However, with the forearm immobilized in the *prone* position (palm facing down), the stronger coordination mode was observed with the opposite pairing of muscle groups: Plantar flexion was now more strongly related to wrist flexion, and dorsal flexion to wrist extension. The common finding among these limb pairings was that the stronger coordination modes occurred for movements in the *same direction*, regardless of the pairings of flexion-flexion or flexion-extension. The evidence for the differential strength of these particular preferred coordination modes was similar to that for the bimanual modes discussed previously; the weaker coordination pattern showed higher relative-phase variability and frequent unintended transitions to the stronger (same direction) pattern.

For the bimanual patterns discussed previously, one could argue that the in-phase bimanual pattern was more stable because it involved the timing of similar muscular groups (simultaneous flexion and extension), since movements in the same direction (i.e., anti-phase) were *less* strongly coordinated than were movements in the

opposite direction. Such an argument fails to explain the findings of Baldissera and colleagues, however, because the coordination strength of the ankle movements with wrist flexion-extension could be *reversed* by simply changing the forearm orientation (i.e., prone or supine). A similar effect of spatial orientation can be seen in the coordination of the wrist and elbow movements within a single arm (Buchanan & Kelso, 1993; Kelso, Buchanan, & Wallace, 1991). This evidence suggests that the pattern of findings for the stability of the different coordination modes is not dependent on the specific muscle groups used, but rather on the *spatial* orientation of the actions.

The effect of spatial orientation in coordinating two limbs is illustrated quite well in studies by Kelso and Jeka (1992) and Serrien and Swinnen (1997a, 1997b). Consider various pairs of limb movements that could be produced in the sagittal plane. Three different types of interlimb pairings can be produced: those involving *homologous* (same) limb pairs (left and right arms; left and right legs), *ipsilateral* (same side) limb pairs (left leg and arm; right leg and arm), or *contralateral* (diagonal) limb pairs (left leg and right arm; left arm and right leg). These three types of coordination patterns were examined by Kelso and Jeka (1992) under conditions in which the limbs moved either in the same direction or in the opposite direction. The results are illustrated in [figure 8.17](#). In general, the limbs moving in the same direction demonstrated more stable patterns than the limbs moving in opposite directions. But this was true only for upper and lower limb combinations, which were more stable for contralateral pairs than for ipsilateral pairs, especially so when the limbs moved in opposite directions (see also Swinnen, Dounskaia, Verschueren, Serrien, & Daelman, 1995).

Figure 8.17 Standard deviation (SD) of relative phase for various interlimb pairings.



Data from Kelso and Jeka 1992.

Again, notice that for this coordination task (sagittal plane), movement of the two limbs in the same direction was as stable as when they moved in the opposite direction. This effect is quite different from that found for bimanual movements in the frontal plane, as we discussed earlier. Thus, these data strongly imply that the *rules* of movement coordination depend on a number of factors, including the effectors involved, their orientation and planes of motion, interactions with the physical environment, and intended goals.

### Complex Timing Patterns

Try the following easy task. Tap the index fingers of both your hands simultaneously on a flat surface. Now, make two taps of the right hand for every single tap of the left hand (i.e., taps of the left hand coincide with every second tap of the right hand—termed a 2:1 rhythm). Then do 3:1 and 4:1 rhythms; all of these should be easy to do when the two hands are performing the same rhythm, that is, when the rhythms are *harmonic*, or integer related (multiples of each other; e.g., Farnsworth & Poynter, 1931; Lashley, 1951).

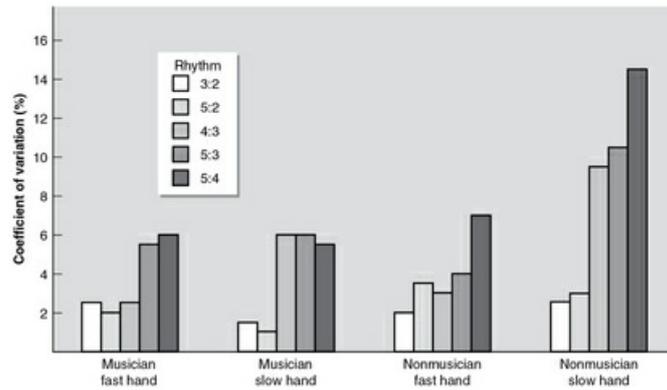
Temporal coordination becomes much more difficult when the rhythms are not harmonic. For instance, it is very “difficult” to maintain a rhythm with one hand while doing something else as rapidly as possible, such as tapping with the other hand (Klapp, 1979) or speaking a syllable (Klapp, 1981). Even more “difficult” is the situation in which two concurrent activities have their own rhythms; for example, reciting a nursery rhyme while tapping a rhythm with a different cadence (Peters, 1977).

Recent studies have focused on nonharmonic rhythms, or *polyrhythms*, to identify what makes certain timing patterns so “difficult” to produce. Consider a situation in which one hand produces three beats during a given interval and the other hand produces two beats during the same time interval (a 3:2 polyrhythm). For example, if the time interval is 1,200 ms, the faster hand produces a beat every 400 ms and the slower hand produces a beat every 600 ms. The two beats occur simultaneously only once every 1,200 ms. Although this 3:2 polyrhythm is much harder to perform than any of the harmonic combinations, it is easier to perform than 5:2, 4:3, 5:3, and 5:4 polyrhythms, which are progressively more difficult (Deutsch, 1983; Summers, Rosenbaum, Burns, & Ford, 1993). What is the basis for these control problems?<sup>6</sup>

[Figure 8.18](#) presents data from an experiment by Summers and colleagues (1993), who compared the coefficients of variation (SD divided by the mean, expressed as a percentage) for various polyrhythms as a function of hand speed and musical training. What is evident from this figure is that nonmusicians were most variable in timing the beats of the hand that was moving *more slowly* in these polyrhythms. Summers and colleagues (1993; Summers & Pressing, 1994) explained these findings by considering the faster hand’s rhythm as the baseline rhythm. The task of coordinating the polyrhythm involved interspersing the slower beats at specific intervals in between the beats of the faster hand. The bars to the right side of [figure 8.18](#) support the conclusion that the variability in performing a polyrhythm is positively associated with the *number of beats* that the slower hand needs to intersperse between

beats of the faster hand (e.g., 5:2 vs. 5:3 vs. 5:4; Deutsch, 1983). Moreover, such a strategy is performed much less effectively by nonmusicians because they tend to intersperse the slow beats at approximately 50% of the interval duration between beats of the faster hand (Summers et al., 1993). This unskilled strategy is rudimentary, although it makes sense because it copes effectively with this situation by drawing upon an *anti-phase* coordination pattern—which, as we have seen, is a relatively natural pattern to adopt. Other strategies can be used, although they require considerable practice in order to be effective (Bogacz, 2005; Kovacs, Buchanan, & Shea, 2010; Summers, 2002).

Figure 8.18 Variability in temporal coordination for polyrhythms of increasing difficulty in musicians and nonmusicians.



Data from Summers et al. 1993.

## Spatial Coordination

Spatial biasing can be observed quite readily in the “pat the head while rubbing the stomach” example (see “Costs and Benefits of Coordinating Two Limbs”). Someone trying to do this task tends to bias the spatial trajectories of both limbs: The limbs are drawn toward performing one or the other task, or sometimes a novel combination of the two tasks. An experimental version of this coordination task by Franz, Zelaznik, and McCabe (1991) suggests that a novel combination may be the more natural coordination pattern. Here the participants’ task was to draw circles and lines. In some conditions, a single hand drew only one pattern; in other conditions, both hands drew the same pattern; and in another set of conditions, one hand drew a line while the other hand drew a circle. Both lines and circles were drawn accurately and consistently in the single-hand and dual-hand “same” conditions. However, when the hands drew different patterns, the variability increased dramatically; the circles became more linear, and the lines became somewhat circular.

One recent study suggests that part of the problem encountered during performance of different spatial tasks with the two hands lies in conceptualizing the nature of the two tasks. Franz and colleagues (2001) required participants to draw semicircles, one above the other, so that one finger drew a semicircle on top and another finger drew one on the bottom. As expected, the bimanual task was easy to perform when both hands drew  $\frown$ -shaped semicircles and when both hands drew  $\smile$ -shaped semicircles. However, the authors found a dissociation in performance when different semicircle orientations were drawn. The task was easy to do when one hand was required to draw a  $\frown$  on top and a  $\smile$  below it; however, the task was nearly impossible to do in the reverse configuration. One possibility is that in the former case the spatial representation drawn with the two hands is a full circle, but in the latter it is a nonidentifiable symbol. The dissociation in performance in these two cases occurred despite the fact that the spatial coordinates to produce the two tasks are similar. Perhaps the contribution of a conceptual model

provided a strategy that was sufficient to reduce the interference inherent in the task. Or perhaps this effect is related to the strong influences of perception on performance that we discussed earlier. Much more study of spatial coordination effects is needed in order to establish firm principles (see Chan & Chan, 1995; Franz, 1997; Franz, Eliassen, Ivry, & Gazzaniga, 1996; Spijkers & Heuer, 1995; Swinnen, Jardin, & Meulenbroek, 1996).

## Social Coordination

Although *interlimb* coordination is organized by the pathways within the CNS (Swinnen, 2002; Swinnen, Heuer, Massion, & Casaer, 1994), this cannot be the case when coordinated actions occur between two (or more) people. Coordinated activities between people often have a well-defined, *explicit mutual goal* (Schmidt, Christianson, Carello, & Baron, 1994), as in music, in sport (e.g., synchronized swimming), and in the workplace (e.g., when several people join forces to move a heavy object). By “explicit” we mean that the actions of two or more people are choreographed with a specific objective of creating something together that could not be achieved individually, such as the effect on the audience of a ballet duet or the impression made on a judge by a synchronized dive. Predetermined “scripts” that describe the unfolding of a play in football or a duet in ballet often require considerable practice before an acceptable level of coordination is achieved among individuals such as athletes, actors, dancers, and musicians. In many respects, social coordination in these situations mirrors the concept of a GMP, as plans for action that describe the order and timing of events remain invariant, with the parameters (e.g., the specific participant) substituted as needed. How this kind of social coordination is achieved in teams represents an important research area in sport psychology (see Eccles & Tenenbaum, 2004).

Motor control researchers have tended to focus on situations in which coordinated actions arise from mutual goals that are *implicit*—situations in which coordination emerges spontaneously when each person is assigned an individual goal. This is more analogous to a self-organizing system, as we have discussed previously, because coordination arises despite the fact that no intention or goal related to coordination was specified. The nature of the coordination also differs from what we have discussed in previous sections; instead of two (or more) limbs becoming locked in a particular coordination mode (called *absolute coordination* by von Holst, 1937/1973), unintentional coordination between people is characterized as a type of *relative coordination*—the tendency to perform with a relative phase *near* a preferred coordination mode(s), but without being phase locked for extended periods of time (von Holst, 1937/1973).

For example, two people sitting in rocking chairs, with no explicit goal to coordinate their rocking, tended to do so near an in-phase pattern about 30% to 70% of the time (depending on the physical similarities of the two chairs), but only if the participants were looking directly at each other (Richardson, Marsh, Isenhowe, Goodman, & Schmidt, 2007; see also Schmidt & O'Brien, 1997). A greatly reduced tendency toward an in-phase pattern was found when only peripheral vision was available, and relative coordination was eliminated altogether when vision was occluded. Thus, in this task, relative coordination was dependent on the availability of direct visual information (see Schmidt & Richardson, 2008, for a review).

But visual information is not the only medium that facilitates social coordination: A conversation between two individuals results in mutual, socially coordinated interactions involving the speaking patterns of the two individuals (see Fowler, Richardson, Marsh, & Shockley, 2008, for a review). Interestingly, shared postural coordination between two individuals was highest when they were engaged in conversation and was influenced by how they spoke to each other (Shockley, Baker, Richardson, & Fowler, 2007) but was not dependent on whether or not the individuals could see each other (Shockley, Santana, & Fowler, 2003).

Coordination can also be studied as a mutual collaboration between more than just a pair of individuals, although such a study is usually designed to investigate explicit cooperation among members of a team, as occurs in sport or the workplace (Eccles & Tenenbaum, 2004). For example, the spontaneous applause that occurs among members of an audience following a concert reveals periods of synchronicity (Néda, Ravasz, Brechet, Vicsek, & Barabási, 2000). We anticipate that more complex forms of unintentional coordination will be studied in years to come.

# A Dynamical-Systems Account of Coordination

This textbook is steeped in the information-processing tradition, and it focuses heavily on the GMP as a theoretical construct to explain movement patterns and coordination. However, since the late revolution in thinking about motor behavior (Turvey, 1977), now called a *dynamical-systems account*, has produced a long set of findings, philosophical thought, and theorizing about motor behavior that cannot be ignored. Much of the empirical work and one model (HKB) were presented earlier in the chapter. To help you understand the philosophical underpinnings of this approach to behavior and performance, the following section presents a much-distilled account of this framework. Every motor scientist should be well versed in both information processing and as dynamical systems. For a more thorough treatment of this participant matter, refer to Kelso (1995) and Turvey (1990).

Newell (1985, 1986) addressed the question of what is the *agent* of coordination (or whether the question of an agent should even be asked). Many of the ideas presented so far in this textbook answer this question with the construct of the GMP. According to proponents of this approach, coordination is invested in the motor program, which controls the coordinative equation; this idea was addressed in the first part of this chapter. Similarly, scholars of traditional motor development would attribute the development of motor milestones to neural maturation (Newell, 1986) so that coordination is a property of the central nervous system, which is the agent of coordination.

Newell (1985, 1986) proposed a framework in which coordination, control, and skill emerge from the interface between environmental information, task constraints, and organism constraints. For example, Thelen (1983; see also “Esther Thelen” in chapter 1) explored the disappearance of the stepping reflex in infants. The reflex, in which infants spontaneously kick their legs as though they are stepping when prone, begins to spontaneously disappear around 9 to 12 mo old. Thelen (1983) demonstrated that when infants were placed in water, which had the effect of making their legs lighter, they showed the stepping reflex. The explanation is simple. As the infant gained body mass due to maturation, the body became relatively weaker and thus could not generate forces necessary to move the legs. Once the infant’s legs became temporarily lighter, the stepping reflex could reappear. This situation is an example of an organismic constraint. Coordination could be evident when the requirement of muscular strength was altered to fit the infant. One can see how the task and organismic constraints interact in youth sports. A young child can play baseball and tennis when the bat and the racquet are reduced in size to fit the strength and size of the child. Youth soccer uses smaller soccer balls to facilitate coordination on the field. Newell (1985, 1986) teaches that the emergence of coordinative behavior is not the provenance of only the nervous system. Coordination resides at the intersection of the person, the task, and the environmental information. Now, we turn attention to more specific empirical issues in coordination.

## Importance of Relative Phase

The choice of using relative phase was based on a theoretical stance taken by Kelso. Two effectors moving cyclically can be described in many differing levels of detail. How can these effectors be described by a simple parameter that captures the global behavior of the two-effector system? This type of variable is called an *order parameter* (Kelso, 1995), a term borrowed from physics; the other variables that could be measured fall into the behavior of this one variable. Kelso proposes that relative phase is the proper order parameter in the study of bimanual coordination (Haken, Kelso & Bunz, 1985). For other movement situations other collective, order parameters have to be proposed or discovered. As discussed earlier in the chapter, efficiency could be considered as the order parameter for phase transitions in gait.

In the dynamical-systems account, it is critical to understand the biophysical descriptions of the rules of motor performance. The reason is that dynamical-systems theorists discount the importance of a central agent orchestrating coordination, such as the GMP, or more generally an internal model (Wolpert & Miall, 2001). Instead, with practice and experience with information, constraints emerge, leading to coordinated movement.

A great example concerning the dynamical-systems perspective is drawn from work on coordination of movement to a metronome. Jantzen, Steinberg, and Kelso (2004) required research participants to either synchronize or syncopate with the rhythm of a metronome; in syncopation, the performer taps in the midpoint of the timing interval. One can also consider timing coincident with maximum extension of the metacarpophalangeal joint. After a series of metronome tones, the metronome disengages and the participant continues to tap at the rate previously specified by the metronome.

In terms of the kinematics of the finger producing taps, the movements are in effect identical, regardless of whether synchronization or syncopation was the task during the presentation of the metronome. Thus, one can infer that a GMP has been set up, and the same GMP is used for both syncopation and synchronization because the movement kinematics are identical. However, Jantzen et al. (2004) also recorded brain activity using the fMRI technique. Their finding was surprising. The brain networks were unique to the task requirement, even though identical movements were now being performed. If in fact the metronome helped the participant set up an internal clock with a phase offset of zero (synchronization) or 180 degrees (syncopation), the neural networks should be extremely similar. They were not. In other words, similar movement patterns are governed by disparate neural networks, based on the context that was set up during metronome presentation. These results seem problematic for information-processing accounts of motor behavior and clock-like performance. From a dynamical-systems perspective, however, they are easy to understand.

From an information-processing account, learning involves the building of bigger and better motor programs. However, Schönner et al. (1992) provide a new way to think about the processes of learning, namely, that learning changes the dynamical landscape such that intrinsic or previously practiced versions of a task are affected by the newly learned task. Furthermore, examining learning through testing for these retroactive transfer effects is the window into seeing the learning process. Lee and colleagues (Fontaine et al., 1997; Lee et al., 1995) show that the specifics are in dispute, thus the theoretical question might not be a supportable framework. At this time, students of motor behavior are left to their own thinking to work through this issue.

All students of motor behavior and control need to decide which approach will guide their research. This story highlights how to navigate this difficult intellectual landscape: Esther Thelen, one of the giants of motor development and a leader of the dynamical-systems approach, was giving a talk at Purdue University (HNZ was in attendance). She was presenting some new and exciting work on a famous developmental behavior, the A not B error. In this situation a very young (less than 1 yr old) child is shown a small toy. The experimenter places the object in an opaque box or covers the object with an opaque cloth. The child uncovers the object. After a few attempts, the experimenter now hides the object in another box or cloth. The child continues to look to uncover the object in its original box or cloth. This inability to know that the object exists under a cloth, or within a box, is thought to reflect an immaturity in the child's cognitive skill development.

Schönner and Thelen (2006) believed that due to the experimental procedures the infant became attracted to the particular location that the object was moved to originally. When the object location was changed, the infant just went to the already practiced location. Schönner and Thelen couched their theory in a mathematical framework called dynamic field theory. However, when explaining this idea to a group of psychologists, Thelen stated that the infant "developed a motor program" to the A location, thus the error. I (HNZ) was sitting in the audience, a bit surprised by the use of the words "motor program," and I decided not to question Dr. Thelen regarding her choice of construct. Instead I realized immediately that the entire audience understood her explanation, and if they were more interested in the details, they could go to the paper and see the math. Thus, even though Schönner and Thelen did not believe in motor programs, they used the construct for pedagogical reasons. After appropriate years of study, you will have figured out how you will navigate this intellectual distinction. As a disciple of Richard A. Schmidt, I (HNZ) grew up in the motor-program (information-processing) perspective, but I have taken a more and more dynamical perspective in my own work. However, in teaching undergraduates, I still rely on the motor program as an important explanatory mechanism.



## Summary

Even quite simple movements require the organization of various (potentially independent) moving parts of the motor system. Aiming movements, though simple at one level, involve the coordination of the eyes, head, and hands when perception and action are guided visually. One method of analyzing the organization of discrete tasks is to search for separate *units* of action—parts of action sequences that are independent temporally from other parts of the action. In contrast, reaching/grasping represents a type of discrete movement in which the limb-transport component is quite obviously distinct from that of object manipulation. Evidence suggests that, although these components seem to be separable, their actions are highly interdependent. Two theoretical views of reaching and grasping have been suggested; these differ in terms of the focus on temporal versus spatial factors during movement planning.

Discrete *bimanual* actions have also been an important focus of study. Studies using a two-hand version of the Fitts' task reveal considerable influences of one limb's movement on the spatial and temporal actions of the other limb. These influences are even more pervasive if the actions of one limb have increased kinematic complexities. Recent evidence suggests that the development of a new GMP that controls the two limbs simultaneously may be a way in which the motor system solves these coordination difficulties.

The coordination of continuous, cyclical actions represents a contrast to that of discrete actions; in the latter, the GMP seems to play an important role. Some continuous interlimb coordination patterns are more stable than others, and these stable states are participant to change. Important insights regarding pattern organization are revealed by *phase transitions*, in which the destabilization of a pattern leads to a change in the basic form of the pattern. These transitions have been shown in animals and in humans, leading some to suggest that these patterns have a strong *self-organizing* basis, as conceptualized in the HKB model (Haken, Kelso, & Bunz, 1985). Evidence from a number of bimanual and interlimb coordination paradigms has provided support for this view. Other patterns of coordination, such as polyrhythm timing, spatial coordination, and patterns of social coordination, have been the focus of recent investigations and pose exciting challenges for future research.

### Student Assignments

1. Prepare to answer the following questions during class discussion:
  - a. Describe the coordination components of reaching for and opening a jar of peanut butter.
  - b. Describe two different methods by which an artificial limb is used to reach for and grasp objects.
  - c. Describe any daily activities that characterize in-phase and anti-phase movements. Describe an activity that either combines in-phase and anti-phase movements or that characteristically has an alternative phasing.
2. Find a research article that uses the Haken-Kelso-Bunz model as a theoretical basis. Be prepared to explain these concepts using examples from daily activities.

### Notes

<sup>1</sup> Different taxonomies have been proposed that extend Napier's (1956) original classification scheme of precision grips versus power grips. However, the choice of which grip to use is determined not by the object but rather by the intentions of the individual regarding how the object will be used (Jeannerod, 1996; Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987). For instance, one normally uses a precision grip to write with a pen. However, if one were intending to use the pen to puncture a cardboard box, use of a power grip would be more likely.

<sup>2</sup> This work extends the pioneering research of Wing and Kristofferson (1973a, 1973b), which was discussed in chapter 7. Analyses of the bimanual coordination data here were done with nonoverlapping intervals among the landmarks, which eliminates the bias in the correlations because of overlapping of some of the landmarks. Heuer and colleagues (1995; Schmidt et al., 1998) have developed a theory of bimanual coordination based on GMPs

that uses a statistic termed a *covariance ratio*, which is sensitive to the extent to which the hands are coordinated together in time. The covariance-ratio data are consistent with the view that the two hands are controlled by a single GMP, but details of this analysis are beyond the scope of this presentation.

<sup>3</sup> The *Froude number* was discovered in the 19th century by a mathematician and naval architect (William Froude) as a way to characterize the efficiency of boats of different hull lengths. An excellent historical review of the application of the Froude number to gait biomechanics of animals, and other uses, is provided by Vaughn and O'Malley (2005).

<sup>4</sup> The measure of accuracy presented here is different from that presented by Yamanishi and colleagues (1980). They reported constant error, averaged over participants. However, as noted in chapter 2, the average constant errors for participants who are biased differently can underestimate the average inaccuracy for a *group*—and these individual differences, in opposite directions of bias, were evident in the data from Yamanishi and colleagues. We have replotted their data in terms of absolute constant error (chapter 2). The results show much the same pattern as the variability data.

<sup>5</sup> Use of this term can be confusing here, as we have defined the word “control,” as in motor *control*, much differently than as it is used in the term “control parameter.” As well, earlier we discussed *parameters* of a GMP (e.g., handwriting in large or small script). A control *parameter* is defined as a nonspecific variable that, when changed, results in a nonlinear change in the behavior of the system as a whole.

<sup>6</sup> Interestingly, the task used by Heuer and colleagues (1995), as described earlier, was a rapid, 3:2 “polyrhythm,” which was performed rather easily (after practice). That discrete and continuous versions of a similar task might have remarkably different effects on coordination performance is deserving of more research.

## Part III

# Motor Learning

- Chapter 9 Motor Learning Concepts and Research Methods
- Chapter 10 Conditions of Practice
- Chapter 11 Augmented Feedback
- Chapter 12 The Learning Process
- Chapter 13 Retention and Transfer

So far this text has been concerned with skilled performance—often at high levels of proficiency—and the numerous internal processes that make these performances possible. In part III the focus shifts to a different but related problem, the learning of skills as a result of practice or experience. This problem is different from the issue of skilled performance because it focuses on the *changes* in skill rather than the nature of skill at some particular level. As such, different methods and logic are needed in order to understand these performance changes. Chapter 9 documents some of the more important methods used to understand the principles that have been discovered about motor learning. Chapters 10 and 11 describe how conditions of practice and augmented feedback influence learning. Chapter 12 presents the various ways in which the learning process has been conceptualized by researchers. Finally, chapter 13 discusses factors that influence retention (how learning is retained over periods of no practice) and transfer (how learned behavior can be applied in novel situations).

# Chapter 9

## Motor Learning Concepts and Research Methods

Learning is a critical part of our existence. Think where humans would be if we could not profit by the experiences and practices in which we all engage. You would not be able to read the words on this page, we would not be able to type the words that appear here, and no one would be able to speak. In short, we would be simple creatures indeed if we were forced to behave in the world equipped only with the skills we inherited. The fact that we can acquire new knowledge and skills has led to a robust interest in the ways in which people learn, in the critical variables that determine how people will profit from experience or practice, and in the design of instructional programs.

We will not attempt to review the entire topic of learning. There are examples of learning in all organisms (even the simplest of single-celled organisms), and the learning that humans enjoy is the most complex of all. Thus, many forms of human learning are not discussed here, such as the learning of verbal materials, the learning of concepts, and the learning of interpersonal skills. We concentrate on the acquisition of motor skills as defined in chapter 2. Essentially, the concern will be with the effects of practice and experience on performance, in an attempt to understand the relevant variables that determine gains in proficiency.

# Defining Motor Learning

Learning in general, and motor learning in particular, have been defined in a variety of ways. Four distinct characteristics are included in the definition: (1) Learning is a *process* of acquiring the capability for producing skilled actions. That is, learning is the set of underlying events, occurrences, or changes that happen when practice enables people to become more skilled at some task. (2) Learning occurs as a direct result of practice or experience. (3) Learning cannot be observed directly, as the processes leading to changes in behavior are internal and are usually not available for direct examination; rather, one must *infer* that learning processes occurred on the basis of the changes in behavior that can be observed. (4) Learning is assumed to produce *relatively permanent* changes in the *capability* for skilled behavior; for this reason, changes in behavior caused by easily reversible alterations in mood, motivation, or internal states (e.g., fatigue) are not thought of as due to learning.

A synthesis of these four characteristics produces the following definition: *Motor learning is a set of processes associated with practice or experience leading to relatively permanent changes in the capability for skilled movement.* We discuss these aspects in more detail next.

## Motor Learning Is a Set of Processes

A *process* is a set of events or occurrences that, taken together, lead to some particular product, state, or change. For example, in reading we are interested in processes that transform visual information to provide meaning; in motor control we may focus on processes of retrieving a motor program from memory; and in physiology we can discuss processes that result in muscle hypertrophy. Similarly, practice and learning can be seen as a set of analogous processes that, taken together, lead to the acquisition of the capability for moving skillfully—with “skill” being defined in chapter 1. These processes are *assumed*; in other words, we assume that some set of processes must have taken place in order for learning to have occurred with practice. However, what these processes are (exactly) is not specified, and in fact the nature of these processes is what learning theorists try to understand. Thus, an important focus is on what happens—in terms of the underlying processes—when people practice and acquire new skills.

## Learning Produces an Acquired Capability for Skilled Movement (Habit)

The processes involved in learning—like all processes—generates or results in a product or internal state. In the case of motor learning, this state is an increased *capability* for moving skillfully in the particular situation. Notice that we have not defined learning as a change in *behavior* per se, as many have done (e.g., Morgan & King, 1971). In this sense, the goal of practice for the learner is to increase the “strength” or the “quality” of this internal state, so that the capability for skill will be maximized in future attempts. The researcher’s goal is to understand the *nature* of the internal processes that have led to the increases in the state; thus, theorists propose hypothetical processes to account for learning in experimental settings. Also, the researcher wants to understand the nature of the state itself, perhaps in terms of the codes involved or the kinds of control it exerts on behavior; such knowledge will tend to provide an answer to the question of *what* was learned.

William James (1890) used the term “habit” for this internal capability for movement (with only minor reference to the usual use of the word), but it has been named in other ways by other theorists. Regardless of its label, the notion of some internal state that is the product of learning represents a critically important distinction. Defining learning as producing a *capability* for movement directs our focus to the internal state and the processes that have led to it, rather than simply to the behavioral changes. More importantly, the concept of a capability for movement implies that if the capability is “strong,” then the skilled behavior may occur if the external conditions, motivation, and other surrounding factors are present; if the conditions are not favorable, then the skilled behavior might not occur—for example, if fatigue is present or motivation is low. That is, behavior may vary for a number of reasons, only some of which are a result of change in the internal capability for movement produced by practice.

This concept provides a basis for the distinction between *learning versus performance*, which is a major theme of this chapter. The distinction between *learning* and *performance* is significant not only in the behavioral sciences but also in the neurobiology of learning and memory (Cahill, McGaugh, & Weinberg, 2001).

Numerous changes in humans can contribute to their capability for movement in skilled situations, but many of these have little to do with learning as defined here. For example, we know that increased maturation or growth can lead to improvements in skill, as older children generally outperform younger ones. Similarly, changes in strength or endurance from physiological training could contribute to certain kinds of skills, such as those used in weightlifting or soccer. However, we would not want to include such improvements in a definition of learning because practice or experience is not the basis for the changes in capability. We will be searching for situations in which changes in capability are primarily related to changes acquired through experience.

## Motor Learning Is Not Directly Observable

It should be clear that motor learning is not directly observable. The processes that underlie changes in capability—and the nature of the capability itself—are highly complex phenomena in the central nervous system, such as changes in functional connectivity between sensorimotor processing areas in the brain or changes in the patterning of muscular action. As such, they are rarely directly observable, and one must infer their existence from changes in motor behavior. This feature of motor learning makes it particularly difficult to study. Experiments must be designed carefully so that the observed changes in behavior allow the logical conclusion that there were associated changes in some internal state.

## Motor Learning Is Relatively Permanent

Another important feature of motor learning is that it is relatively permanent. Something lasting occurs when one engages in practice and learns some activity—something that does not simply pass away in the next few minutes or hours. More dramatically, we could say that when you practice and learn, you will never be quite the same person as you were before. Learning has the effect of changing the learner (if only slightly) in a relatively permanent way.

With respect to skill learning, this distinction is important because it rules out the changes in skills that can come from a variety of temporary performance factors. For example, skills might improve if the person is in the “right” mood or if certain drugs are administered. Yet each of these changes in behavior will probably vanish when the temporary effect of the mood, for example, “wears off.” Thus we should not attribute these changes in behavior to motor *learning*, because they are not sufficiently permanent. The following text discusses a caveat to the importance of temporary effects in the context of motor adaptation.

An analogy may help to clarify this point. If you cool water sufficiently, you will find that it becomes solid (ice); you can reverse the effect completely to produce water again simply by warming the ice. This is not so with grilling a steak. Grilling a steak for 10 min produces changes that are not reversible when the steak is cooled. Some relatively permanent change has been made in the steak that was not the case with the water.

This analogy applies well to the concept of motor learning and performance. The nature of the water or of the steak can be observed directly, and they both behave in predictable ways when the independent variable (temperature) is applied. But beneath the surface is some unobservable change in the nature of the substance; in one case (the water), this change is completely reversible and not relatively permanent, while in the other (the steak), the change is not reversible. With human learning, many analogous variables can be applied in order to change the observed behavior (skill), but these may or may not change the internal structure of the person in a relatively permanent way. If the effect of some independent variable can appear and disappear as the value of the variable is changed, then this change in behavior cannot be associated with anything relatively permanent, hence is not thought to be due to learning.

How permanent is “relatively permanent”? This is a vague concept, and scientists who study learning are rarely clear about it. But the intention of this discussion should be clear; learning should have some lasting effect.

## Comparing Motor Adaptation and Motor Learning

Adaptation is the iterative process of adjusting one's movement to new demands. In spite of the abundantly complex human motor control system (see chapters 5 and 6), the nondisabled person is capable of making smooth and accurate movements with little effort and even under constantly changing conditions. We often overlook the processes that allow such flexibility, only recognizing the challenges to the motor control system when something breaks or goes wrong. The two phenomena considered critical for motor flexibility are motor adaptation and motor learning.

The term *motor adaptation* has taken on several different definitions in the literature. Motor adaptation is commonly described as the trial-to-trial modification of a movement based on error feedback in which the following criteria are met:

1. The movement retains its identity of being a specific action (e.g., walking) but changes in terms of one or more parameters (e.g., force or direction);
2. the change occurs with repetition or practice of the behavior and is gradual over minutes to hours;
3. once adapted, the performer does not exhibit the prior behavior; instead, they show after-effects and must de-adapt the behavior with practice in the same gradual, continuous manner back to its initial state.

A key distinction between adaptation and learning is the relatively transient nature of motor adaptation compared to the relatively permanent nature of motor learning. In spite of its transient nature, motor adaptation is important for human behavior and particularly for rehabilitation (Bastian, 2008). This is partly because motor adaptation allows a highly flexible control that can account for transient but predictable changes in task demands that frequently occur in the natural environment. As such, a finite number of "learned" motor patterns can be appropriately adapted to a number of situations. From the researcher's perspective, motor adaptation to a split-belt treadmill (see [figure 2.5d](#)), for example, can be used to determine whether some patients can generate a more typical motor walking pattern. Repeated exposure to the split-belt adaptation paradigm can lead to motor learning of a new, relatively permanent motor calibration. The processes whereby motor adaptation can be transformed into motor learning are not fully understood. However, adaptation paradigms including force fields for reaching (Marko, Haith, Harran, & Shadmehr, 2012) and split-belt treadmills for locomotion (Finley, Statton, & Bastian, 2013) are likely to offer methods for rehabilitation of people with movement disorders.

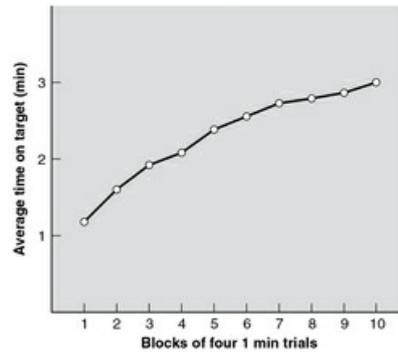
## Measuring Motor Learning

Given that motor learning is a set of processes that underlie the changes in a capability for movement, how can such a capability be measured in order to understand what variables affect it during practice? It will be helpful to consider a typical motor learning experiment to explain some of the major points in the measurement process.

### Performance Curves

In a simple experiment on learning, a large group of individuals are asked to practice on some motor task, and the experimenter charts their performances as a function of “trials,” resulting in a *performance curve*. For example, [figure 9.1](#) is a graph from Fleishman and Rich (1963) showing performance on the two-hand coordination task. Participants had to follow a moving target through movements of two crank handles, one controlling the forward–backward direction of a pointer and one controlling right–left movements. The average time on target (in minutes) for a group of 20 performers is plotted as a function of successive blocks of four 1 min trials. A clear trend can be seen for the scores to increase with practice, with the increases being somewhat more rapid at first and then leveling off later.

Figure 9.1 A performance curve showing increases in the score with practice.



Reprinted, by permission, from E.A. Fleishman and S. Rich, 1963, "Role of kinesthetic and spatial-visual abilities in perceptual motor learning," *Journal of Experimental Psychology* 66: 9. Copyright © 1963 by the American Psychological Association.

When the measure of performance is an error score, the error scores will usually decrease with practice. In Quesada and Schmidt (1970), the participant's performances on a timing task improved with practice. Here, the performer's task was to operate a switch when a moving pointer became aligned with a stationary one, and error was the time interval between the switch movement and the actual moment of coincidence. Average absolute error decreased rapidly at first, and more gradual decreases occurred later in practice.

Even though the performance curves just described change in opposite ways with practice, they both represent gains in performance and almost certainly can be interpreted as caused by motor learning. Such effects are usually among the most powerful in the study of motor behavior. But what is usually of more interest than whether or not learning occurred is whether learning was greater in one condition than in some other condition. Thus, the question of interest relates to the role of *variables that influence learning* of the motor task. In order to make meaningful inferences about whether or not condition *A* produced more learning than condition *B*, special procedures are needed to analyze these performance scores in motor learning experiments.

## Motor Learning Experiments

Graphs such as that shown in [figure 9.1](#) and described in the previous section for practice of a coincident-timing task are often thought to represent the acquired capability for movement in participants during practice from trial to trial, and to some extent they probably do. For this reason, such curves are often loosely termed *learning curves*, as it is tempting to regard the changes in performance as reflecting the product of the internal capability for movement generated by learning. The notion that these curves "mirror" the internal state (the amount of habit) is oversimplified, however, and scientists are very cautious about interpreting the changes in curves like [figure 9.1](#) as a reflection of the *amount* of motor learning. Some reasons for this caution are outlined next.

### *Performance Measures*

The first reason performance curves perhaps should not be assumed to reflect learning is that skilled *performance*—not the *capability* for moving skillfully—is plotted as a function of trials. Since the capability (habit) cannot be measured directly, any change in habit that has occurred must be inferred from the changes in performance. Thus, it seems more logical to refer to the curve exemplified in [figure 9.1](#) as a *performance curve* rather than a learning curve. As such, it reflects both the momentary changes in performance and the relatively permanent consequences of practice.

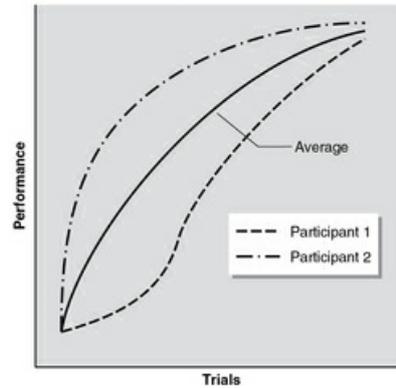
### *Between-Participant Variability*

A second problem in making inferences about learning from performance curves is that they are insensitive to the differences in individuals that arise as a function of practice. Consider how a performance curve is produced. A large number of people (the larger the better, usually) is used. The first-trial scores for all of the people are

averaged to obtain the data point for trial 1; trial 2 scores for all persons are averaged to obtain the data point for trial 2, and so on. This averaging procedure has a number of advantages, such as “smoothing” or “canceling out” many random (perhaps meaningless) variations in scores due to inattention, errors in measurement, and other factors not directly related to the internal habit changes. But at the same time, this averaging procedure tends to hide any interindividual differences that may have existed on a particular trial, or it may hide important trends in improvement with practice.

These effects can be particularly important in the study of learning. Consider two hypothetical people whose performances over a number of trials are shown in [figure 9.2](#). Participant 2 seemed to improve in performance early in the sequence, with little change occurring later. Participant 1 has a difficult time improving in the task until later in practice, when finally, performance improves markedly.

Figure 9.2 Hypothetical performance curves for two individuals, together with the curve representing the average of their performances.



Now consider what happens if these two performers' scores are averaged in ways that are typical for studies of larger groups. In [figure 9.2](#), the center line is the average of the performances for the two persons for each of the trials. The pattern of improvement with practice is considerably different now. It might be tempting to say that the average capability for responding accumulated gradually and consistently. This, of course, would be misleading, as neither of the participants whose data produced the average performance curve showed this trend. Thus, it could certainly be that learning does not occur gradually at all, as is usually evidenced by the individual performance curves. Rather, learning might sometimes occur as more of an abrupt "revolution" than a gradual "evolution" in the ways in which the participants perform the task.

### *Within-Participant Variability*

As mentioned previously, one of the important aspects of the averaging procedure is the reduction of errors in measurement and of factors that seem to obscure the "true" capabilities of the people on a particular trial. As discussed in chapter 7, a typical finding is that people inherently vary from trial to trial, even if they are attempting to do the "same" thing each time. But is trial-to-trial variation for a particular person due to some meaningless random fluctuation in the motor system, or is it due to some meaningful change in the way the person attempted the task on a particular trial?

The problem can be better illustrated with an example. Consider the task of free-throw shooting in basketball when the performers are relatively inexperienced. Certainly a great deal of variability exists in this task's performance from trial to trial, and much of this variability does not seem to represent fundamental changes in the ways that people attempt the task. If a large group of people is examined on this task, with performance scored as "correct" or "incorrect," each person will have a pattern of scores that shows a large number of apparently randomly ordered hits (baskets made) or misses, with somewhat more hits as practice continues. And different people will have the hits and misses scattered across the trials differently.

Imagine a performance curve with these data, with the measure for a particular trial being the *probability of success* on that trial. With this measure, the data point for trial 1 will be the total number of hits divided by the total number of attempts (i.e., the number of participants)—that is, the proportion of people that shot successfully on trial 1; the method is similar for trial 2. When plotted, the average performance curve usually rises gradually, perhaps moving from 0.10 to 0.40 in 100 trials. From such a curve it is tempting to conclude that the *capability* for accurate shooting grew slowly as a result of practice. But note that not a single participant could have shown this pattern of performance! Indeed, there is no way that a given person could ever achieve a score of 0.20 on a particular trial, as a single participant can only achieve 1.0 (hit) or 0 (miss) on a single trial. Thus, our imagined average performance curve obscures all the variations that occurred within people across trials and encourages us to draw conclusions about the learning process that may be incorrect.

### *Ceiling and Floor Effects*

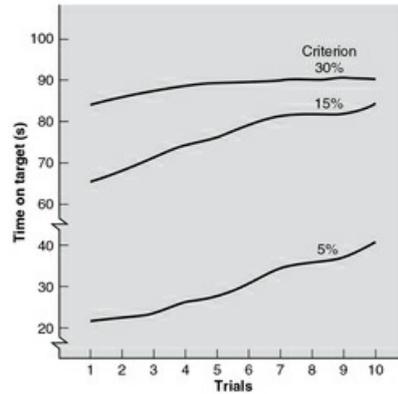
Ceiling and floor effects are a third kind of problem that can lead to erroneous conclusions about learning processes from group performance curves; these are present in many of the tasks used in motor learning experiments. In most tasks, absolute scores exist that no person will ever exceed. For example, there can be no fewer than zero errors on a trial, no less than 0 s for some movement-time task, and no more than 30 s for a time-on-target score in a 30 s performance trial. Thus, as people approach these *ceilings* (the limitation in score at the top of the scale) or *floors* (the limitation at the bottom of the scale), the changes in the performance levels of the people doing the task become increasingly *insensitive* to the changes in learning that may be occurring in the people as they practice. As a person approaches some ceiling or floor, it becomes increasingly “difficult” to improve performance; in gymnastics, for example, it is far “easier” to improve one’s score from 6.0 to 6.5 than it is to improve from 9.0 to 9.5, when “perfect” is 10.0. Similarly, in golf it is much easier to reduce one’s average total score by five strokes, say from 140 to 135, than it is to improve by five strokes from 75 to 70. In addition to these absolute scoring ceilings and floors, psychological or physiological floors and ceilings can be present. For example, the 4 min mile was at one time a barrier that we thought would remain unbroken. Now the barrier is considerably lower, but it could very well be that no human will ever break a 3 min mile. Will anyone ever long jump more than 30 ft? As performers approach these physiological limits, it becomes increasingly more difficult to improve.

### *Scoring Sensitivity and the Shape of Performance Curves*

The primary problem is that the “rate” of progress (the slope of the performance curve) toward some ceiling (or floor) is usually quite arbitrary and dependent on the ways in which the task is measured. The rate does not seem directly linked to the rate of change in the capability for movement that underlies this change in behavior. A powerful example of this principle comes from a study by Bahrick, Fitts, and Briggs (1957, their “simple task”). The authors studied 25 male participants on a continuous tracking task for ten 90 s practice trials. The pattern of the track that the performers had to follow, and the movements of the lever that they made when following it, were recorded for later analysis.

The authors then analyzed the single set of performances in three different ways. First, they assumed that the width of the target the performer had to follow was small, 5% of the total width of the screen. (There was, in fact, no target width as far as the participants were concerned, as all they saw as a target during the performance trials was a thin line that moved on the screen.) By going over the tracking records and examining the number of seconds in a trial during which the participant was in this imaginary 5% target band, the authors obtained a separate measure of the “time on target” for every person and trial. Then, the data from trial 1 were averaged for all the participants to form the trial 1 data point in [figure 9.3](#) for the curve marked “5%.” The data for other trials for this target size were handled in a similar way.

Figure 9.3 Time on target for a tracking task as a function of trials for three different scoring criteria. (The 5% criterion indicates that the target used for scoring was 5% of the screen width, and so on.)



Reprinted from H.P. Bahrick, P.M. Fitts, and G.E. Briggs, 1957, "Learning curves: facts or artifacts," *Psychological Bulletin* 54: 260.

The authors then performed this procedure a second time, scoring the participants using a different tolerance for error (remember, there was no target width as far as the participant knew). Here, the target width was 15% of the width of the screen, and the participants were evaluated in terms of the number of seconds during a trial the pointer was in this target zone. As the criterion of success was much more lenient (the "target" was wider, therefore hit more often), the time-on-target scores were naturally larger, forming a second performance curve marked "15%" in [figure 9.3](#). Finally, the procedure was done again, this time with a very wide target that was 30% of the width of the screen. In [figure 9.3](#), the performance curve for these data is labeled "30%."

The important point about the data in [figure 9.3](#) is that all three curves are based on the *same* performances, but the differences between them are produced by the ways in which the experimenter has chosen to evaluate those performances. We might conclude (if we did not know that all the data came from the same performances on the same people) on the basis of the 5% curve that habit gains are a *positively accelerated* function of trials (because the shape of the curve is concave upward), and on the basis of the 30% curve that habit gains are a *negatively accelerated* function of trials (because the shape of the curve is concave downward). This is, of course, nonsense; only one pattern of habit gain emerged (whatever it was), but evidence about this gain was obtained in three different ways that gave three different answers about how the capability for performing progressed with practice.

The differences are apparently caused by the fact that making the criterion "easier" (moving from 5% to 30% target widths) moves the person through the range from floor to ceiling at different rates, depending on the *sensitivity* of the scores and the level of skill. Thus, despite the fact that the same learning occurred in all three curves from trial 1 to trial 10, very different amounts of *performance improvements* are displayed depending on which target zone one chooses to use. So, what is the pattern of habit change that occurred with practice? We have no idea, on the basis of these data, and we can conclude (erroneously) just about anything we choose merely by selecting the "right" target width to study (see also Wilberg, 1990).

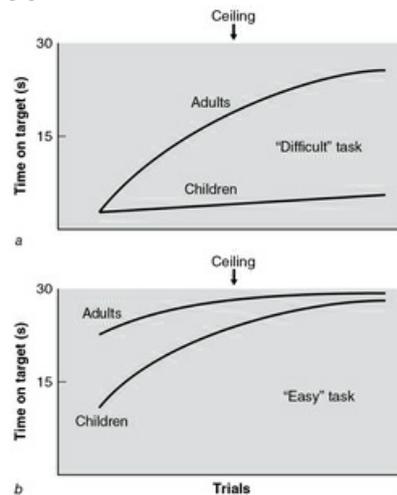
### *Implications for Experiments on Learning*

These considerations present strong limitations on what can be understood from experiments on learning, often making it impossible to provide clear interpretations about what happened to habit in the study. Consider this hypothetical example. We want to study whether children learn more than adults as a result of a given amount of practice at some new task. (We could as easily ask about males versus females, older versus younger adults, and so on.) We choose a task such as the pursuit rotor ([figure 2.5a](#)), which is foreign to both the children and the adults, and allow both groups to practice.

A finding that emerges consistently from the work on children's motor behavior is that adults nearly always perform better than children (although video game performance may be an exception). If we were to use a pursuit rotor with a very small target and a fast speed of rotation (a relatively "difficult" task), allowing the children and

adults to practice for fifty 30 s trials, we might expect curves such as those that appear in [figure 9.4a](#). Here, both hypothetical groups begin with nearly no time on target, but the adults improve more than the children because they are relatively closer to hitting the target than are the children. With a little practice, their initial advantage in motor control begins to show up in terms of increased time on target, whereas the children show no such effects even though they may be moving slightly closer to the target. We may (erroneously) conclude that the adults learned more than the children because their performance gains were larger.

Figure 9.4 Hypothetical performance curves for adults' and children's performances on a "difficult" or an "easy" task. (Depending on the scoring criterion, one can [erroneously] conclude [a] that adults learn more than children or [b] that children learn more than adults.)



Now consider what happens if we do the "same" experiment, but with an "easy" version of the pursuit rotor task in which the target is large and the speed of rotation is slow (figure 9.4b). Now the adults begin very near ceiling, and the children are somewhere in the middle range. The adults have little capability to demonstrate continued improvement, whereas the children start in a sensitive area of the scoring range where a little practice produces maximum score gains. In this case, the gains in score are much larger for the children than for the adults. We might (again, erroneously) conclude that the children learned more than the adults.

This nonsense is caused by the marked differences in the sensitivity of the scoring system to changes in the performers' behaviors and movement patterns—that is, in the sensitivity to changes in the level of habit of the people. The central region of the scoring system (around 15 s time on target) is very sensitive to changes in the performers' habit, whereas the regions near the ceiling and floor tend to be relatively insensitive to such changes in habit. In fact, if we wanted to show that children and adults learned the same amount, we could easily choose a scoring criterion intermediate in "difficulty." So, given the choice of the sensitivity of the scoring system, we can produce just about any conclusion we desire about the relative amounts of learning in children and adults.

But games like this are not science, and it makes no sense to play them. Even so, scientists do not know how to resolve this particular problem, and thus, we have no idea whether children learn more than adults or vice versa. The lesson is that such effects are always present in learning studies, and scientists have to be aware of the potential artifacts that they may produce in coming to their conclusions about learning (see also Estes, 1956; Sidman, 1952). Fortunately, experimental designs that minimize this kind of problem are available. Some of these designs are described in the next section.

# Designing Experiments on Learning

One of the major goals in the study of motor learning is to understand which independent variables are involved in maximizing learning, which variables impair learning, and which have no effect whatsoever. Clearly, such knowledge is important both for the development of useful theories of learning and for practical application in teaching and other learning situations.

Given the definition of learning and the limitations on the kinds of behavioral changes that scientists are willing to classify as learning changes, how do we go about deciding whether a certain variable influences learning or not? What follows is a discussion of a rather typical, but hypothetical, example of an experiment on motor learning. Imagine that one is interested in some “new” method for practice and wishes to contrast this method with a more traditional “old” method, where the independent variable is the method used in practice. (Many other examples could have been chosen.) We begin by assigning participants from a large group of people at random to two groups. Then we administer one level of the independent variable (the “new” method) to one group and another level of the independent variable (the “old” method) to the other group, and record the performance levels achieved during considerable practice of a novel motor skill. It might seem logical that the answer to the question of which of the two methods produced more learning would be based on the performance levels achieved during practice, and especially at the end of practice. But, for the reasons discussed in the previous sections, we need a way to separate the relatively permanent effects of the independent variable from the transient effects on performance. To do this, researchers have typically used so-called transfer (or retention) designs.

## Transfer or Retention Designs

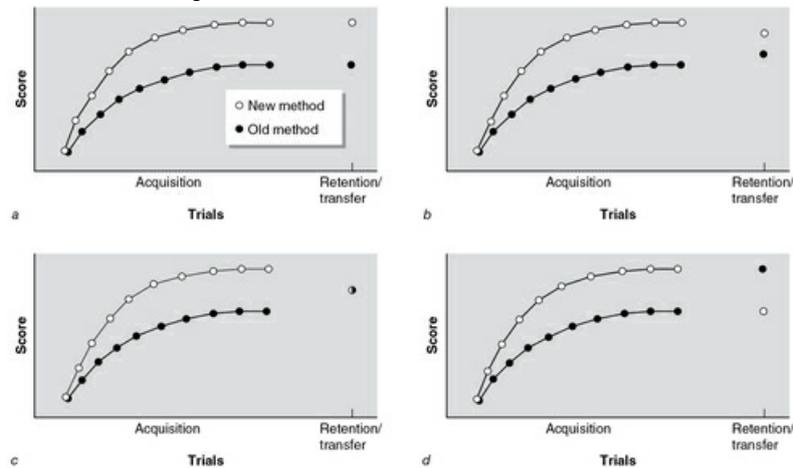
Transfer or retention designs in their simplest form involve two related operations. First, the learners are provided a retention interval (or rest period away from practicing the task) of sufficient duration that the transient effects of the experimental variable (here, the practice method) will dissipate. It is difficult to say how long such an interval must be, but it is clear that we are interested in the lasting, relatively permanent effects of practice and not the momentary benefits afforded by the experimental variable. As a result, retention intervals of 24 h or more are commonly used before the participants perform the transfer test. The second feature is that the learners are all tested under a *common* level of the independent variable—that is, under identical conditions. This is done so that any transient effects of the independent variable (especially ones that are different for the different experimental variables) will not return in the test to again hide the relatively permanent effects. Thus, in the retention test, we assume that the transient effects of the independent variable have dissipated, but that the relatively permanent effects of the variable have, by definition, remained, so that performance on the retention or transfer test will reveal differences in amount learned.

Transfer and retention designs are quite similar, and often the terms are used interchangeably by researchers to refer to the same test. In general, however, tests involving the same task as practiced in the acquisition phase are called retention tests, as they evaluate the extent to which a given skill has been retained over the retention interval. Transfer tests, on the other hand, typically involve new variations of the tasks practiced in acquisition (e.g., performing the task at a new speed, or with different lighting conditions), or they might involve essentially new tasks that have not been practiced before. The essential feature of both retention and transfer designs, however, is that the tasks and conditions are the same for the two groups.

Returning to the example of the “new” and “old” practice methods, the results might look something like those shown in shown in [figure 9.5](#), where the curves in acquisition are plotted for each of four different hypothetical situations. In each of the four cases, the “new” method (the open circles in [figure 9.5](#)) exerts an effect that tends to increase the performance measure relative to the “old” method (the filled circles). We consider next some of the possible effects that could occur on retention or transfer tests, and the interpretations we could make.



Figure 9.5 Hypothetical effects of an independent variable on performance (in acquisition) and learning (in retention or transfer): (a) Size of the performance effect in acquisition is maintained in retention or transfer; (b) size of the performance effect in acquisition is reduced somewhat in retention or transfer; (c) size of the performance effect in acquisition is eliminated in retention or transfer; and (d) the performance effect in acquisition is reversed in retention or transfer.



In the first case, shown in [figure 9.5a](#), the levels of performance after the retention interval are essentially similar to those shown at the end of acquisition. Here we are forced to conclude that the “new” method is better than the “old” for learning. Further, all of the effect of the different methods in acquisition was apparently due to the variable’s relatively permanent effects, and there was no transient effect to dissipate.

In the second case, shown in [figure 9.5b](#), the “new method” group still outperforms the “old method” group on the retention test, but the differences are not as large as they were in acquisition. Still, though, we conclude that the “new” method produced more learning than the “old” because the performances still favor the “new” group in retention. We also see that not all of the difference present in acquisition was relatively permanent, as some of the advantage seen for the “new” group dissipated with rest, bringing the groups closer together than they were in acquisition. In the situation shown, we conclude that there is a learning advantage for the “new” method.

In the third case, shown in [figure 9.5c](#), performance of the two groups in retention is essentially equivalent. Our decision rule leads to the conclusion that there is no learning benefit of the “new” method over the “old.” During acquisition, the “old” method tends to produce somewhat depressed scores, whereas the “new” method tends to elevate performance. We see this by viewing the retention performances in relation to those in acquisition; the “new method” performers have lost some of their gains in acquisition (which gains, therefore, must have been temporary), and the “old method” group shows gains (i.e., from acquisition to retention), presumably resulting from the dissipation of temporarily depressing effects in acquisition. Overall, though, because (and *only* because) the two groups performed similarly in the retention/transfer test, we argue that there was no learning benefit for the “new” versus “old” methods at all.

Finally, the case shown in [figure 9.5d](#) is an interesting one. Here, the groups on the retention test have *reversed* their orders relative to their performance in acquisition. Of course, we argue that the “old” method is better for learning than the “new,” based on the better performance in retention. Yet, the “new” method was better for performance in acquisition. Apparently, the “new” method involves many temporary benefits to performance, but these benefits do not survive in the retention test. The effect is stronger than that, however. With the “new” method—even though it is performing very well in acquisition—participants are learning the task less effectively than with the “old” method, which we see only on the retention or transfer tests. It may seem that such reversals in performance level from acquisition to retention would never occur in real situations. However, there are several cases like this, highlighted in chapters 10 and 11, that force rather counterintuitive conclusions about the effects of practice.

## *Double-Transfer Designs*

There is a potential problem with using only one level of the independent variable for the transfer or retention test as was done in the previous examples. Consider [figure 9.5d](#) again, and further assume that all participants switch to the “old” method in retention or transfer. This naturally favors the “old” practice method in acquisition, because those learning under the “old” conditions are tested under the same conditions while those learning under the “new” conditions must switch conditions in the transfer test. The same problem, but in reverse, would have occurred if we tested all participants under the “new” conditions in retention or transfer.

One way to reduce this difficulty is to use so-called double-transfer designs, in which the two acquisition groups are each split into two subgroups for the retention test. For each of the acquisition groups, one of the subgroups has its retention test under “new” conditions and one under “old” conditions. This forms essentially four groups in the experiment—“new” and “old” in acquisition and “new” and “old” in retention. As we will see, these methods are frequently used to avoid problems in interpretation, and we give many examples of them in chapters 10 and 11.

### *Which Group Learned More?*

Notice that in all of these cases, the fundamental question “Which group learned more?” was answered by an analysis of the performance levels in the retention or transfer test. We did not consider the level of performance in acquisition *at all* when considering the question of learning, because this performance confounds relatively permanent and transient effects of the independent variable. Nor did we use the difference between the performance at the end of acquisition and the performance in retention as a basis for the answer. Simply, the group that performs better on the retention or transfer test was concluded to have learned more.

## Learning and Performance Variables

With the use of these experimental designs, it has been possible to classify experimental variables into essentially two categories. One of the categories is that of the *performance variable*. According to its definition, this kind of variable has effects on performance while it is present, but when the level is altered in transfer, the effect is altered as well. A performance variable is thus one that influences performance but not in a “relatively permanent” way. Using the analogy presented earlier, cooling water to make ice is only a “performance variable” and not a “learning variable” because the effect of the variable vanishes when it is taken away.

A *learning variable*, on the other hand, affects performance after the variable has been removed. That is, the variable influences performance in a “relatively permanent” way, affecting the learning of the task. Examples can be seen in the first hypothetical outcome in [figure 9.5a](#), where the effect of the independent variable remains even when the level of the variable is changed. To extend our analogy, grilling steak is a “learning variable.”

Finally, variables may be both learning *and* performance variables. Like the hypothetical examples in [figure 9.5](#), many of the variables that will be examined influence performance when they are present, with some part of the effect dissipating when the variable is taken away. Yet some other part of the effect remains when the level of the variable is changed, suggesting that the variable also has affected learning in the task. Examples like this can be seen in the hypothetical situation in [figure 9.5b](#), where not all of the effect of the independent variable has dissipated upon transfer. We will see other examples of effects like these in chapters 10 and 11.

## Using Alternative Methods to Measure Learning

Many situations exist in which the measurement of performance, and thus the measurement of learning, does not give a good estimate of the relative “amount” that someone has learned in practice. The problem is often that the performance scores have approached a ceiling or floor during the course of practice, so that all the participants appear to be the same on the task because all the scores hover close to the ceiling or floor. In such situations, attempts to show that a given independent variable has effects on learning are thwarted because continued practice on the task can result in no apparent changes, as the scores are already maximized or minimized.

These problems can arise in at least two different settings. One of these involves simple tasks, for which all persons perform nearly maximally in only a few practice trials. Here, continued practice can result in no effects on the performance score. A second situation relates to a particular type of complex task—those that people have had a great deal of experience with in the past, such as driving a car. Because people are so well practiced, little improvement in skills will be evidenced as they continue to practice. The problem again is that participants are so close to a performance ceiling that no additional improvements can be shown. Other examples are the performance of high-level sport skills and the performance of various highly skilled jobs in industry.

In chapter 2, we discussed secondary-task methods for the measurement of skills. The problem is similar to the present one, as the measures of the performer’s behaviors on a particular task may not give a good indication of the level of skill this person possesses. The example we used was driving under the influence of fatigue. The accumulations of fatigue from long, uninterrupted stretches of driving were not observed in vehicle-control movements at all. However, decrements were observed as a function of the duration of the previous driving when people were asked to perform a simultaneous secondary task, suggesting that there was a decrement in “spare capacity” with increasing levels of fatigue (e.g., Brown, 1962, 1967).

### Secondary Tasks and Alternative Learning Measures

The measurement of performance on a task often does not tell us much about the person’s level of learning. Additional practice (e.g., driving a car) will probably result in some additional learning of the skill even at advanced levels of proficiency, but the experimenter may not be able to detect these effects because the people are so close to the performance ceiling or floor, as the case may be. By using secondary-task methods, one can often see these changes more clearly.

Assume that two groups of people practice a task and that they have reached a performance ceiling. Now, suppose that one of the groups (A) is told to discontinue practice, whereas the other group (B) continues to practice. Group B’s performance is shown as a continuation of the earlier curve along the ceiling, as there can be no further improvements in the *score* after the ceiling has been reached. This procedure, in which a person practices further after having reached some criterion of success, is often called *overlearning*.

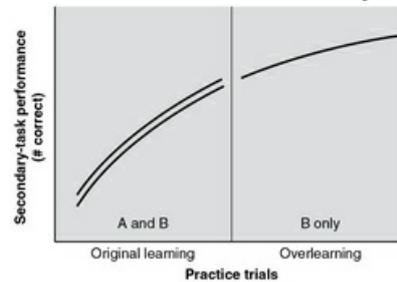
Did any learning of the task go on during the overlearning trials? Which of the two groups had learned more after all the practice had been completed? We might suspect that the continued practice at the ceiling did something to the participants, but we have no way to make this conclusion from the performance curves as both groups have the same final score—essentially at the ceiling. We address these questions using this basic experimental design in the next three sections, so keep this situation in mind. In each case, various methods with secondary tasks can be used to answer these questions.

#### *Automaticity and Learning*

One hypothesis that has received considerable empirical support is that skills become more *automatic* (see chapter 4) with practice, in the sense that systematically less interference with certain simultaneous secondary tasks will be shown. What would be the effect of imposing a simultaneous secondary task in the example described in the

previous section? We could (as Brown [1962] did) have the participants do a mental task requiring the detection of a duplicated letter in a stream of auditorily presented letters. The measure of importance would be the extent to which the participants could improve on this secondary task as they practice the main task. Some hypothetical results are presented in [figure 9.6](#). We would probably see continued improvement in the accuracy of the secondary task, even during the overlearning trials for which the score for the main task was essentially fixed at the ceiling. The improvement in the secondary task would suggest that learning was going on during the overlearning trials, with practice reducing the attentional load and allowing more accurate task performance. This technique has not been used often, but it is useful in situations like this.

Figure 9.6 Hypothetical data from a secondary task measured during practice trials of the task described earlier where a performance ceiling had been achieved. The secondary-task score continues to increase even though the main-task score was at a ceiling.



### *Effort and Learning*

Closely related to the notion of automaticity is the notion of *effort* (Kahneman, 1973). As people learn a motor skill, they appear to be able to do the task with less and less physical and mental effort, possibly because they learn to perform with more efficient movements or because they process information more efficiently. If so, then simultaneous physiological measures could be used to show that, during the overlearning trials in which the participants are practicing the task at the ceiling, the effort in the task continues to be reduced with additional practice. Measures like oxygen consumption (assessed by techniques associated with physiology of exercise) or pupil dilation (also a measure of effort) are frequently associated with levels of effort. If we find less effortful performances during these overlearning trials, such data could be interpreted as showing that the continued practice trials produced some additional learning, and that it was manifested as a decrease in the effort expended.

### *Speed of Decision and Learning*

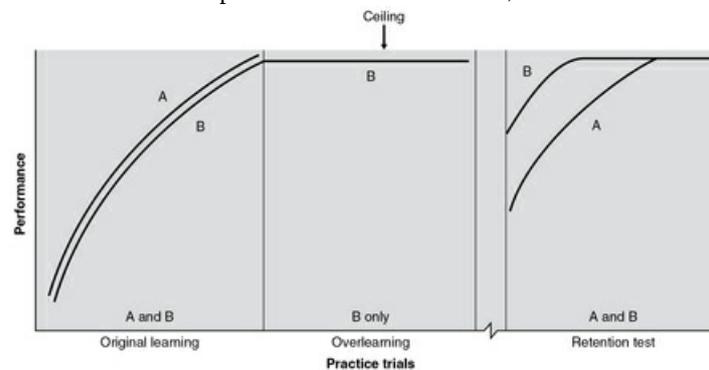
Another method is effective in situations for which the main task involves decision making, such as in learning to make the correct movement when one of several different stimuli is presented. Early in the overlearning trials, participants are just able, with much time and effort, to generate the correct response. But, later in overlearning, they can choose the correct answer more easily and far more quickly. What if, in addition to measuring whether or not the person could make the correct response, we measured the *latency* with which they did so (Adams, 1976a)? We would probably see that the latency of the response (which is not yet at a floor) would decrease markedly even though the accuracy of the response did not change at all (since accuracy of performance was at the ceiling). This procedure will not work with all motor tasks, but it seems ideally suited to those situations in which there are time pressures to make accurate decisions, such as deciding where to throw a fielded baseball, or choosing a defensive maneuver in a dangerous driving situation. If such outcomes occurred, we would conclude that the decreased response latencies indicated a continuation of learning even though the participants were at the ceiling, the learning being manifested as increases in *speed* with constant accuracy.

### *Memory and Learning*

Inherent in the notion of learning is the concept of memory (see chapter 13). In fact, most experimental psychologists define learning in terms of memory, saying that something has been learned when a person has a memory of it. In this sense, memory and habit are very similar constructs. Memory is evident when one has learned a skill or can perform it again at some time after the original-practice session. Kantak and Winstein (2012) proposed an empirically based framework that they termed *motor behavior–memory framework*. This framework integrates the temporal evolution of motor memory processes with the time course of practice and delayed retention frequently used in behavioral motor learning paradigms. The framework allows that motor memory processes of encoding, consolidation, and retrieval correspond to the behavioral motor learning paradigm of acquisition, end-of-practice/immediate retention, and delayed retention (Kantak & Winstein, 2012). These concepts are discussed in more detail in chapter 13.

With respect to the problem of overlearning, if the group with overlearning trials was practicing at the ceiling, the two groups should differ on a *retention* test given some weeks later, perhaps producing a pattern of results something like that shown in [figure 9.7](#). Here, the group with overlearning trials should outperform the group without these trials on the first retention-test trial. Both groups would have lost, in this hypothetical example, some of what they had learned in the original session; but the group without the overlearning would be farther below the ceiling than the group with the overlearning trials, leading to the conclusion that a stronger memory (habit) for the task existed after the overlearning condition. Evidence for a stronger habit after a retention interval could indicate that learning continued during the overlearning trials, even though the ceiling prevented a change in performance scores in these trials.

Figure 9.7 Retention as a measure of original learning. (Original learning and overlearning trials are shown at left, with hypothetical scores from a retention test shown at right; the finding that B outperforms A on the retention test indicates that B learned something during the “overlearning” trials even though no change in task performance could be seen.)



In addition to data on the initial performance in the retention test, useful information can be found in the patterns of improvement during retention-test performance. Typically, group B would be expected to improve at a faster rate than group A, re-attaining the ceiling somewhat more quickly as a result (and because they had less loss in the first place). But another measure, first discussed long ago by Ebbinghaus (1913) and more recently by Nelson (1985) and Seidler (2007), is the *savings score* (see also chapter 13). Here, the amount of additional practice “saved” in reaching some criterion score (in this case, the ceiling) on the retention test is measured. From [figure 9.7](#), if group A required, for example, 25 trials to reach the ceiling again, and group B reached the ceiling in about 10 additional trials, overlearning would have produced an average “savings” of 15 trials. Savings scores are also of considerable practical interest in industry and the military because they indicate the amount of additional (time-consuming and costly) practice that will be needed to return people to various criteria of “readiness” for a particular job.

## Generalizability as a Learning Criterion

We normally think of learning as having the goal of improving our behavior on a *particular* movement (e.g., to serve more effectively in tennis), but broader benefits of practice should also be recognized. One of these is *generalizability*—the extent to which practice on one task contributes to the performance of other, related skills, perhaps in different contexts. As highlighted in chapter 6 in the section on generalized motor programs (GMPs), our capability to perform a task like throwing is not based on one particular throwing movement. Rather, we appear to be able to use a generalized throwing program for a variety of throwing tasks but with the selection of appropriate parameters for the kind of object to be thrown as well as parameters to achieve the distance and trajectory of the throw. We could regard throwing practice as having the goal of contributing to one’s *overall* throwing capability as well as to the skills actually practiced. In this sense, we can measure the effectiveness of a practice session not only by how well the particular skills practiced are acquired but also by how well performance improves on similar skills (that are not practiced directly). This would involve measuring performance on other similar skills in a transfer test—analogueous to the measurement of the retention characteristics of some task as in [figure 9.7](#). The acquisition condition producing the most effective performance in this transfer test would be judged as having the highest generalizability. We can therefore think of the measurement of generalizability as another in a group of alternative measures of learning. The details of these evaluations are related to the measurement of *transfer*, which we consider in detail in chapter 13.

## Summary of Alternative Learning Assessments

All these methods are consistent with the fundamental notion that learning is the set of internal, unobservable processes that occur with practice or experience, resulting in a changed underlying capability for moving. Therefore, it is not surprising that even when obvious changes do not occur in the main task, these learning

processes can be demonstrated by a variety of other means, such as decreases in the interference created for other simultaneous activities, reduction in effort, increases in the speed with which a main task demanding accuracy is completed, changes in retention capabilities, or alterations in generalizability to other similar skills. These techniques highlight the idea that learning is internal and complex, having many forms in many different situations. Above all, we stress here the deficiency in the oversimplified idea that learning is merely a change in behavior on the task in question. It is clearly a much more complex set of processes than that.

## Understanding Issues About the “Amount” of Learning

On the basis of experiments on learning, researchers are often tempted to make statements phrased in terms of the *amount* of learning that has occurred as a result of practice. For example, we might wish to say that a group of people practicing with one condition learned 20% less than a group with another condition. Or you may wish to say that Luc learned twice as much as Jack on this task. Do such statements really have any meaning?

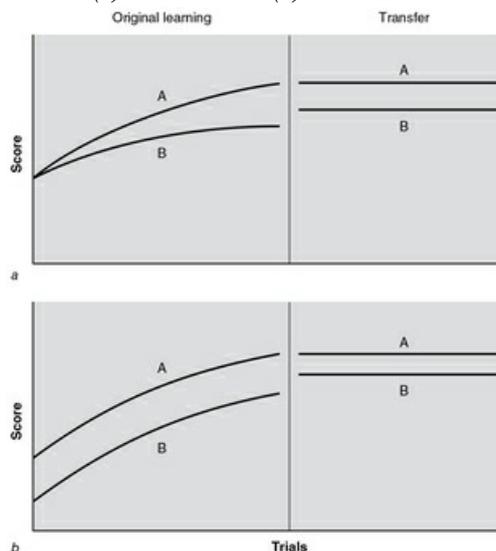
The problem is that habit is a construct that cannot be observed directly. Usually little basis exists for making quantitative statements about it, because it can only be estimated from performance scores. Recall the experiment by Bahrick and colleagues (1957) discussed earlier. By a simple change in the way the task was scored (change in the strictness of the criterion of success), the authors obtained almost any scores they wanted, and they could easily change the shapes of the performance curves. For example, looking back at the data from their experiment in [figure 9.3](#), we computed that the participants with the 5% scoring criterion improved 86% as a result of practice, that the same participants improved 29% with the 15% criterion, and that they improved 8% with the 30% criterion. How can we assess the “amount” of habit gain that occurred here? Will we say that it was 8%, 29%, or 86%? That decision is purely arbitrary, and we would be equally wrong in making any of these claims.

The best one can do is to make statements about the *relative* amounts that two groups have learned, or about the relative amounts that two people have learned, essentially with statements like “group A learned more than group B.” The issues are somewhat different for the case in which groups are compared to each other versus the case in which individuals are compared against each other, so we discuss these two situations in turn.

### Group Differences

[Figure 9.8a](#) is a typical example of the transfer paradigm discussed earlier, where practice tends to increase the scores on the task. Here, the experimenter does not really have any idea about *how much* learning occurred but can make statements about two things: the fact that both groups learned, and the fact that group A learned more than did group B. Because the two groups began practice on trial 1 with the same level of performance, and because, during the course of practice, they progressed to different levels of performance, the conclusion that group B learned less than group A in this case seems unavoidable. Remember that the test of the relative amount learned should always be on the transfer trials, as it is only there in the sequence that the temporary effects of the independent variable are equated for the two different levels of initial capability.

Figure 9.8 Outcomes from an experiment on learning in which the original level of proficiency for the two groups was (a) controlled or (b) not controlled.



Now consider [figure 9.8b](#), where the two groups *began* practice at different levels of performance and hence different levels of initial capability. This initial difference could be attributable to some systematic difference in the nature of the participants (e.g., males vs. females or children vs. adults), or it could be attributable to simple random sampling effects, whereby the groups simply differ by chance. In either case, both groups learned, but we are in a difficult position with respect to saying which group learned more. You can see that both groups gained about the same amount in terms of the score on the task, but you have no way of knowing whether the amount of change in the capability (i.e., habit) was larger or smaller for group A or group B.

The problem is that the differences in the initial level of performance have confounded interpretation about which of the groups learned more. Thus, in designing these kinds of experiments it is essential, if this question is to be asked about the data, to be certain that the two groups of participants are equated at the beginning of practice so that differences in the performance on the transfer test can be attributed to changes in the amount learned.<sup>1</sup> This can be accomplished by administering a pretest on the learning task, ranking participants from highest to lowest on this test, and then assigning the participants with odd-numbered ranks to one group and those with even-numbered ranks to the other group. In this way, the groups are almost exactly equal on the first trial, and the problem is eliminated. (Other matching techniques are available as well.)

There are some drawbacks to using a pretest. One is that the pretest provides some practice on the experimental task, which then reduces the size of the changes to be observed under the different levels of the independent variable. This procedure has the additional limitation that the first trials on a motor task are usually not strongly correlated with the last trials in the sequence—that is, with the final trials on which the relative amount of learning is assessed. Such correlations are frequently as low as 0.20. If so, then the variable that is matched (initial performance) is not going to influence the “equality” of the groups on the transfer trials to a very strong degree.

A second method is to use large groups that are randomly formed from some larger group. In this way the groups will be expected to differ due to chance effects; but if the groups are large (e.g., 25 people per group), then the chance differences in the group means on the motor task should be relatively small. This procedure has the advantage that it does not give people experience on the task before the independent variable is administered, but it has the disadvantage that chance differences can still occasionally occur. More on this issue can be found in Schmidt (1971a, 1972a).

Could you “correct for” the initial differences in performance (e.g., see [figure 9.8b](#)) by subtracting the initial difference from the differences that occurred in the transfer trials? While arithmetically this can be done, such procedures produce nearly meaningless interpretations of the relative amount learned. The problem is that the

sensitivity of the scoring system to changes in the internal capability is different at various places on the performance scale. Thus, subtracting the initial differences in performance from the differences in performance at the end of practice will probably lead to an adjustment that is far too large. Because we have no idea how much too large this adjustment will be, and we have no way to find out, such adjustments probably should not be used.

Of course, these adjustments are exactly equivalent to computing “learning scores,” or the differences between the initial and final performance for one group, and comparing these differences to the difference between the initial and final performance scores for the other group (Schmidt, 1971b). The use of “learning scores” or “gain scores” is not as prevalent as it was some years ago, largely for the reasons mentioned.

## Individual Differences

The problem just raised is similar in many respects to that of comparing the amount learned by one person to the amount learned by another person. This is a common problem in the study of individual differences in learning, as sometimes it is of interest to determine whether or not some measure of an ability correlates with the amount that someone will *learn* (e.g., Bachman, 1961, and many others). Naturally, in order to compute the correlation, one must achieve a measure of the “amount learned” by each person. But we have just argued that such measures are not meaningful if they are based on the differences between the initial and final performance.

A second situation in which these kinds of measures are usually taken is in determining grades. Often, a measure of the student’s initial level of proficiency is taken at the beginning of instruction, and another measure of proficiency is taken after the instruction has been completed; grades are then assigned on the basis of the difference between the initial and final performance levels, presumably in terms of “amount learned.”

The fundamental problem with this technique is that the difference between initial and final performance is not an adequate measure of the “amount learned,” for the reasons already discussed. Also, in philosophical and educational terms, in most aspects of life we are judged on the basis of what we can *do*, not on the basis of how much we have *improved*. If someone received an A in physics because he or she could pass the examinations at the end of the course, no one cares that he or she could have passed the examinations on the first day of class. Evaluating improvement scores in teaching or research settings is generally laced with difficulty and should be avoided.

## “Rate” of Learning

We have argued that using scores from acquisition data to calculate measures of “amount” of learning leads to many problems in interpretation. A problem similar to those already noted arises in the measure of “rate” of learning. The idea of a learning rate has been common in sport folklore (“so-and-so is a fast learner”). Attempts to measure the speed of acquisition are often based on the steepness or slope of the performance curve. For instance, look back at the plot of the two hypothetical performers in [figure 9.2](#). It might be tempting to say that participant 2 is a “faster” learner than participant 1 because the slope of the curve is much steeper in the early stages of practice. However, such conclusions fall prey to exactly the same problems as with trying to measure the *amount* of learning.

# Understanding Learning and Performance Variables

The problem of identifying which of the many independent variables are critical for learning, and which are relevant only for performance, is important not only for development and testing of theories of motor learning but also for application to a variety of practical situations. We treat these two issues briefly here but discuss them again throughout the remainder of the text.

## Importance for Theory

Learning theories make predictions about how certain independent variables will affect learning. In such cases, experimental tests of the theory involve evaluations of, among other things, the extent to which one group of people learned more than some other. As we have argued, valid tests of such questions ultimately rest on which of the two groups performs most effectively on retention or transfer tests. Thus, such research designs become the key way in which theories of learning are tested in the laboratory. Many examples of this kind of theory testing are presented in the following chapters.

## Importance for Application

A second practical outcome is that knowledge about which variables affect performance temporarily, and which affect learning, allows the production of more effective settings for instruction in various motor tasks in sport, industry, therapy, and so on. Naturally, if the goal of practice in such application areas is to maximize learning, variables that influence learning (as measured on retention or transfer tests) should be emphasized during practice, and variables that influence performance only temporarily can be ignored. The topic of this relation between research and practice, as it pertains specifically to issues of learning, will arise numerous times throughout the remainder of the book.

## Summary

The study of motor learning is considerably different from the study of performance in that the focus is on the *changes* in performance that occur as a direct result of practice. Motor learning is defined as a set of internal processes associated with practice or experience leading to a relatively permanent change in the capability for skilled behavior, a state sometimes termed *habit*. Such a definition must be carefully worded to rule out changes in behavior that are due to maturation or growth or to momentary fluctuations in performance attributable to temporary factors.

In the typical motor learning experiment, two or more groups of participants practice a task under a different level of an independent variable. A common method of data analysis involves *performance curves*, or plots of average performance on each trial for a large number of people. These curves can hide a great deal of important information about learning, however, such as individual differences in learning or changes in strategies. They tend to characterize motor learning as a slow, constantly evolving process requiring continued practice, whereas other evidence suggests that learning is often sudden, insightful, or even “revolutionary.” As a result, interpretations about the nature of learning from performance curves must be made carefully.

Learning experiments usually involve what is called a *transfer (or retention) design*, in which the groups of participants practicing at different levels of the independent variable are transferred to a common level of that variable. These designs provide for the separation of the relatively permanent effects (due to learning) and the temporary effects of the independent variable. Those independent variables affecting performance “relatively permanently” are called *learning variables*, and those affecting performance only temporarily are called *performance variables*.

In many situations, the performance scores are near a ceiling or floor, at which no changes can occur because of task-imposed or biologically imposed limitations on performance. In such situations, a number of secondary-task methods can be used, such as measures of latency, measures of attention or effort, measures of retention, or measures of generalizability. Even with all the methods, it is seldom possible to speak meaningfully about the actual *amount* a person or a group has learned or the rate of learning.

### Student Assignments

1. Prepare to answer the following questions during class discussion:
  - a. Motor learning is defined in terms of four distinct characteristics. Use an example of learning a real motor skill to illustrate these four characteristics.
  - b. In your own words, describe how you would explain to an athlete the distinction between performance and learning. Why might this distinction be important to the athlete?
  - c. Using an example of research discussed in chapter 10 or 11, describe how an experimenter might devise a double-transfer design to assess learning.
2. Find a research article that illustrates one of the hypothetical learning and performance effects depicted in [figure 9.5](#).

### Notes

<sup>1</sup> Some research examples presented in chapters 10 and 11 will *appear* to show group differences on the very first trial (e.g., Shea & Morgan, 1979). In these cases, however, it is important to recognize that the first data point on the graph does not correspond with the first trial but rather with the first *block* of trials, which may represent the average of 5 to 10 or more trials. Thus, the learning variable is revealing rapid effects on the performance of the groups, which we assume, were equated on trial 1.



# Chapter 10

## Conditions of Practice

Time is a key constraint in many situations in which individuals are asked to learn (or relearn) motor skills. An insurance company may dictate that a maximum of nine rehabilitation sessions will be paid by insurance. A badminton practicum may involve three sessions per week for 14 weeks. A tool and die worker is given one training session to learn to use a new piece of equipment. A microsurgeon takes a two-day course involving a new technique before surgery on patients begins. In all of these situations that invoke specific temporal limitations on practice, the implicit understanding is that practice should be *organized* in a way that maximizes the amount of potential learning. To meet the demands of these time constraints, the learning facilitator must be aware of the variables, or the *conditions of practice*, that influence performance and learning, and adjust them so that learning will be maximized.

This chapter is about these variables and techniques, with the focus on the major ones that are important for motor learning. There are many such variables, and we have confined the discussion to those variables having the largest effects (i.e., those that make the biggest difference) and those that are usually under the direct control of the experimenter or teacher. With this emphasis, the material relates rather closely to the design of instructional settings such as would be seen in schools, in training for jobs in industry or the military, and in rehabilitation. Also, we stress those variables in which there is the greatest theoretical interest. This emphasis also provides a strong contribution to practical application, because well-established theories have many real-world implications (Kerlinger, 1973). Generally, the chapter is about attempts to understand the many variables that determine the effectiveness of the conditions of practice. These variables include the verbal information about the task provided to the learner, the learner's focus of attention that is promoted by instructions or feedback, the motivational impact of different practice conditions, observational and mental practice, practice scheduling (distribution of practice, variable practice, contextual interferences), and the effectiveness of guidance procedures.

# Verbal Information

Learners are often given some information about a task before physically practicing it. One aspect of verbal instruction is teaching the learner about the skill and sometimes explaining the mechanical principles underlying the skill. Although it may seem that detailed knowledge about the task aids the learning process, studies have shown that receiving too many details can sometimes hinder learning, and learning without awareness can be more effective.

## Learning Without Knowledge

How much should learners know about mechanical properties underlying a particular movement task? Will such knowledge, if provided before the learning of the task begins, be an aid to future performance and learning? Early work by Judd (1908) on throwing darts to targets submerged underwater gave initial indications that such information was useful. Judd taught his participants the principles of refraction, whereby the light rays from the submerged target are bent so that the target is not really where it appears. This instruction provided initial advantages when the targets were moved to different depths of submersion. Hendrickson and Schroeder (1941) obtained similar results in a task that required shooting an air gun at underwater targets.

Mechanical principles are also a part of instruction in sport skills, such as in swimming (propulsion) and billiards (ball spin, geometry). However, explicit knowledge of mechanical principles is not always necessary for performance of certain tasks. In an often cited example, Polanyi (1958) points to a champion cyclist who did not know the mechanical principles involved in the maintenance of balance on a bicycle, implying that such principles may not be critical for learning the task.

Learning can even be degraded when learners are informed about how to perform a task. In one study (Wulf & Weigelt, 1997), participants practiced a complex ski-simulator task that required them to perform slalom-type movements. The apparatus consisted of bowed rails and a platform on wheels that was attached to each side of the apparatus by elastic rubber belts. The performer's goal was to make oscillatory movements by exerting force against the platform and producing the largest possible amplitudes. One group of participants was given instructions about an efficient movement pattern, namely, to wait until they reached the middle (to take advantage of the energy stored in the stretched rubber belts) before pushing against the platform. One would probably expect this "tip" to enhance their performance. On the contrary, performance of the informed group was impaired relative to participants who were free to discover the correct technique for themselves. The instructed group made less progress across 3 days of practice. Also, on a stress test (the stress was that participants were told that a ski expert would evaluate their performance), noninstructed participants tended to have an even greater advantage.

Another study, in which a bimanual coordination task was used, found similar benefits of *not* giving learners instructions about how exactly to perform the task (Hodges & Lee, 1999). Participants had to move two handles, which were attached to slides, back and forth in the horizontal plane; one hand followed the other by a quarter of a cycle. This motion created a circle pattern on a computer screen. Different groups of participants were given specific or general instructions about how to coordinate their hand movements in order to produce a circle pattern. Another group was simply instructed to produce a circle; that is, these participants were left to their own devices and had to figure out how to create the circle. The most interesting finding was seen on a transfer test after 2 days of practice. On this test, an attention-demanding task was added, requiring participants to produce the circle while counting backward in threes. The results showed that the group that had *not* been given instructions performed more effectively than the groups that had received instructions about the correct coordination pattern. The implications of these findings are consistent with the point made in the next section—that at least some learning can occur in the absence of explicit information (Krist, Fieberg, & Wilkening, 1993), and that implicit learning (learning without awareness) can be superior to explicit learning.

## Learning Without Awareness

Some research suggests that learning of some tasks can occur even though the participant is oblivious to the perceptual regularities of the task. In a classic study by Wickens and Pew (see Pew, 1974b), participants practiced a pursuit-tracking task; they had to move a lever in order to try to match a perceptual input signal on a computer monitor. A trial comprised three segments of 20 s each. During the first and last of these segments, the perceptual signal was generated randomly by the computer, and the random sequence was different on each of the 24 trials completed during each session on 16 days of practice. However, the perceptual signal during the middle segment was always the same. Improvements on the repeated, middle segment were greater and occurred much faster than on the random segments. Interviews with the participants after day 11 revealed that *none* had any idea that the middle portion of the trial was always repeating! That the enhanced learning of the middle segment seemed to occur even though the participants were unaware that any part of the task had been different from the others. These results have been replicated in experiments in which the first segment was repeated—with *none* of the participants aware of any regularities in the perceptual stimuli (see Magill, 1998). Studies have also shown that these effects persist in transfer tests, again without the participants' awareness (Wulf & Schmidt, 1997).

Similar to providing learners with information about how to perform a task (see previous section), informing them about the presence of regularities in the stimuli can be detrimental to learning compared with not informing them. Green and Flowers (1991) used a simulated ball-catching task to compare the effects of informing learners about an underlying rule versus not informing them. Participants were to catch "balls" that were moving downward on a computer screen with a "paddle" on the bottom of the screen by manipulating a joystick. They were or were not told about the probability relationship between characteristics of the ball's pathway and its final position where it was to be caught. The results showed that participants were able to take advantage of the probability relationship, independent of whether or not they had been informed about it. Furthermore, compared with informing learners about this relationship, withholding that information actually enhanced the learning of the task.

One might guess that the uncertainty inherent in a probability rule may have overwhelmed learners and prevented them from responding more "naturally" to the approaching ball. However, findings by Shea, Wulf, Whitacre, and Park (2001) showed that even informing performers about the existence of the same repeated stimulus pattern can impair learning. Similar to the studies by Pew (1974) and Magill and Hall (1989), Shea and colleagues used a tracking task in which a third of the tracking pattern was repeated on every trial. However, rather than using a handheld manipulandum, they used a dynamic balance task. Participants stood on a balance platform while watching the movements of a target line on a computer screen. The task was to attempt to move the platform in a manner that would mimic the movement of the target line. A second line was used to indicate platform position so that the participants' task was essentially to keep the two lines as close to each other as possible. Thus, participants had to respond to complex waveforms with actions that required whole-body coordination—a situation that is more representative of skills encountered in practical settings than previously used tasks. Participants indeed learned the repeated movement pattern implicitly, as demonstrated by more effective performance on that pattern relative to surrounding random patterns and their lack of awareness of the repetitions (Shea et al., 2001, experiment 1). Compared with not informing participants about the existence and location of the repeated pattern, informing them of it *degraded* learning.

These findings suggest that information or instructions intended to help learners acquire motor skills are not always effective and can actually hinder the learning process. The learner's thought processes, particularly self-related thoughts in response to certain instructions, can interfere with optimal motor control and learning. A major factor that determines the effectiveness of instructions is the type of attentional focus that instructions or feedback promote. This issue is discussed next.



# Focus of Attention

Chapter 4 discussed the effects of attentional focus on motor performance and learning. Since 1998, numerous studies have consistently shown that an instructed external focus on the intended movement effects is necessary for optimal learning (see Lohse, Wulf, & Lewthwaite, 2012; Marchant, 2011; Wulf, 2007, 2013; Wulf & Lewthwaite, 2016; Wulf & Prinz, 2001; Ziv & Lidor, 2015, for reviews). In contrast to an internal focus on body movements, an external focus leads to greater automaticity and generally more effective motor coordination and movement outcomes. In studies examining the effects of attentional focus, the wording of the instructions is typically similar in terms of the content and amount of information they provide. Often the instructions differ in only one or two words to direct attention externally versus internally. For example, when hitting a golf ball, an instruction promoting an external focus would be “Focus on the swing of the club,” while a comparable internal focus instruction would be “Focus on the swing of your arms” (Wulf & Su, 2007). For a task involving balancing on an inflated rubber disk, the instructions might be “Focus on keeping the disk still” (external) versus “Focus on keeping your feet still” (internal) (Wulf, Landers, Lewthwaite, & Töllner, 2009). In this section we discuss some issues related to how instructors and performers can use the attentional focus effect to optimize practice. The benefits of an external focus are generalizable across tasks, skill levels, age groups, and levels of ability. Practice with an external focus influences performance relatively permanently; that is, it affects learning. We also discuss how one might find the optimal focus of attention.

## Generalizability of the External Focus Benefits

Performance or learning advantages of an external compared to an internal focus (or control conditions) have been shown for a variety of skills, including diverse skills such as discus throwing (Zarghami, Saemi, & Fathi, 2012), swimming (e.g., Freudenheim, Wulf, Madureira, & Corrêa, 2010), gymnastics (Abdollahipour, Wulf, Psotta, & Palomo Nieto, 2015) and singing (Atkins & Duke, 2013). They have been found for different levels of expertise, ranging from novices to experienced performers (e.g., Bell & Hardy, 2009; Wulf, McConnel, Gärtner, & Schwarz, 2002; Wulf & Su, 2007). Furthermore, external focus advantages are seen for people of various age groups, including children (Abdollahipour et al., 2015; Wulf, Chiviawowsky, Schiller, & Ávila, 2010), young adults, and older people (e.g., Chiviawowsky, Wulf, & Wally, 2010). Benefits of external focus instructions have not only been found for healthy participants but also those with injuries (Laufer, Rotem-Lehrer, Ronen, Khayutin, & Rozenberg, 2007; Rotem-Lehrer & Laufer, 2007) and motor impairments caused by stroke or Parkinson’s disease (Fasoli, Trombly, Tickle-Degnen, & Verfaellie, 2002; Landers, Wulf, Wallman, & Guadagnoli, 2005, Wulf, Landers, Lewthwaite, & Töllner, 2009), and children with intellectual disabilities (Chiviawowsky, Wulf, & Ávila, 2012). Thus, having an external attentional focus appears to be a necessary condition for optimal motor performance and learning (see Wulf, 2013; Wulf & Lewthwaite, 2016).

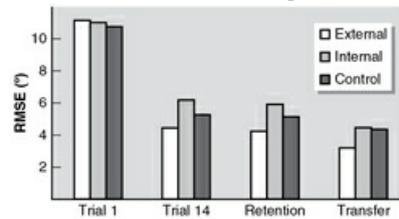
## Performance and Learning

Performance differences are often seen immediately when a person is asked to adopt an external versus internal focus (or no particular focus). Many studies have used within-participant designs, in which all participants perform under all conditions—internal focus, external focus, and sometimes control conditions, in a counterbalanced order. Typically, an external focus results in superior performance. This result has been shown for many skills, including dart throwing (e.g., Lohse, Sherwood, & Healy, 2010), standing long jump (Wu, Porter, & Brown, 2012), vertical jump (Abdollahipour, Psotta, & Land, 2016), isokinetic force production (e.g., Marchant, Greig, & Scott, 2009), and sprinting (Porter, Wu, Crossley, Knopp, & Campbell, 2015).

Most studies have used traditional learning designs, in which different groups of participants practice with different attentional focus instructions (and occasional reminders) and then perform retention or transfer tests (without reminders). In those studies, advantages of practicing with an external focus are generally maintained across retention intervals. Moreover, the advantages transfer to novel situations (e.g., Duke, Cash, & Allen, 2011;

Lohse, 2012; Ong, Bowcock, & Hodges, 2010; Wulf et al., 2010). Some transfer tests involved pressure situations (Bell & Hardy, 2009) or distracter tasks to prevent the use of the instructed focus (e.g., Totsika & Wulf, 2003). Even when the performer does not or cannot maintain an external focus, the benefits gained during practice persist. Perhaps the most direct evidence that the changes in performance are relatively permanent effects (therefore considered learning) comes from a study by Wulf, Weigelt, Poulter, and McNevin (2003). In that study, attention was directed to a suprapostural task during practice of a balance task. The suprapostural task involved holding an object still with both hands, either by directing attention to the hands (internal) or the object (external). The group asked to adopt an external focus on the suprapostural task did a better job on that task and their balance performance was also improved. This was the case even when the suprapostural task was removed on the transfer test, thereby eliminating the opportunity to adopt the original external focus ([figure 10.1](#)). Thus, the benefits of practicing with an external focus seem to be relatively permanent. One reason is that presumably good performance during practice enhances the participant's expectancy for future performance, that is, her or his self-efficacy (see chapter 12, "OPTIMAL Theory").

Figure 10.1 Effects of attentional focus instructions on stabilometer performance on the first and last practice trial, retention, and transfer. RMSE is root-mean-square *error*, so lower scores are better.



## Distance Effect

Many motor skills have more than one movement effect, so the performer may have a choice in terms of which one to focus on. For example, when striking a volleyball, the player can concentrate on the part of the ball they plan to strike, the intended trajectory of the ball, or on hitting a certain target area. Are all external foci similarly effective, or do some lead to better outcomes than others?

One factor to consider is the distance of the movement effect from the body. Several studies have found that external foci that are more distal (farther away) from the performer's body are more effective than those that are more proximal (closer to the body). McNevin, Shea, and Wulf (2003) first showed this effect with a balance task using a stabilometer. Different groups of participants were asked to focus on keeping sets of two markers on the stabilometer platform horizontal. The learning advantage increased when those markers were placed farther away from the feet. McNevin and colleagues argued that a more distal focus makes the movement effect more easily distinguishable from the body movements that created the effect, compared with a more proximal focus, and therefore the benefits are greater. Results of various follow-up studies have confirmed the *distance effect*. For instance, for skilled kayakers a focus on the finish line (distal) as opposed to the paddle (proximal) or a control condition led to reduced wildwater racing times (Banks, Sproule, Higgins, & Wulf, 2015). Golfers demonstrated greater accuracy in hitting golf balls when their focus was on the ball trajectory and landing point (distal) compared to the club (proximal) in a study by Bell and Hardy (2009). Furthermore, accuracy in dart throwing showed improvement with a focus on the bull's-eye (distal) as opposed to the flight of the dart (proximal) (McKay & Wulf, 2012). Porter, Anton, and Wu (2012) showed that participants jumped farther when they focused on jumping as close as possible to a target (distal) than jumping as far as possible past the start lines (proximal). Thus, consistent evidence supports the distance effect. Does this mean an instructor should always direct the learner's attentional focus to the most distal movement effect? The story is likely to be more complicated. In the next section, we take a look at additional factors that might play a role.

## Finding the Optimal Focus

While systematic investigations are lacking, there is reason to assume that the optimal external focus for a given task may differ depending on the performer's level of expertise. While an external focus is generally beneficial for both experts and novices (e.g., Wulf & Su, 2007), some evidence shows that novices may benefit more from a relatively proximal external focus, whereas a distal focus may be more appropriate for experts. In an experiment by Wulf, McNevin, Fuchs, Ritter, and Toole (2000, experiment 2), the participants' task was to hit golf balls to a target. One group was asked to focus on the swing of the club (proximal), while the attention of another group was directed to the anticipated trajectory of the ball and the target (distal). The results showed that focusing on the club motion resulted in a greater accuracy, not only in practice but also on a retention test. In contrast, in Bell and Hardy's research with experienced golfers (2009), accuracy in hitting a target was greater when they adopted a distal focus (ball trajectory, target) rather than proximal focus (clubface).

It makes sense that relatively inexperienced performers, who are still in the process of acquiring the basic movement pattern, would benefit more from an external focus that is technique related (or more proximal). For example, asking a novice tennis player who is attempting to serve a ball to simply focus on the service box would

probably not be as effective as an instruction related to the motion of the racquet. For a skilled tennis player, on the other hand, focusing on the racquet would likely not be ideal and would disrupt the fluidity on the motion. A focus on the intended flight path of the ball or target area (distal) would most likely be more effective. Similarly, a young pianist's attention might need to be directed to the piano keys (proximal), whereas a concert pianist would perform better when focusing on the intended sound of the music. Thus, the optimal focus of attention is presumably more distal for the expert performer.

The physical distance of the movement effect from the body is not the only factor that determines the effectiveness of the external focus. Often a greater distance, such as a concentration on the target one plans to hit; also means that the action is controlled at a higher hierarchical level of representation (Vallacher, 1993). With increasing proficiency, action control tends to move to higher levels of representation (e.g., Vallacher, 1993; Vallacher & Wegner, 1987). Going back to lower levels will likely disrupt automaticity and the fluidity of movements seen in skilled performers (e.g., an expert golfer focusing on the club motion). In contrast, for a novice who has not yet developed the ability to control the entire action automatically, a lower hierarchical level of control or more proximal focus may be more advantageous.

Given that the optimal focus is most likely a function of the performer's expertise, it is perhaps not surprising that in a few studies with expert performers, external focus instructions did not result in more effective performance relative to control conditions without specific focus instructions (e.g., Porter & Sims, 2013; Schücker, Anheier, Hagemann, Strauss, & Völker, 2012; Stoate & Wulf, 2011; Wulf, 2008). Continuous skills, such as swimming, running, or balancing, were used in those studies. These skills have become highly automatic after millions of repetitions over the career of an athlete. Clearly, it is difficult to improve performance that is already at a very high level. If movement control is highly automatic—and performers already direct their attention to the intended movement outcome—there may be little or no room for further improvement (see also Wulf, Töllner, & Shea, 2007). Also, it is possible that the instructed foci used in these studies were not optimal because they were too proximal for the participants' levels of expertise.

## Practical Implications

Even subtle differences in the wording of instructions or feedback toward a participant can have a profound impact on immediate performance as well as learning. Performers do not always adopt the optimal focus, which is partly the result of prior instruction (e.g., Durham, van Vliet, Badger, & Sackley, 2009; Guss-West & Wulf, 2016; Porter, Wu, & Partridge, 2010). In interviews with track and field athletes who competed at national championships, the majority (84.6%) reported that their coaches gave instructions related to body movements (Porter, Wu, & Partridge, 2010). As a consequence, most of them also indicated that they focused internally when competing. The importance of maintaining an external focus in competition was seen in a study by Stoate and Wulf (2011). Expert swimmers who indicated that they used an internal focus (e.g., high elbow, hip rotation) in the control condition swam more slowly than those who reported using an external focus (e.g., tempo, getting to the other side).

The extent to which performers focus internally or externally is also a function of the type of skill. Skills that involve the manipulation of an object make it easier for performers to adopt an external focus. For example, skilled horseshoe pitchers mostly have a distal external focus on the stake (Fairbrother, Post, & Whalen, 2016). In contrast, when performing form-based skills (e.g., gymnastics, diving, ballet), it may be tempting to focus on body movements. Indeed, a survey with professional ballet dancers showed that many of them focused on body positions or movements (Guss-West & Wulf, 2016). However, even in ballet, the type of focus appears to be dependent on the skill. Skills requiring complex static balance over a longer period of time (e.g., arabesque) tend to promote an internal focus (legs, arms, shoulders, etc.). In contrast, skills that are more dynamic and ballistic in nature (e.g., grand jeté)—and leave little time for conscious control—facilitate the adoption of an external focus. Dancers frequently reported using external images, such as “gliding through air,” “jumping over something,” or “reaching for the sky.” In the same way, coaches use analogies with athletes (e.g., Lam, Maxwell, & Masters, 2009; Liao & Masters, 2001). For example, basketball instructors may tell a player to finish the shot with a hand position “like reaching into a cookie jar.” Analogies are effective because they give performers an image of how an

action should be performed, without referring to body movements per se.

Instructors, coaches, therapists, and performers should be aware of the attentional focus effects and develop strategies to keep performer's attention focused externally. As the performer's skill level increases, shifts in attentional focus become necessary. It may require some creativity, but the benefits for performance and learning are almost guaranteed.

# Motivational Influences on Learning

In the motor learning literature, researchers have long considered cognitive influences on learning. For example, the effects of random versus blocked practice, variable versus *constant practice*, or self-controlled practice have been examined and interpreted mainly from an information-processing perspective. *Motivation* used to be seen as having only an indirect effect on motor learning, such that “motivating” practice conditions might encourage learners to practice more. However, the *direct* motivational (e.g., social-cognitive and affective) impact of various practice conditions has become clear only in recent years (Lewthwaite & Wulf, 2010a). For example, studies have shown that feedback not only provides a learner with information about performance relative to the goal movement, but also its influence on the learner’s motivation appears to have a direct and powerful impact on the learning and control of movements as well (see chapter 12).

It is not a coincidence that the words “motivation” and “motor” have the same Latin root: *movere* (“to move”). From a behaviorist perspective, motivation is typically used to describe the drive toward some goal, in terms of level of intensity and direction of movement. In more contemporary psychological accounts, the causes and consequences of that drive are of greater interest. Social-cognitive-affective influences on human behavior (constructs such as self-efficacy, attitudes, intentions, and emotional and affective states) play prominent roles. Individuals’ expectations for future performance and perceptions of autonomy are particularly relevant for motor performance and learning. Conditions that enhance learners’ performance expectancies or support their need for autonomy have been shown to facilitate motor learning.

## Enhancing Learners’ Expectancies

There is plenty of anecdotal evidence that confidence, which is reflected in movement fluidity or automaticity, leads to successful performance. Success, in turn, breeds confidence and can potentiate further success (see “Nothing Succeeds Like Success”). The converse is true as well; mistakes can lead to further mistakes, such as the six putts from within 3 ft by Ernie Els, a World Golf Hall of Famer, at the 2016 Masters tournament. Findings from a number of lines of research demonstrate that learner confidence is a precondition for successful learning as well. Practice conditions that increase learners’ *self-efficacy* (or confidence in their ability to perform well in the future) have been shown to facilitate learning. Some of these findings come from investigations into the effects of positive feedback; they are discussed in more detail in chapter 11. Other evidence that motor learning is facilitated by enhanced performance expectancies (e.g., high self-efficacy) comes from studies showing that learning is more effective when the performer receives positive social-comparative information, when the task is made to appear less difficult, or when learners’ concerns about their abilities are reduced.

### Nothing Succeeds Like Success

Swedish researchers Olof Rosenqvist and Oskar Nordström Skans analyzed the performance of professional golfers in European tournaments over 2 years. In particular, in each tournament they looked at the last player to make the cut and the first player who did not make the cut. In most tournaments, the difference in performance between these two players is very small. However, the consequence of this difference is huge. The golfer who just makes the cut feels like a winner, gets to play the rest of the tournament, and receives some prize money, whereas the golfer who missed the cut receives no prize money and goes home.

The researchers were particularly interested in how likely each of these two players were to make the cut in the *next* tournament. They asked whether the player who happened to make the cut in one tournament, largely by chance, would have higher chances of making the cut in the next tournament; in other words,

would success breed more success?

Indeed, that is what the researchers found. Players who barely made the cut in the first tournament were more likely to make the cut in the second tournament. Thus, small initial differences led to greater differences in performance, likely because the players' confidence that they could win again increased. Success produced confidence, and confidence produced more success. This effect was especially pronounced when the second tournament involved high pressure (e.g., a large amount of prize money), that is, when optimal performance was of the essence (Rosenqvist & Skans, 2015).

### *Social-Comparative Information*

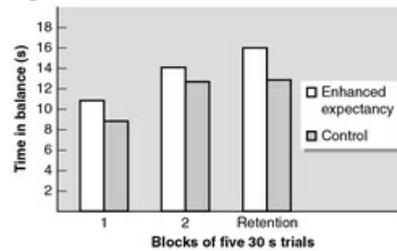
A few studies have examined how learners' beliefs that they are performing better (or worse) than average affect learning. In those studies false feedback about average performance scores (norms) was provided to participants. While this type of feedback is not recommended for practical application, the experimental findings provide interesting insights into how people's convictions with respect to their performance relative to others impact learning. Social-comparative information or feedback is typically provided in addition to augmented feedback about the learner's own performance. In the first study that examined the effectiveness of social-comparative feedback (Lewthwaite & Wulf, 2010b), using a balance task, participants were given bogus feedback about the "average" performance score on a given trial in addition to their own actual score. Specifically, in one group participants received feedback suggesting that their performance was better than average, whereas in another group the feedback led them to believe that they were performing worse than average. Participants who assumed their performance was above average demonstrated more effective learning, as determined by a delayed retention test without feedback. Participants who were given negative feedback showed learning that was similar to that of a control group without social-comparative feedback. Thus, motor learning was *enhanced* by the false positive feedback.

Positive social-comparative feedback has been found to increase learners' perceived competence (Ávila, Chiviawsky, Wulf, & Lewthwaite, 2012), increase their satisfaction with performance and motivation to learn (Wulf, Lewthwaite, & Hooyman, 2013), and reduce concerns and nervousness about performance and ability (Wulf, Chiviawsky, & Lewthwaite, 2012). In practical settings, providing learners, patients, or clients with false information would be ethically problematic. Their self-efficacy can be increased in other ways, some of which are discussed next. Creative instructors, teachers, or coaches will likely come up with more.

### *Perceptions of Task Difficulty*

There are surprisingly subtle, but effective, ways of enhancing performers' expectancies or alleviating their concerns in order to facilitate learning. In one study, older adults were asked to learn a novel and challenging balance task (Wulf, Chiviawsky, & Lewthwaite, 2012, experiment 2). Before the beginning of practice, the enhanced expectancy group was told, "Active people like you, with your experience, usually perform well on this task." This simple statement was sufficient to facilitate their learning relative to a control group. Also, the former group had increased self-efficacy. Thus, a general comment about a peer group's performance presumably made a task less daunting and alleviated concerns older adults may have had, with the result that learning was enhanced ([figure 10.2](#)).

Figure 10.2 Time in balance of the enhanced expectancy and control groups during the first and second half of practice, and on the retention test.



Data from Wulf, Chiviawsky, and Lewthwaite 2012.

Many tasks involve hitting a target (e.g., dart throwing, archery, pistol shooting, golf). Would making the target *look* larger or smaller by using optical illusions have an influence on the accuracy with which performers strike the target? If so, how would the apparent size of the target influence accuracy? One might think that a target that appears larger than it actually is would decrease the learner’s effort or concentration and may be less effective for performance or learning. However, if a larger-looking target increases the learner’s confidence in his or her ability to hit the target, compared with a smaller-looking target, it may actually have a beneficial effect. Witt, Linkenauger, and Proffitt (2012) first used optical illusions to make a golf hole on an artificial putting green appear larger or smaller by placing small or large circles around the hole, an effect called the Ebbinghaus illusion. The results showed that participants putted more successfully when the hole appeared larger than it was. In a follow-up study, Chauvel, Wulf, and Maquestiaux (2015) addressed the question whether practicing with visual illusions would not affect only performance but also learning. These authors used a delayed retention test during which the optical illusion was removed. In addition, they assessed participants’ self-efficacy as a function of the perceived target size. When the target appeared larger, self-efficacy was indeed higher than when it appeared smaller. In addition, the retention test results showed that the performance-enhancing effects of a larger-looking target were relatively permanent. Thus, when the target appeared larger, participants’ confidence in their ability to hit the target was higher and, as a consequence, learning was enhanced. These findings were replicated with 10-year-old children (Bahmani, Wulf, Ghadiri, & Karimi, 2017).

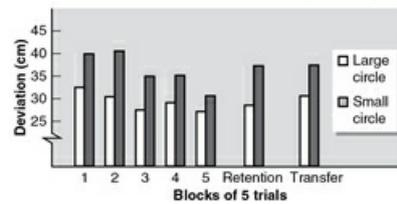
For practical purposes, creating optical illusions to make a target look larger may be somewhat cumbersome. However, there are other ways in which a coach or instructor can raise performers’ expectancies to facilitate learning. One way is related to how performance success is defined.

### *Definitions of Success*

If good performance is defined liberally by setting performance criteria that can be reached relatively easily, learners will feel more successful. Would those who experience greater success during practice learn more effectively? In a study by Palmer, Chiviawsky, and Wulf (2016) this was indeed the case. Using a golf-putting task, the researchers put two concentric circles around a target (2 cm in diameter) on a putting green, a smaller one with a 7 cm diameter and a larger one with a 14 cm diameter. One group of participants (nongolfers) was informed that putting within the smaller circle would constitute “good” golf putts, while another group was told that balls coming to rest in the larger circle would represent good performance ([figure 10.3](#)). The group for whom the large circle was identified putted more accurately in practice than did the other group (small circle). On a retention test and a transfer test with a greater target distance performed 24 h later, the circles were removed. The group whose “success” was defined by the larger circle putted significantly more accurately on both tests. Thus, the higher success rate experienced during practice had a positive impact on learning.



Figure 10.3 Deviations from the target in golf putting.



Data from Palmer, Chiviawowsky, and Wulf 2016.

Similar findings were obtained in a study by Chiviawowsky, Wulf, and Lewthwaite (2012), although in this study participants received feedback at their request. The task was a coincident-timing task and required participants to press a button coincident with the illumination of a target light. A group that was informed that errors within a very small bandwidth (4 ms) constituted good performance showed less effective learning than a group with a relatively large bandwidth (30 ms) or a control group that had not been given a criterion.

Another method of increasing confidence some athletes use in preparation for a competition is to start the warm-up with relative easy tasks on which errors are minimal. The confidence resulting from good performances helps them successfully perform subsequent tasks with higher levels of difficulty. For example, golfers often begin their preparations with short putts, followed by putts from increasing distances. Research findings have shown the effectiveness of this approach. Putting practice with increasing distances from the hole, sometimes called errorless practice, has been found to result in fewer putting errors than putting with increasing distances, which would be errorful practice (Maxwell, Masters, Kerr, & Weedon 2001).

Reasons for why feeling successful, or at least not unsuccessful, seems to be important for learning is discussed in more detail in chapter 12. Suffice it to say here that self-efficacy resulting from successful experience is important for memory consolidation. Trempe, Sabourin, and Proteau (2012) nicely demonstrated this effect in an experiment. Their study showed that for learning to be enhanced, it is sufficient for learners to *feel* successful during practice rather than be successful. The authors used an eye–hand coordination task. Different groups of participants were given a relatively easy or difficult goal, touching versus covering a target with a cursor, respectively. Even though movement accuracy during practice was actually similar for all groups, participants who experienced greater success (easy goal) demonstrated more effective performance on a delayed retention test.

### *Highlighting the Learnability of a Task*

Learners' conceptions of abilities—that is, whether they view them as reflecting a fixed capacity or as being a function of practice (Dweck, 1999)—have been shown not only to affect their motivation to practice but also to have a direct influence on motor performance and learning. Although most adults and likely some children already have certain dispositional conceptions of ability that they bring to the laboratory, playground, or baseball diamond, they can be influenced relatively easily by task instructions or feedback.

The benefits of instructions emphasizing the acquirability of a motor task were first demonstrated by Jourden et al. (1991). Participants who were informed that the task they were about to perform (a pursuit rotor task that involved tracking a moving cursor with a stylus) was “learnable” showed greater self-efficacy, positive affect, greater task interest, and greater improvement across trials than did participants who were told that the task measured a certain natural capacity. It is easy to see that learners, who believe that their performance is a reflection of an inherent ability, approach practice with apprehension, tend to be more nervous and concerned about their ability—conditions that are not ideal for learning (Wulf, Lewthwaite, & Hooyman, 2013). In contrast, if the acquirability of a task is pointed out to them, people are more likely to interpret the situation as an opportunity to learn and improve.

Conceptions of ability induced by instructions not only influence performance temporarily, they have more permanent effects, therefore enhancing learning. In one study that assessed learning by including a retention test, the learning of a balance task was enhanced by instructions that portrayed the task as an acquirable skill rather

than something that reflected an inherent balance ability (Wulf & Lewthwaite, 2009). Overall balance performance as well as automaticity in movement control, measured on the retention test, was enhanced in the acquirable skill group. A control group demonstrated similar learning as the inherent-ability group. These findings highlight the importance of stressing that errors are part of the learning process, thereby *alleviating* concerns that learners may have about their performance.

Similar learning differences were seen in children. Children aged 6 to 14 learned a throwing task more effectively when the instructions given to them before practice suggested that performance was a function of practice rather than the result of an inherent ability (Drews, Chiviacowsky, & Wulf, 2013). Children might be particularly susceptible to the influence of ability-related instructions or feedback. Even subtle differences in the wording of feedback have been shown to impact motor performance and learning in children (Chiviacowsky & Drews, 2014; Cimpian, Arce, Markman, & Dweck, 2007). For example, feedback such as “You are a great soccer player” or “You are a good drawer” promotes the view that motor abilities are inherent and fixed in nature. In contrast, feedback such as “Those kicks were very good” or “You did a good job drawing” suggests to people that their performance reflects their effort or experience. While learners might like both types of feedback similarly, differences in motivation, performance, and learning become obvious when the children make mistakes (e.g., Chiviacowsky & Drews, 2014). In the study by Cimpian et al., children who had been told that they were “good drawers” showed more negative self-evaluations and diminished motivation to continue drawing when they were led to believe that they made a mistake than did children who had been praised for “good job” they had done on their drawings.

The findings have important implications for applied settings. Teachers, coaches, occupational therapists, and others will likely see benefits in the performance and learning of their clients when they simply highlight the fact that a skill is learnable. Alleviating learners’ concerns about their performance or ability will reduce a detrimental self-focus and allow learners to focus on the task at hand.

## Providing Autonomy Support

Many studies have shown that giving the learner control over a certain aspect of the practice conditions (called self-controlled practice) enhances motor learning. These findings contrast with approaches that seem to be predominant in practical settings. Often instructors, coaches, or physical therapists prescribe the task they want a learner to practice, or the order of different practice tasks, they provide feedback about correct or incorrect aspects of the movement pattern, and they give demonstrations of the skill when they believe it is necessary or helpful. In this section, we review the evidence that learner control, with respect to various aspects of practice, positively affects learning relative to prescribed practice conditions. In more recent years, it has become increasingly clear that the choices learners are given do not have to be related to the task in order to be effective. Even choices that are *incidental* to the task, or instructions that suggest to learners that they have options, can benefit learning. These findings have shed a new light on the benefits of self-controlled practice. The overall picture that emerges is that practice conditions that provide *autonomy support* satisfy a basic psychological need (Deci & Ryan, 2000, 2008). Supporting learners’ need for autonomy in turn facilitates learning. Some of these findings are reviewed next.

### *Learner-Controlled Practice Conditions*

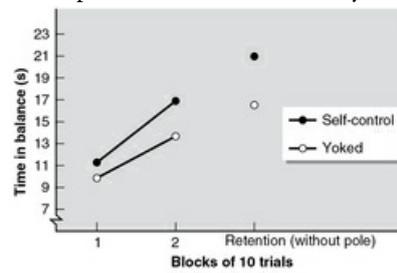
When learners are given the opportunity to decide when to receive feedback, use an assistive device, view a *demonstration* of the skill, decide in which order they want practice different tasks, or even how much to practice, learning benefits. Compared with control groups that are not given choices, self-control groups generally demonstrate superior learning (see Sanli, Patterson, Bray, & Lee, 2013; Wulf, 2007b, for reviews). It is typical for these studies to use a so-called *yoking* procedure, in which each participant in a self-control group is paired with another participant in a control group. Assume participants in a self-control condition are allowed to decide when they are given feedback. Each yoked control participant would receive feedback on the same trials as their counterpart in the self-control group. Because the frequency of feedback and the timing of its delivery are identical for both groups, any group differences that emerge on retention or transfer tests can be attributed to the fact that

one group had control over the feedback while the other group did not.

Janelle, Barba, Frehlich, Tennant, and Cauraugh (1997) were the first to demonstrate that self-controlled feedback enhanced movement form on a task that involved throwing with the nondominant arm. Other researchers have found similar learning advantages for throwing (e.g., Chiviakowsky, Wulf, Medeiros, Kaefer, & Tani, 2008), timing (e.g., Chen, Hendrick, & Lidor, 2002; Patterson & Carter, 2010), landing a virtual aircraft (Huet, Jacobs, Camachon, Goulon, & Montagne, 2009), and other tasks. The frequency of feedback requests is sometimes relatively low; for example, it was 11% in Janelle et al.'s study and 28% in Chiviakowsky et al.'s study. Thus, it appears that the feedback frequency is less important than the learner's opportunity to choose or not to choose feedback. It would also be difficult to see why learning advantages for self-controlled feedback occurred when the feedback frequency was almost 100% (Chen et al., 2002). This finding suggests that learners' need for autonomy plays an important role in this context.

Sometimes assistive devices (e.g., training wheels on a bicycle, balance poles, floatation devices), or physical support by another person, are used to aid in the process of learning motor skills. Instructors might be reluctant to leave the decision about whether or not the device should be used up to the learner. However, evidence suggests that learning is sped up when the learner is put in charge. In several studies, participants who were given control over the use of poles to assist with the learning of balance tasks outperformed those who had no control over the use of those devices (yoked conditions; e.g., Chiviakowsky, Wulf, Lewthwaite, & Campos, 2012; Hartman, 2007; Wulf & Toole, 1999). For example, in one study participants practiced a ski-simulator task and either did or did not have the opportunity to decide on which trials to use poles. The poles were placed on the floor to help them maintain their balance. Participants in the self-control group showed more effective task learning (measured by performance on a delayed retention test without the poles) than did their yoked counterparts. While those poles had previously been shown to facilitate the learning of that task (Wulf, Shea, & Whitacre, 1998), Hartman (2007) demonstrated that even a device that is in and of itself relatively *ineffective* can in fact be helpful if the learner has control over it. Hartman found in a pilot study that holding a balance pole horizontal provided no advantage for learning a stabilometer task, relative to balancing without the pole. However, despite the pole's ineffectiveness, learning was facilitated when participants could choose to use the pole on certain trials rather than being told when to use it ([figure 10.4](#)). In another study, participants with Parkinson's disease also showed enhanced balance learning when they had control over the use of the pole (Chiviakowsky et al., 2012).

Figure 10.4 Time in balance ( $\pm 3$  degrees from horizontal) for groups that were able to control the use of the balance pole (self-control) or not (yoked).



Some skills require learning the correct sequence of movements (e.g., manual gestures of sign language, typographical script, dance routines) or relatively complex movement patterns that involve whole-body coordination (e.g., basketball jump shot, skip on the uneven bars, hitting a golf ball). Reminders about the movement or sequence of movements are often necessary in those situations. They can be in the form of pictures or video demonstrations. Does it make a difference if the instructor decides when to provide reminders or if the learner is provided with them only at their request? Studies show that the answer is yes. In a study by Patterson and Lee (2010), participants were asked to learn symbols of a graffiti language. A group allowed to decide before a trial when to view the correct pairing of the English cue and respective symbol, as well as the viewing duration, outperformed a yoked control group. Also, the self-control group showed equivalent recall of the symbols as a group that was presented the pairings *after* the respective practice trials, and who therefore had the opportunity (and advantage) to engage in memory retrieval. Other studies have shown learning benefits when learners were able to request a video of a skilled model for shooting accuracy in basketball (Wulf, Raupach, & Pfeiffer, 2005) or movement quality in performing ballet positions (Lemos, Wulf, Lewthwaite, & Chiviacowsky, 2017).

Allowing learners to choose the extent of practice or the spacing of practice trials has also been found to lead to more effective learning of dart throwing and basketball skills than yoked control conditions (Post, Fairbrother, & Barros, 2011; Post, Fairbrother, Barros, & Kulpa, 2014). Finally, the way in which task instructions are worded—that is, whether the language is autonomy-supportive or controlling—has been shown to influence motor learning. Hooyman, Wulf, and Lewthwaite (2014) varied the way in which instructions for performing a modified cricket bowling action were presented. Instructions that used autonomy-supportive language, giving participants more choice, led to more effective learning than those that used controlling language, which offered little option for how to execute the bowling action.

### *Incidental Choices*

In the studies just reviewed, learners were given control over factors deemed relevant to task learning. The results have been interpreted almost invariably from a motivationally neutral information-processing perspective; it is assumed that learning advantages of learner- or self-controlled practice conditions are due to enhanced information processing (e.g., Carter, Carlsen, & Ste-Marie, 2014; Carter & Patterson, 2012; Carter & Ste-Marie, 2016; Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997; Wulf, Raupach, & Pfeiffer, 2005). While it is likely that task information is processed more effectively when the learner is in control, this effect most likely has a motivational basis (Grand, Bruzi, Dyke, Godwin, Leiker, Thompson, Buchanan, & Miller, 2015). Since 2015 researchers have examined how giving learners choices that are incidental (not directly relevant) to the task impacts learning (Lewthwaite, Chiviacowsky, Drews, & Wulf, 2015). It turns out that those choices also enhance learning, strongly suggesting that the root cause of the benefits of self-controlled practice is the satisfaction of learners' need for autonomy (see also Patall, Cooper, & Robinson, 2008).

Giving participants choices that are incidental to the motor task has been demonstrated to have positive effect on the learning of that task. In one experiment (Lewthwaite, et al., 2015, Experiment 1), allowing participants to choose the color of golf balls they were putting led to more effective task learning than a yoked condition. Giving participants a choice of ball color has also been found to increase the learning of a throwing task (Wulf, Chiviacowsky, & Cardozo, 2014). Even more compelling were findings showing that the learning of a balance

task was enhanced when learners were given a choice related to a task they would practice afterward, as well as when they were asked their opinion as to which of two pictures should be hung in the laboratory (Lewthwaite et al., 2015, experiment 2). Compared with a yoked group that was simply informed of the second task or the picture to be hung, the choice group demonstrated superior performance on the balance task on a delayed retention test.

Does the extent of learning depend on the type of choice? Would learning be enhanced even more if the choice were task-related rather than incidental to the task? This question was examined in a study by Wulf, Iwatsuki, Machin, Kellogg, Copeland, and Lewthwaite (2017). Participants were asked to learn a novel task, throwing a lasso. One group of learners was given a choice ostensibly irrelevant to the performance of this task, namely, choosing the color of a mat under a cone that served as the target. A second choice group was given a task-relevant choice. These participants were able to choose video demonstrations of the skill, which arguably provided visual and verbal information about the skill, throughout the practice phase. Participants in all groups, including a control group, were yoked to each other, so that all received the same mat color or saw the video demonstration, respectively, as chosen by their counterparts in the other groups. On a retention test, the two choice groups showed similar performances, and both outperformed the control group. The fact that task-relevant and task-irrelevant choices resulted in similar benefits for learning is consistent with the idea that the perception of autonomy impacts learners' motivational state and, consequently, their motor control and learning (see also chapter 12).

# Observational Learning

Learning from a model (*observational learning*) is a specific kind of perceptual learning. One important way to use modeling is to demonstrate the skill so that learners can observe the elements of the action directly. Another variant is to use video or photos of skilled performers. At a superficial level, these procedures seem to be the same, with the live or archived model providing information about the task to be learned and perhaps some essential details about technique. But, while these specific techniques may seem to have intuitive appeal, there is reason to doubt the learning benefit they provide (Druckman & Bjork, 1991). Nevertheless, there is mounting evidence that observation is an effective method for learning motor skills (see Ferrari, 1996; McCullagh & Weiss, 2001; Maslovat, Hayes, Horn, & Hodges, 2010; Scully & Newell, 1985, for reviews). In the following sections we discuss some of the important issues regarding observational learning.

People observe for different reasons. While one person may go to a concert solely to be entertained, another may be there to observe the musicians play, perhaps trying to pick up skills to practice later. An aspect of this latter situation—how and what information is learned from observation—is our interest in this section. Much of the early work credited Bandura with the theoretical framework for the development of this research (see Adams, 1987). However, some argue that Bandura's theory, which was developed to explain the acquisition of *social* behaviors, is not appropriate for understanding the learning of motor skills (e.g., Maslovat et al., 2010), and recent advances in research specifically involving motor skill observational learning have provided new insights. Research on perceptual learning (see previous section) provides evidence that acquisition of environmental regularities is an important aspect of skilled performance. And the discovery of the mirror neuron system in the brain has elicited much excitement and research regarding the possibility that specific neural mechanisms provide the foundation for learning through observation (Rizzolatti & Craighero, 2004; Rizzolatti & Fabbri-Destro, 2010). These developments in research and theory have resulted in a rapid increase in the amount of research conducted on observational learning in recent years.

## What Is Learned?

One of the earliest studies on modeling effects showed quite clearly that movement *strategies* could be learned by observation. The task used by Martens, Burwitz, and Zuckerman (1976) involved trying to move a ball rolling on top of two rods by varying the distance between the rods. Two strategies for success were modeled. The “creeping” strategy was a conservative approach to the task whereby the distance between the rods was adjusted slowly in order to move the ball. This strategy typically produces consistent but only moderately successful results. In contrast, the “ballistic” strategy involved a rapid and more violent adjustment of the rods. This strategy typically produces quite variable levels of achievement; yet when scores are high, they can be very high. When given the opportunity to perform the task, observers of these two different modeling strategies tended to imitate deliberately the actions they had observed. Similar beneficial effects for learning a three-ball juggling task by imitating the actions of the model were reported by Hayes, Ashford, and Bennett (2008).

Information that can be represented spatially can be modeled quite readily, especially if the spatial attributes are presented in a static, discrete manner. For example, the acquisition of sign language is a frequently used task for observational learning because the actions are discrete and also associated with a verbal label (e.g., Carroll & Bandura, 1990; Steffens, 2007; Weeks, Hall, & Anderson, 1996). Spatial sequences represent another type of task that appears to be readily learned through demonstration (e.g., Heyes & Foster, 2002; Kelly, Burton, Riedel, & Lynch, 2003). Modeling of dynamic skills is also effective. For example, a study of females with no prior dance training revealed more benefit after participants watched videotaped ballet sequences than after they looked at a series of still photographs of the dance (Gray, Neisser, Shapiro, & Kouns, 1991). The investigators concluded that the modeled information contributed to learning the qualitative features of the ballet routine. These conclusions are supported by experiments that modeled skiing actions (Whiting, Bijlard, & den Brinker, 1987) and gymnastics rope skills (Magill & Schoenfelder-Zohdi, 1996). In one practical study in this area, medical students performed surgical techniques more accurately after watching a skilled surgeon perform the surgery, compared to

students without the benefit of observation (Custers, Regehr, McCulloch, Peniston, & Reznick, 1999). This finding suggests that even very fine spatial information can be successfully learned through demonstration.

Watching another's motor behavior can have a more subtle influence on the observer, sometimes perhaps even without the observer's awareness. Participants in a study by Mattar and Gribble (2005) watched a video of a model who learned to manipulate a robot arm in an environment where the movement path was deflected away from the target by an invisible force field provided by a robot. Observers who watched the model perform in the same force field environment as they would later perform the task were more effective than no-observation controls, even when attention was engaged in a secondary task.

Timing is another type of information that can be successfully learned through observation, and various methods for presenting temporal information have been used (Adams, 1986; Doody, Bird, & Ross, 1985; McCullagh & Little, 1989; Meegan, Aslin, & Jacobs, 2000; Zelaznik, Shapiro, & Newell, 1978; Zelaznik & Spring, 1976). For example, Zelaznik and colleagues (1978) provided one group of participants with the recorded sounds of another participant making a correct timing movement prior to any practice. After the presentation of the modeled information, this group performed the timed movement more accurately than another group who had not listened to the sounds. The "listening group" could even improve slightly in the task without any knowledge of results. The interpretation of these findings is that the listening experience provided the participants with a reference of correctness, and the reference allowed an evaluation of the auditory feedback produced by the movement and subsequent adjustments on the upcoming trials (see also Blandin & Proteau, 2000; Wrisberg & Schmidt, 1975). Timing information can also be successfully modeled when auditory and visual information is presented in a spatial timing task (e.g., Vogt, 1995).

## Model Skill Level

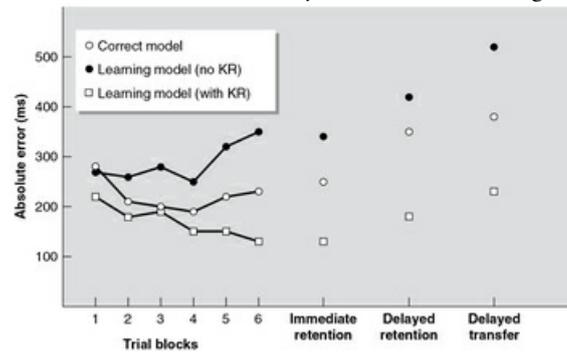
One of the implicit assumptions regarding the use of videos that provide sport instruction is that highly skilled performers are more effective than unskilled models. This assumption may be true, depending on how the unskilled model demonstrates the task to be learned. The evidence suggests that the assumption is not true when people observe unskilled models *learn* a motor task. For instance, Pollock and Lee (1992) studied the effectiveness of demonstrations of a computer video game to groups of individuals who had had no prior practice on the task. Participants either watched an expert perform the task or watched a novice who was learning the task for the first time (*a learning model*). After a series of modeling trials, the observers in both groups showed a substantial benefit of having watched their respective models (as compared to a no-model control group). However, there was no advantage to having viewed the expert model compared to the learning model. Similar findings were reported by McCullagh and Meyer (1997) using a weightlifting task.

A more surprising finding in this research is that, under some circumstances, the provision of a learning model can result in *stronger* observational learning than an expert model. This research area was initiated by Adams (1986), who used learning models to demonstrate the performance of a manual timing task. Adams found that observation alone was insufficient for learning this task. However, considerable learning was seen if the model's feedback from the experimenter (termed knowledge of results, or KR) was also presented to the observer (Blandin, Lhuisset, & Proteau, 1999). In this dynamic observation environment, the observer can gain information (a) from the model about the movement performed (both visual and auditory), (b) from the augmented feedback presented to the model (as KR), and (c) from seeing the success of the model's attempt to use that feedback on the next performance of the task. In this way, the observer benefits not only from "observing" the performance but also from observing the processing operations of the model in the attempt to improve performance, which becomes increasingly important as the difficulty of the task is elevated (Laguna, 2008).

The research method used by Adams (1986) was extended by McCullagh and Caird (1990), who directly compared the effectiveness of learning models and expert models on Adams' task. Three observation groups were compared. One group had repeated exposures to a tape of a perfect execution of the timing goal. Two other groups watched a tape of a model who was learning the task; one group also received the model's KR and one did not. As illustrated in [figure 10.5](#), the largest effects were found for those who observed the learning model and also

received the model's KR (open squares). These participants improved their performance consistently over the acquisition period, in the absence of any KR about their own performance, and both retained their performance levels and transferred to a novel timing goal better than either of the other observation groups.

Figure 10.5 Effects of model skill level and availability of model's knowledge of results (KR) on learning.



Adapted, by permission, from P. McCullagh and J.K. Caird, 1990, "Correct and learning models and the use of model knowledge of results in the acquisition and retention of a motor skill," *Journal of Human Movement Studies* 18: 107-116. By permission of P. McCullagh.

These findings suggest an important application to modeling real-world tasks. Novice athletes are likely to gain relatively little insight from watching experts unless they are specifically cued regarding where to watch and what to look for (Janelle, Champenoy, Coombes, & Mousseau, 2003). While viewing professional golf on television, for example, we likely get the greatest *learning* benefit when experts make mistakes. The mistakes occur so infrequently that the commentators usually replay the action and point out exactly what went wrong—what movement error resulted in the flubbed shot. In other words, the “model” demonstrated an incorrect action, which was accompanied by KR that identified the error. Thus, the issue of essential importance in this research may not be the skill level of the model at all, but rather about what type of information is being demonstrated—errors or perfect templates of an action. The research findings suggest that we learn more from observing mistakes than we do from correct performances.

## Scheduling Observations

Although this part of the chapter is about “off-task” practice considerations, perhaps the most successful strategy in the use of models is to intersperse the demonstrated information with physical practice trials performed by the observer. Similar to the conclusion from the previous discussion, this scheduling of observation and physical practice has the advantage of engaging the learner more in the active problem-solving process of learning than would be the case if all demonstrations were presented prior to physical practice. This scheduling also has the advantage of providing the performer with some rest between physical trials, which, as we discuss in a later section, is also important for learning. The literature is quite consistent in showing that interspersing physical and modeled trials results in better learning (retention and transfer) than a single block of observations prior to physical practice of the task (Deakin & Proteau, 2000; Granados & Wulf, 2007; Shea, Wulf, & Whitacre, 1999; Shea, Wright, Wulf, & Whitacre, 2000; Weeks & Anderson, 2000). In this sense, interleaving information gained from off-task observation with on-task practice appears to optimize the benefits gained from observations.

## Mental Practice

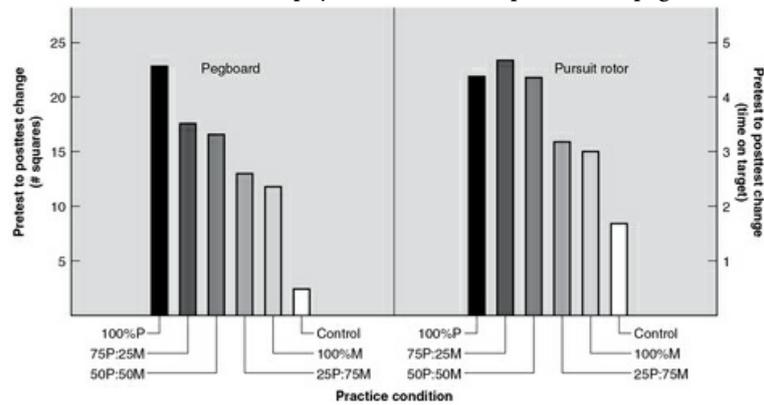
One of the most frequently used and advocated off-task methods to promote learning is *mental* practice, in which the performance of a task is mentally rehearsed, often using imagery techniques, in the absence of overt physical practice. Experimental assessment of mental practice effects usually requires several different groups of participants, at a minimum (Goginsky & Collins, 1996): All participants are given a pretest on a task to be learned, followed by the experimental manipulation, then a posttest on the learning task. The mental practice manipulation often entails covert rehearsal of the task, sometimes involving strategies such as imagery. In this case, however, the learning that can be attributed only to mental practice effects cannot be inferred just from a retention test. Rather, one must demonstrate that performance on the posttest exceeded performance in a control group that did not perform intervening practice or that performed practice on an unrelated task. In addition, mental practice is usually compared to a third condition in which a group *physically* practices the task for the same amount of time as the mental practice group. Some experiments also include *combination* conditions with alternation between trials of mental and physical practice. Of course, many experiments use other variations of these mental practice manipulations (see Feltz & Landers, 1983; Feltz, Landers, & Becker, 1988; Lotze & Halsband, 2006, for reviews).

### Is Mental Practice as Effective as Physical Practice?

A nice demonstration of all these various practice conditions and their effects was provided in a complex study by Hird, Landers, Thomas, and Horan (1991). Twelve groups of participants participated in the experiment. Six groups were asked to learn a pegboard task, inserting pegs of different colors and shapes as rapidly as possible into squares cut in a board. The other six groups performed the pursuit rotor task. For each task, participants performed a pretest, seven sessions of training (on separate days), and a posttest. During the training sessions, the 100% physical practice group performed 8 trials on the task while the 100% mental practice group covertly practiced the task for the same amount of time. Three other groups involved combinations of practice, consisting of 2, 4, or 6 trials of physical practice combined with 6, 4, or 2 trials of mental practice (i.e., 75% physical practice [P], 25% mental practice [M]; 50P:50M; and 25P:75M groups). The control group performed an unrelated task (stabilometer) for the same amount of time during these training sessions.

The difference in performance between the pretest and posttest for each group in Hird and colleagues' study is presented in [figure 10.6](#).<sup>1</sup> The sets of findings for the two tasks are remarkably similar. The groups given mental practice (100%M) were more effective than the no-practice (control) groups, but not nearly as effective as the groups given the same amount of physical practice (100%P). In addition, the results for the combination groups showed that learning was enhanced with higher proportions of the training trials spent in physical, compared to mental, practice (e.g., compare the 75P:25M groups with the 25P:75M groups in [figure 10.6](#)).

Figure 10.6 Effects of various combinations of physical and mental practice on pegboard and pursuit rotor tasks.



Adapted, by permission, from J.S. Hird et al., 1991, "Physical practice is superior to mental practice in enhancing cognitive and motor task performance," *Journal of Sport and Exercise Psychology* 13(3): 286-287.

The findings of Hird and colleagues (1991) have been replicated (Allami, Paulignan, Brovelli, & Boussaoud, 2008) and concur with the reviews of the mental practice literature conducted by Feltz and Landers (1983; Feltz et al., 1988; Lotze & Halsband, 2006). The results suggest that *whenever possible*, physical practice is preferable to mental practice for learning. However, when physically practicing a task is not possible, as when an individual is away from a clinical rehabilitation setting, then mental rehearsal is an effective method for augmenting learning (Dickstein & Deutsch, 2007; Mulder 2007).

## Hypotheses About Mental Practice Effects

Why then, is mental practice effective for learning a motor skill? Certainly, one of the components of mental practice involves learning the *cognitive elements* in the task; that is, learning what to do (Heuer, 1985). Given the requirement of rehearsing mentally, the learner can think about what kinds of things could be tried, can predict the consequences of each action to some extent on the basis of previous experiences with similar skills, and can perhaps rule out inappropriate courses of action. This view suggests that not very much *motor* learning is happening in mental practice, the majority being the rapid learning associated with the cognitive elements of the task. Such a view fits well with data from Minas (1978, 1980), who used a serial throwing task in which participants had to throw balls of different weights and textures into the proper bins. The main finding was that mental practice contributed to the learning of the sequence (the cognitive element) but did not contribute very much to learning the particular throwing actions (the motor elements).

Another view, however, suggests that there is more to mental practice than the learning of the cognitive elements in a task. Some suggest that the motor programs for the movements are actually being run off during mental practice but that the learner simply turns down the "gain" of the program so that the muscular contractions are not visible. Research on so-called *implicit speech*, in which participants are told to imagine speaking a given sentence, shows patterns of electromyographic activity from the vocal musculature that resemble the patterns evoked during actual speech. One possibility is that very small forces (not sufficient to cause movements) are produced and the performer receives Golgi tendon organ feedback about them (see chapter 5), as the Golgi tendon organs are extremely sensitive to small loads. Another possibility is that the "movements" are sensed via feedforward and corollary discharge (i.e., "internal feedback"), generated when the motor programs are run off (see chapter 5). Yet another possibility discussed earlier in this chapter is that *planning* a movement (which should be part of mental practice) is, in itself, beneficial to learning.

Most recent hypotheses about the effects of mental practice have focused on the specific role of *imagery*. Many researchers now agree that imagined actions share similarities with the actual movements being imaged. For example, performance times are similar for imaged and physically performed trials of the Fitts reciprocal tapping tasks with different indexes of difficulty (Cerritelli, Maruff, Wilson, & Currie, 2000; Decety & Jeannerod, 1996; Kohl & Fisicaro, 1995; Stevens, 2005). Similar effects are also observed in grasping tasks (Frak, Paulignan, &

Jeannerod, 2001) and when a mass either is loaded or is imagined being loaded to a limb (Papaxanthis, Schieppati, Gentili, & Pozzo, 2002). Studies involving brain mapping techniques (see chapter 2) also point to similar activation regions in the brain when movements are produced and imagined (Jeannerod, 2001; Jeannerod & Frak, 1999). Together with observations that apraxia patients sometimes fail to inhibit imagined movements (without awareness; Schwoebel, Boronat, & Branch Coslett, 2002), the findings suggest that imagery is a process by which actions are programmed as in normal movements but are *inhibited* from being executed. According to this view, at least some learning can be attributed solely to the motor programming process, in the absence of movement execution.

# Distribution of Practice

Our discussion of on-task conditions of practice begins with one of the variables that instructors and therapists have under their control: the scheduling of periods of *work* (i.e., time spent in actual practice) and *rest* (i.e., time not practicing the task). This scheduling can be considered within the constraints of a short time frame, such as the amount of work and rest during a 45 min therapy session. Or the scheduling may be considered in terms of a longer time scale, as when one chooses the length and frequency of sessions per week. The question of importance concerns whether or not the frequency and length of rest periods have an effect on learning the skill being practiced in the work periods. What is the best way to distribute the time spent in work versus the time spent resting—or simply, what is the best *practice distribution*?

## Defining “Massed” and “Distributed” Practice

Research on practice-distribution effects has frequently used the terms *massed practice* and *distributed practice*. In one sense, “massing” means to put things together—in this case, running work periods very close together with either no rest at all or very brief rest intervals between periods of work. By default, distributing practice means *spacing* these periods of work apart with longer intervals of rest. The labels are not truly satisfactory, however, because researchers often use these terms to describe the two extremes of practice distributions within a particular experiment, and because many experimenters use more than two distribution conditions (e.g., Ammons, 1950; Bourne & Archer, 1956). Thus, these terms must be considered relative to the context of other conditions within any particular experiment and relative to the context of other experiments.

The vast majority of the research on distribution-of-practice effects has been conducted using continuous tasks, for which the work period might be 20 or 30 s in duration. The task most commonly used for this research was the pursuit rotor tracking task (see [figure 2.5a](#)). However, tasks such as mirror tracing, the Bachman ladder, and inverted-alphabet printing were also popular in the early research studies of this area. We first discuss the effects of practice distribution using continuous tasks. Only a few studies have been done using discrete tasks; however, the findings are quite different from those of studies using continuous tasks and are presented later.

## Distribution-of-Practice Effects on Performance

Many experiments were done in the 1940s and 1950s on practice-distribution effects (see Donovan & Radosevich, 1999; Lee & Genovese, 1988, for reviews). Even though these experiments involved wide differences in methods (such as the length of work and rest periods, the number of trials), the results are remarkably similar. Put simply, the findings converge on a very straightforward statement about the effect on performance: *Given constant periods of work, short rest periods degrade performance relative to performance with longer rest periods.*

Findings from a study by Bourne and Archer (1956) are typical of the performance effects seen in experiments on practice distribution. The task was pursuit rotor tracking. Five different groups of participants were compared; all groups had work periods of 30 s. In one group (the 0 s rest group), participants practiced continuously for 21 trials, with no rest at all. For the other four groups, a period of rest was interspersed between each work period. One group had rest periods of 15 s, and the other three groups had rest periods of 30, 45, or 60 s.

Bourne and Archer found that longer rest periods resulted in more effective performances. Many other examples of effects like these have been documented, and reviews by McGeoch and Irion (1952), Bilodeau and Bilodeau (1961), Lee and Genovese (1988), and Donovan and Radosevich (1999) describe details of this literature.

## Distribution-of-Practice Effects on Learning

For tasks such as the pursuit rotor, practice with little or no rest would likely cause muscular fatigue to develop;

this fatigue could be expected to depress performance. Thus, because at least part of the decrement in performance displayed by these groups was due to temporary fatigue, not all of the performance depression could be attributed to differences in the relatively permanent development of skill. So, how much was due to learning?

To assess this issue, Bourne and Archer (1956) gave all of their participants a 5 min rest period following the last acquisition trial. After this rest period, participants performed a common transfer test in which all groups were shifted to a massed schedule—all trials were performed with 0 s rest between 30 s work periods. The rationale was that if muscular fatigue was responsible for *all* of the differences between groups during the acquisition trials, then the groups should be similar in performance after the dissipation of the fatigue. This was not the case.

Several items in these transfer data are noteworthy. The most important is that substantial differences were maintained between the groups after the rest period, with initial transfer performance being increasingly more skilled for groups that had longer periods of rest between work periods during the acquisition trials. This finding suggests that the practice distribution had a relatively permanent effect, which is supported by many other studies in the literature (Lee & Genovese, 1988).

Another item worth noting in these data is that the differences between the groups on the first transfer trial (trial 22) are smaller than the differences between groups on the last acquisition trial (trial 21). Thus, some of the practice-distribution effect seen in the acquisition data was due to the temporary, detrimental influence of fatigue. Still, the differences due to changes brought about by learning remained large on the transfer trials. The last item to notice is that massing the transfer trials also had a depressing effect on performance. However, even after 9 transfer trials with no rest (i.e., on trial 30), the groups that had initially practiced with some rest between trials still outperformed the group that had practiced with no rest.

We have used the Bourne and Archer (1956) study to illustrate the effects of practice distribution on performance and learning. It is a particularly good example of this effect because more than two distribution groups were used and because a transfer design was used to separate the temporary from the permanent effects of the practice variable. However, several conclusions drawn from this study require further discussion.

### *Length of the Retention Interval*

One complicating factor about the Bourne and Archer experiment is that a 5 min rest period following continuous practice may not have been long enough to allow the temporary influence of muscular fatigue on performance to dissipate (Ammons, 1988; Lintern, 1988). Thus, the transfer trials may have been influenced by the same temporary effects that influenced acquisition performance (e.g., fatigue). Several studies have addressed this issue using longer rest intervals following practice (e.g., one day in Adams, 1952; 10 weeks in Reynolds & Bilodeau, 1952) and have shown that the learning effect remained even when these temporary effects had surely dissipated. These findings support the conclusion about the learning difference from the Bourne and Archer study.

### *Do the Learning Effects “Wash Out”?*

The Bourne and Archer data show that performance differences in transfer began to converge by trial 30 (after 9 transfer trials). The convergence of effects in transfer has been argued by some to cast doubt on the “relative permanency” of the learning effect. An important study by Adams and Reynolds (1954) further calls this issue into question. In this study, distributed practice was defined as 30 s of work with 30 s rest. Massed practice involved the same trial duration but with only 5 s of rest. One group received 40 trials under distributed conditions. Four more groups received initial practice for 5, 10, 15, or 20 trials, respectively, under massed conditions; they then rested for 10 min, and finally transferred to the distributed-practice condition for the remainder of the 40 practice trials. Adams and Reynolds found that when the various massed-practice groups were shifted to distributed practice, they caught up (though not entirely) within a few trials to the level of performance of the group that had practiced entirely under distributed-practice conditions. A small flaw in the design, however, makes these effects difficult to interpret. The problem is that the groups that transferred to distributed-practice conditions received the benefit of a 10 min rest. The distributed group, which may have experienced some

temporary fatigue effects, did not have such a rest. Thus, it is difficult to know whether or not the differences observed were temporary or permanent.

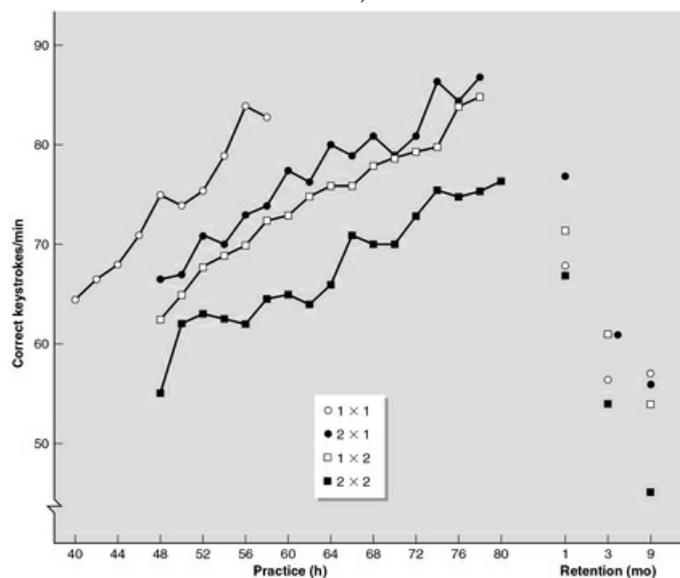
A clever design by Ammons (1950) helps to clarify this issue. Groups received rest periods that ranged from 0 s and 20 s to up to 12 min between each 20 s trial on the pursuit rotor task. One group even had *24 h* between each of the 36 practice trials. A 20 min rest period followed the 36th practice trial, after which participants performed an additional 36 transfer trials with no rest between trials (many more transfer trials than had been used by Bourne & Archer [1956]). By the end of this transfer period, only small differences remained between the groups. However, Ammons (1950) asked participants to return to the lab for *another* set of transfer trials one day later. The differences that had been seen on the first transfer test—and apparently washed out by the transfer trials—were “restored” after this additional rest period. These data are strong indicators that practice distribution has large effects on temporary performance levels *and* relatively permanent influences on learning.

### *Distributing Practice Over a Longer Time Scale*

Perhaps of more direct significance to instructors and therapists are the effects of practice distribution when practice takes place on a much longer time scale. A few such studies have been performed, and the results are generally similar to those of the studies done in a single session. In a very early investigation of this type, right-handed participants were asked to throw javelins with their left arm (Murphy, 1916). All participants practiced on 34 separate days. Massed-practice participants performed on consecutive days (Monday to Friday) for 7 weeks. The distributed group practiced three times per week for 12 weeks. Results at the end of the 34th day of practice and on a retention test performed three months later showed both performance and learning benefits for the distributed group.

Similar findings were reported by Baddeley and Longman (1978) for postal workers who were training to use a keyboard. In this study, separate groups of postal workers trained for 60 to 80 h using one of four schedules: Work periods were conducted either once or twice per day, and the duration of each work period was 1 or 2 h. The data for the practice period and for retention tests performed one, three, and nine months later showed that the condition that massed the practice the most (2 x 2) resulted in the lowest performance and learning ([figure 10.7](#)). Although the other three groups did not differ in these retention tests, the effects of the “most distributed” group (1 x 1) are likely diminished because practice for this group was stopped after a total accumulation of 60 h, as compared to the 80 h of practice for the other three groups. These data appear to suggest that there is some generalizability of the results obtained in experiments of relatively short duration to studies involving practice and retention over much longer periods of time (see also Shea, Lai, Black, & Park, 2001).

Figure 10.7 Training postal workers to use a keyboard under different practice-distribution schedules (1 x 1 refers to sessions conducted once per day of 1 h duration each; 2 x 2 refers to two sessions per day of 2 h duration each, etc.).



Data from Baddeley and Longman 1978.

### Total Practice Time

From the previous sections, it would appear that it is not beneficial for learning to mass trials in a practice session. But there is another important variable that coexists with massing—the total *time* involved in practice. Recall that in the experiments presented so far, the number of practice trials was held constant; and because the amount of time between practice trials was different for the massed and distributed conditions, the overall practice time was allowed to vary. That is, a group receiving massed practice will have a shorter total practice period than will an equivalent group with distributed practice.

Consider the Baddeley and Longman (1978) study just described. Although the group that practiced for 2 h per session twice per day (2 x 2) showed the poorest acquisition and retention performance, their practice period was completed in one-half the time used by two groups (1 x 2 and 2 x 1) and one-quarter of the time used by the 1 x 1 group. Additional training for this 2 x 2 group would likely have resulted in improved performance and learning.

The issue of practice distribution and total practice time involves a *trade-off*. Distributed practice results in the most learning per time in training but requires the most total time to complete. Massed practice results in reduced benefits per time in training but requires the least total time. Thus, what is most *effective* for learning may not always be the most *efficient*, at least in terms of time required to optimize learning.

### Safety Issues

Finally, it should be clear that massing has strong effects on performance of many tasks and that the risks of injury in dangerous tasks are likely to increase with massed practice. The laboratory tasks described here are not particularly dangerous, but many tasks used in sport (e.g., giant swings on the horizontal bar) and industry (e.g., work with a hydraulic paper cutter) entail considerably more opportunity for serious injury if errors are made. And most certainly for people in rehabilitation, whose motor coordination has already been affected, the risk of injury is of vital concern to the therapist. Thus, caution should be used in designing training regimens in situations in which factors such as fatigue could put the learner at risk.

### Discrete Tasks

The amount of evidence about discrete tasks is far less than for continuous tasks. Carron (1967, 1969) used a peg-turn task in which the participant moved 44 cm from a key to grasp a peg in a hole, turned the peg end-for-end to reinsert it into the hole, and then returned to the key again as quickly as possible. This movement was discrete and required a movement time (MT) of from 1,300 to 1,700 ms, depending on the level of skill of the performers. Carron had participants learn this task under two conditions: distributed (the amount of rest between trials was 5 s) and massed (the amount of rest between trials was only 300 ms, with a 5 s rest every 10 trials). Carron found no effect of the massing conditions on performance of the task while the massing was present. When he tested the participants 48 h later as a measure of learning, he found that the participants in the massed condition actually performed slightly faster than the participants in the distributed condition (1,430 vs. 1,510 ms), but it is probably more reasonable to say there were no real differences. For this discrete task, massing appeared to be neither a performance variable nor a learning variable, contrary to the rather strong effects of massing found for continuous tasks.

Lee and Genovese (1989) investigated this apparent continuous–discrete difference directly, in parallel experiments employing very similar timing tasks. For the continuous task, there was a tendency for participants in the distributed conditions in acquisition to perform more effectively than those in the massed conditions. This effect carried over into the delayed (seven days) transfer test, so that practice under distributed conditions in acquisition resulted in more learning, regardless of whether the transfer-test conditions were distributed or massed. This was essentially the same as had been found with the other continuous tasks (see previous section). However, for the discrete task, there was a slight tendency for the massed condition to be more effective in acquisition. In a delayed transfer test performed under massed conditions, there was an advantage to the group that had massed practice in acquisition compared to distributed practice. This provides at least one example indicating that massed practice can be more effective for learning than distributed practice.

A different interpretation of the distribution-of-practice effect can be made when considered over a longer-term time scale. For example, in a golf putting study by Dail and Christina (2004), novice participants performed 240 practice putts of 3.7 m distance. Participants in the massed group performed all of their trials in one session, whereas the distributed group practiced 60 trials on each of four consecutive days. All participants returned either 1, 7, or 28 days later for retention tests. The findings from the Dail and Christina study revealed small but consistent advantages for distributed practice by about halfway through the practice trials. More importantly, these performance advantages were maintained on each of the retention tests, conducted up to one month later (see also Shea, Lai, Black, & Park, 2000, experiment 2). Thus, it would appear that the effects of distributed practice on performance and learning in continuous and discrete tasks might have more similarities than previously thought.

## Variability of Practice

Another factor that has been shown to affect learning is the amount of *variability* in a practice sequence. In one sense, this is obvious. Many tasks have inherent variability, such as fielding ground balls in baseball or steering a car down an unfamiliar road (so-called *open skills*; see chapter 2). An important part of learning such tasks is acquiring the capability to cope with novel situations; practicing under constant (unvarying) situations would probably not be appropriate. But in another sense, the effect of *variable practice* is not so obvious, especially when the task involves *closed skills*, for which the environmental conditions are always similar (e.g., archery, bowling). Here, because the criterion task to be learned is always performed under the same environmental conditions, it would seem that practice under these exact conditions would be most effective for learning. Yet the evidence suggests that varied practice may be important in closed tasks as well.

Much of the research on variability of practice has been conducted to test certain predictions of *schema theory* (Schmidt, 1975b; see chapter 12). One prediction was that transfer to novel tasks would be enhanced after practice in variable, as compared to constant, practice conditions. We discuss only a few of these studies; reviews of many more of these experiments are available (Lee, Magill, & Weeks, 1985; Shapiro & Schmidt, 1982; Van Rossum, 1990).

### Variability-of-Practice Effects in Retention

One way to obtain an indication of the effect of practice variability is to assess retention performance after a period of time following the acquisition session (see chapter 9). A few experimenters have done this by comparing the relative impacts of constant and varied practice on retention of the tasks that were practiced. There is a design complication with this type of study, however, as participants in the different groups practice different tasks; thus what has been practiced and what is assessed in retention cannot be equated. But this does not pose a problem for results such as those we see in studies conducted by Shea and Kohl (1990, 1991).

Participants in the Shea and Kohl experiments learned to generate a goal force by squeezing a handgrip that was connected to a force transducer. In one experiment (Shea & Kohl, 1991, experiment 1), participants performed 100 trials to acquire a criterion force of 150 N. One group received only these acquisition trials. Another group (“criterion + variable”) received the same number of acquisition trials on the criterion task but, in addition, practiced goal forces that were  $\pm 25$  or  $\pm 50$  N relative to the criterion task (i.e., 100, 125, 175, and 200 N). Notice, however, that this variable-practice group not only had the same amount of specific practice as the criterion group, but also practiced at tasks that surrounded the criterion task—which confounds the role of the variable practice with the amount of additional practice. So, Shea and Kohl also included a third group of participants (“criterion + criterion”) that practiced the criterion task, as well as performing additional practice trials on the criterion task, so that the total number of practice trials was equal to the total practiced by the variable group.

The criterion + variable practice group performed less accurately on the criterion task throughout most of the acquisition period in comparison to the other two groups. However, after a rest period of no practice, participants in the criterion + variable practice group performed *more* accurately in a retention test on the criterion task than both the criterion-only group and the criterion + criterion group. These findings indicate that practice at tasks that were similar to (and that “surrounded”) the criterion task actually *facilitated* its retention.

### Variability-of-Practice Effects in Transfer

In one of the first studies investigating practice variability, McCracken and Stelmach (1977) had participants move their right arm from a starting key to knock over a barrier, with a 200 ms goal MT from initiation to barrier contact. The distances to the barrier could be changed in different conditions (15, 35, 60, and 65 cm), with a constant 200 ms goal in the practice phase. [Table 10.1](#) presents the details of the experimental design. A Constant group was actually made up of four subgroups, each of which had practice at only one of the barrier distances for

300 trials. The Variable group, on the other hand, had the same number of trials as the Constant group (i.e., 300), but these trials were varied in that all four barrier distances were practiced in a random order (75 trials of each).<sup>2</sup>

**Table 10.1 Experimental Design for an Experiment on Variability in Practice**

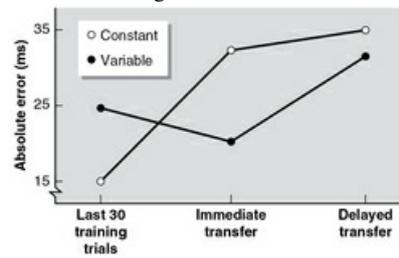
Group	ORIGINAL PRACTICE	TRANSFER-TEST PHASE	
	300 Trials Day 1	Immediate Day 1	Delayed Day 2
<b>CONSTANT</b>			
Subgroup a	15 cm only	50 cm	50 cm
Subgroup b	35 cm only	50 cm	50 cm
Subgroup c	60 cm only	50 cm	50 cm
Subgroup d	65 cm only	50 cm	50 cm
Variable	15, 35, 60, 65 cm	50 cm	50 cm

Adapted from McCracken and Stelmach 1972.

In a transfer-test phase, the two groups performed a *novel* (50 cm) distance, both immediately after training and after a two-day interval. With this design the authors evaluated the effect of variable versus constant practice on the performance of a variation that had never been performed previously. This transfer design addresses an effect of learning quite different from that studied in the retention design by Shea and Kohl (1991) discussed in the preceding section. In that research, Shea and Kohl assessed how well one *common* task, practiced by all the groups, was *retained* as a function of the other tasks that had also been practiced. In the McCracken and Stelmach study, the primary research interest was the effect of varied versus constant practice on the capability to perform a *novel task*.

The results are shown in [figure 10.8](#), where the absolute errors are plotted for the trials at the end of the acquisition phase, as well as for the trials on the two transfer-test phases. In the original-practice phase, the Constant group had less absolute error than the Variable group. This finding is similar to the results shown by Shea and Kohl. The critical contrasts, however, are in the transfer-test phases, when the task was novel for both groups. In immediate transfer, the order of the groups was reversed, with the Variable group now having less absolute error than the Constant group. This trend persisted into delayed transfer, 48 h later, but with the difference between groups being considerably smaller. Thus, it appeared that variability in practice (during the original-practice phase) allowed the participants to learn the task more effectively, permitting them to perform a new version of it on the transfer phase with less error than the Constant group (see also Wrisberg & Ragsdale, 1979). Variable practice seemed to be important in generating a capacity to perform a novel version of this task. But this novel task (50 cm) was clearly within the original range of experience of the Variable group (i.e., from 15 to 65 cm), and one could argue that the Variable group had more practice than the Constant group at tasks closer to the transfer task. Would such effects also be seen if the novel transfer task was *outside* the range of previous experience?

Figure 10.8 Performance in a ballistic-timing task as a function of variability in practice conditions.



Catalano and Kleiner (1984) used a timing task in which the participant was to press a button when a moving pattern of lights arrived at a coincidence point. Using a design much like that of McCracken and Stelmach (1977), they had a Variable group practice at speeds of 5, 7, 9, and 11 mph; a Constant group (with four subgroups) practiced at only one of these speeds. Then, on a subsequent transfer test, all participants transferred to four *novel* light speeds that were outside the range of previous experience (i.e., 1, 3, 13, and 15 mph). The absolute errors were smaller for the Variable group than for the Constant group, and the differences were present even when the “distance” from the range of previous experience was quite large. Variable practice appeared to increase the “applicability” of the learning that occurred in acquisition, contributing to the performance of novel variations of the task that were well outside the range of the stimuli experienced in the acquisition phase. One cannot argue that the Variable group was more effective simply because the participants had experienced the range of speeds involved in the transfer test, as neither group had experienced them. In other words, variable practice seemed to increase *generalizability* (see Roller, Cohen, Kimball, & Bloomberg, 2001, for a different demonstration of generalization following variable practice).

## Other Factors Influencing Effects of Practice Variability

When adults are used as participants, there is reasonably strong evidence that increased practice variability is beneficial for learning (as measured on novel transfer tests), and basically no evidence that variable practice is detrimental to learning (Shapiro & Schmidt, 1982). However, a number of studies show very small effects, and others show essentially no effects, casting some doubt on the “strength” or generality of these effects (Van Rossum, 1990). Overall, in practical settings it is reasonably safe to say that attempts to make the practice more variable for learners will result in greater learning and generalizability. However, in the following paragraphs we discuss some of the issues that complicate this general statement.

### *Age of the Learner*

The effects of practice variability seem to depend on the nature of the learners. Certainly the most obvious classification is that of children versus adults. In their review of the literature on practice variability, Shapiro and Schmidt (1982) noted that the advantage for variable versus constant practice for children was strong in nearly every study conducted. For example, using a strictly closed throwing skill with young children, Kerr and Booth (1977, 1978) found in two experiments that variable practice was more effective than constant practice when participants were transferred to a novel version of the task. Even more surprising was the finding that for learning this novel variation of the task, practice at variations of the task approximating the novel task was more effective than was practicing the *novel task itself!* Practice variability appears to be a powerful variable in children’s motor learning (see also Green, Whitehead, & Sugden, 1995; Wulf, 1991).

### *Nature of the Task*

Similar to the practice-distribution effects, it appears that some of the differences in the effects of variability of practice may be accounted for by the nature of the task. For example, a study by Shea, Lai, Wright, Immink, and Black (2001) showed that the *relative timing* of a closed task was learned more effectively with practice conditions that promoted movement consistency (e.g., constant practice) compared to practice conditions that promoted

variability. In contrast, learning the *absolute timing* of the task was better under variable- than consistent-practice conditions. These recent findings support the intriguing possibility that some aspects of the *same task* may be learned more effectively through constant-practice conditions and other aspects through variable-practice conditions (see Wulf & Shea, 2002, for more discussion).

### *Scheduling Variable Practice*

We mentioned earlier that the effects of variable practice in adults have not always been consistent—some studies showing positive effects and others showing no effects. A review of those studies showing no effects by Lee and colleagues (1985) revealed an interesting pattern of findings. Many of these experiments had structured the variable-practice sessions such that most or all of the practice on any single variant of the task was conducted together, in what is called a *blocked practice* sequence. Although we will have much more to say about the effects of random and blocked practice in the next section, the conclusion drawn by Lee and colleagues (1985) was that for variable practice to be most effectively utilized (relative to constant practice), the order should be randomized, rather than blocked.

## Interpreting Variability-of-Practice Effects

Most of the studies on variability have been done in the context of schema theory (see chapter 12). The basic premise is that with practice, people develop rules (called *schemas*) about their own motor behavior. Think back to the ideas about the generalized motor program (see chapter 6), indicating that a set of parameters must be applied to the program in order for it to be performed. Schema theory proposes that participants learn a rule in the practice sequence. The rule is a relationship between all the past environmental outcomes that the person produced and the values of the parameters that were used to produce those outcomes. This rule is maintained in memory and can be used to select a new set of parameters for the next movement situation—even a novel variation—that involves the same motor program. Knowing the rule and what environmental outcome is to be produced, the person can select the parameters for the program that will produce it. The schema theory is related to variability in practice because the theory predicts that learning the rule will be more effective if the experience is varied rather than constant.

Another important finding from the literature on variability in practice is that the occurrence of learning during the acquisition phase was revealed by performance on a *novel* version of the task in transfer. This was true regardless of whether the novel version was inside (McCracken & Stelmach, 1977) or outside (Catalano & Kleiner, 1984) the range of variation experienced in the acquisition phase. As we will point out in chapter 12, such evidence suggests that what was learned was *not* some particular movement, but rather the (generalizable) capability to produce any of a variety of movements of this type. These results are explained well by schema theory, in that the variable practice produces a rule (or schema) for selecting parameters of the generalized motor program (e.g., for throwing), and this rule can be used for any novel movement using the same motor program.

Why should variable practice be more effective for children? One idea is that children are less experienced at motor skills than are older (adult) participants, so the rules (schemas) that the children acquire in laboratory settings have already been achieved by the adults in their earlier experiences with motor tasks. Also, when the task used in the research is simple, it is possible that the adults already have at their disposal the rules (schemas) necessary to perform novel tasks whereas the children must learn some of the rules in the experimental setting. Here, then, variable practice is more effective for children than for the adults because the children have considerably “more to learn” than the adults.

# Contextual Interference

The preceding section focused on practicing a number of task variations, compared to practice on only one task variation, as measured in retention and transfer tests (i.e., tests of learning). In this section we assume that variable practice is more useful for learning, and ask the question whether or not it makes a difference how the variable practice is *scheduled*.

## Blocked Versus Random Practice

Research on the scheduling of practice for multiple tasks was popularized in the motor skills area with the study by Shea and Morgan (1979), although a few isolated studies of practice-scheduling effects had been published earlier (e.g., Pyle, 1919). The Shea and Morgan study was influenced considerably by the ideas of William Battig (see “William Battig and Contextual Interference”), and together, their work has made a substantial impact on research in motor learning and practical application to real-world skills. One of the main issues was the finding that variables that made the organization of practice more “difficult” during acquisition degraded performance during acquisition (not surprisingly), but also made performance in retention and transfer tests *more* effective. This latter effect was surprising and attracted considerable attention from researchers. Battig’s notion was that *contextual interference*—which he defined as interference generated due to the context in which the skills were being practiced—produced decrements in performance during practice, but made the learning of these tasks more effective. This advantage for learning showed up in later tests of retention and transfer. Shea and Morgan (1979) operationalized Battig’s notion of contextual interference in terms of the order of practice among several tasks during acquisition. Their notion was that, by randomizing the order in which several tasks were practiced, high levels of contextual interference would be generated, and the learning advantage of this interference would then be seen later in retention and transfer tests.

### William Battig and Contextual Interference

Research on practice schedules owes a huge debt of gratitude to William F. Battig. Throughout a distinguished career, this cognitive psychologist maintained an interest in memory and learning, conducting studies using both verbal and motor tasks. Early in his research, Battig found that factors that make a task more “difficult” for the participant to perform actually enhanced remembering and transfer. For example, requiring (vs. not requiring) learners to pronounce nonsense “words” (e.g., XENF), whose letters corresponded to individual finger movements, made performance on *another* version of the finger task more effective (Battig, 1956).

Battig interpreted these and related findings in terms of the principle that “intertask facilitation is produced by intratask interference” (Battig, 1966, p. 227). *Intratask* interference referred to the performance decrement caused by attempting to keep multiple items in working memory at one time (e.g., the interference between the “word” pronunciations and the finger movements). By *intertask* transfer, Battig was referring to the beneficial transfer of learning to other motor tasks. These findings ran counter to intuition, as many researchers believed that transfer to other tasks would be strongest if the first task had been learned under the most optimal conditions for performance during practice.

But the field of psychology was not prepared to consider such radical ideas, perhaps because the concepts ran so counter to existing theories of memory and learning. Little attention was paid to Battig’s ideas, even though he continued to publish more demonstrations of these counterintuitive findings (e.g., Battig, 1972; Hiew, 1977). A responsive chord was finally struck with the publication of Battig’s expanded ideas on *contextual interference*. In this paper (Battig, 1979), he presented a wider framework that

conceptualized the findings he had accumulated over the years. These ideas were expanded shortly thereafter to motor skill learning (Battig & Shea, 1980), where Battig's influence has made a very important mark.

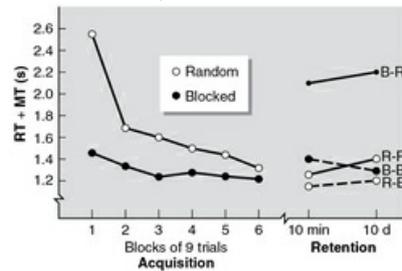
Battig identified two important sources of interference that could arise during practice. One factor related to the *order* in which multiple items were studied or practiced. If the same task was practiced repeatedly, then only this one task needed to be held in working memory, and interference should be *low*. However, if practice involved frequent switching among multiple tasks, then interference should be *higher*. This source of interference has been the object of considerable study and is the focus of the present discussion on contextual interference. The other source of interference was the nature of the material to be practiced. If the items (or motor tasks) were quite similar, then the interference arising during practice would be *high* because of the increased confusion among them. Items or tasks that were quite different or distinct would cause lower interference. Battig showed that the presence of these factors both (a) degraded performance in acquisition and (b) facilitated performance in retention, transfer, or both.

Above all, the most important element of the contextual interference arising from a set of tasks or items to practice was *how the learner responded to the interference*. Battig suggested that participants respond to situations of high or low interference with correspondingly high or low levels of elaborative and distinctive processing (which are effortful). These ideas have been expanded for motor behavior and motor learning by John Shea and his colleagues; today, they represent an important account of the contextual-interference effect.

In their study, Shea and Morgan (1979) used two kinds of practice sequences in acquisition, and learners practiced three different tasks. *Blocked practice* is a sequence in which all the trials on one task are done together, uninterrupted by practice on any of the other tasks. On the surface, a blocked practice sequence seems to make good "common sense," in that learners can concentrate on improving one task before moving on to the next task. For *random practice*, on the other hand, the same task is rarely repeated on consecutive trials. Notice that, in both practice sequences, the same number of trials is performed on each task, the only difference being the order in which the various task variations are presented. The task variations involved rapid arm movements to produce three different movement patterns and were evaluated by measures of reaction time (RT) to initiate and the movement time (MT) to produce the pattern; total time (RT + MT) was also used. There were 54 trials in acquisition, 18 on each of the tasks. Retention and transfer tests were given after 10 min and 10 days, administered under both random and blocked conditions for different subgroups of participants.

The Shea and Morgan results are shown in [figure 10.9](#), here with total time as the dependent variable. The findings are very clear. Blocked practice resulted in an immediate performance advantage during acquisition compared to random practice (blocks 1-6, during acquisition, in [figure 10.9](#)). And, though the performance difference was reduced over blocks of trials, there remained an advantage favoring the blocked group at the end of practice.

Figure 10.9 Blocked and random practice effects during practice and in various conditions of immediate and delayed retention.



Adapted, by permission, from J.B. Shea and R.L. Morgan, 1979, "Contextual interference effects on the acquisition, retention, and transfer of a motor skill," *Journal of Experimental Psychology: Human Learning and Memory* 5: 183. Copyright © 1979 by the American Psychological Association.

The performances in the retention tests are presented on the right side of [figure 10.9](#). Consider first the tests given under random conditions, seen as the solid lines in the figure; the first letter in the label gives the acquisition condition (R or B), and the second letter gives the retention condition (R or B). The group that received random practice in acquisition (R-R) far outperformed the group with blocked conditions in acquisition (B-R) in both the 10 min and 10-day random retention tests. That is, the performance advantage seen during acquisition was *reversed* when learning was assessed in these retention tests. Now examine the data for participants in the blocked retention test (dotted lines). Here, the group with random conditions in acquisition (R-B) outperformed the group with blocked conditions in acquisition (B-B) but not by as large an amount as was seen for the R-R and B-R groups. In summary, regardless of the scheduling in the retention trials, learning was always enhanced when practiced under random conditions. Random practice degraded performance in acquisition but facilitated learning. Similar findings were seen in transfer tests to novel patterns. These findings strongly supported Battig's ideas that contextual interference during practice would facilitate retention and transfer—that is, would facilitate learning.

These effects of blocked versus random practice on learning have been termed *contextual-interference (CI) effects*, based on Battig's original notions. However, notice that the CI manipulation is just one of many ways in which contextual interference could be generated or manipulated (or both) during practice (see Brady, 1998, 2004; Lee & Simon, 2004; Magill & Hall, 1990, for a review).

## Generalizability of Contextual-Interference Effects

Issues about the *generalizability* of CI effects might be rephrased to ask the question, "How much faith should I put in the implications arising from the Shea and Morgan study?" Should random and blocked differences be expected to emerge under a variety of different conditions, using different tasks, for different participants, and so on? Research suggests that, while there is overall rather wide generalizability, certain conditions tend to influence the size of the CI effect (for review see Lee, 2012).

### *Task Influences*

The original Shea and Morgan (1979) experiment used a laboratory task in which participants were required to make rapid patterns of arm movements by knocking over small wooden barriers in response to a stimulus light. These findings have been replicated a number of times using similar task requirements (e.g., Del Rey, Liu, & Simpson, 1994; Lee & Magill, 1983b; Shea & Wright, 1991; Wright, 1991). Other laboratory studies have revealed similar results using tasks that emphasize the timing of actions (e.g., Lee & Magill, 1983b; Proteau, Blandin, Alain, & Dorion, 1994; Wulf & Lee, 1993), perceptual anticipation (e.g., Del Rey, 1989; Del Rey, Wughalter, & Whitehurst, 1982), force regulation (Enebo & Sherwood, 2005; Shea, Kohl, & Indermill, 1990; Shea, Shebilske, Kohl, & Gudadgnoli, 1991), force field adaptation (Osu, Hirai, Yoshioka, & Kawato, 2004; Overduin, Richardson, Lane, Bizzi, & Press, 2006), and error-detection capabilities (Sherwood, 1996), to list just a few.

Many studies of CI effects have used relatively simple laboratory tasks, leading some to suggest that the potential value of this research for practical situations would be greater if the findings were replicated in more complex tasks (e.g., Wulf & Shea, 2002). For example, Tsutsui, Lee, and Hodges (1998) and Pauwels, Swinnen, and Beets (2014) showed that random practice facilitated the learning of new bimanual timing patterns—tasks that are difficult to acquire because of the inherent stability of competing in-phase and anti-phase patterns (see chapter 8). And Ollis, Button, and Fairweather (2005) found that random practice facilitated the learning of knot-tying skills, regardless of the complexity of the knots. In contrast, Albaret and Thon (1998) found that random practice facilitated learning only for a version of a drawing task that had the smallest number of component parts. No CI differences were found for the complex version of the task.

Despite some uncertainty about the role of task complexity, the typical CI effect has been replicated in a number of sport tasks (which are, arguably, more complex than laboratory tasks) such as badminton (Goode & Magill, 1986; Memmert, Hagemann, Althoetmar, Geppert, & Seiler, 2009; Wrisberg, 1991; Wrisberg & Liu, 1991), rifle shooting (Boyce & Del Rey, 1990), volleyball skills (Bortoli, Robazza, Durigon, & Carra, 1992), kayaking (Smith & Davies, 1995), snowboarding (Smith, 2002), tennis serving (Hernández-Davo, Urbán, Sarabia, Juan-Recio, & Moreno, 2014) and baseball batting (Hall, Domingues, & Cavazos, 1994). Moreover, it is important to note that CI effects have also been found in many other tasks as well, such as learning logic operations (Carlson & Yaure, 1990), automatic teller operations (Jamieson & Rogers, 2000), foreign language vocabulary (Schneider, Healy, & Bourne, 2002), artwork identification (Kornell & Bjork, 2008), handwriting in children (Ste-Marie, Clark, Findlay, & Latimer, 2004), and many others (Lee, 2012).

In contrast to these replications of CI effects in “complex tasks” are a number of studies in which no differences were found, including investigations using tasks such as dart throwing (Meira & Tani, 2001; Moreno et al., 2003), volleyball skills (Jones & French, 2007), and gymnastics cartwheels (Smith, Gregory, & Davies, 2003). However, in most of these studies it was only rarely the case that blocked practice resulted in more learning than random practice (e.g., Shewokis & Klopfer, 2000; see also Wulf & Shea, 2002; discussion later in this section). In general, random practice has almost always been found to be as beneficial as, if not superior to, blocked practice for learning.

### *Learner Influences*

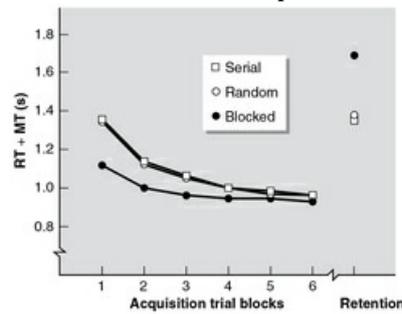
In the preceding section we presented evidence that variability-of-practice differences were larger in children than in adults. The evidence relating to CI effects is not quite as clear, however, as some studies have shown these effects in children (e.g., Pollock & Lee, 1997; Ste-Marie et al., 2004; Wulf, 1991) whereas others have not (e.g., Brady, 2004; Del Rey, Whitehurst, & Wood, 1983; Jarus & Goverover, 1999; Pigott & Shapiro, 1984). There is some evidence that the magnitude of CI effects may also depend on experience. Del Rey and her colleagues have shown, for example, that transfer in an anticipation task after random practice is facilitated more for participants with experience in open skills than for novices (Del Rey, 1989; Del Rey et al., 1982).

A particularly interesting finding was reported by Hall and colleagues (1994), whose participants were college-level baseball players and thus already quite skilled at the task. All participants performed two extra batting practice sessions per week for six weeks. The batting sessions involved practice in which the pitcher threw 15 fastballs, 15 curves, and 15 change-ups. Groups of batters received these pitches in either a blocked or a random order over the entire 6-week period. They also performed two transfer tests in which pitches were delivered in both random and blocked orders. The control group performed more poorly on the transfer tests than did either practice group, suggesting that the extra batting practice was beneficial regardless of the order in which the pitches were thrown. However, the most interesting finding was the observed CI effect in practice and transfer. The performances of the blocked group on the blocked transfer test and of the random group on the random transfer test were nearly identical to their respective performances in the eighth practice session. It was when performance was assessed on the *common* transfer tests that the true value of the practice sequences in learning came through, as random practice facilitated transfer under both orderings of pitches. Thus, it would appear from this study that even highly skilled athletes benefited from random practice.

### *Other Practice Schedules*

There are a wide variety of ways in which practice could be scheduled, given  $X$  tasks and  $N$  trials per task. Having *all* of the trials for one task performed in a drill-type sequence represents an extreme scheduling manipulation. Alternatively, *never* performing two consecutive trials on the same task might be considered the opposite extreme. A serial practice order might be considered “moderate,” relative to these extremes, because it combines the predictability of blocked practice with the nonrepetitiveness of random practice (Lee & Magill, 1983b). In one study, however, as shown in [figure 10.10](#), the performance of the serial group was nearly identical to that of the random group, leading to the suggestion that the lack of repetitiveness of random practice—and not its unpredictability—may be the key factor that both degrades acquisition performance and facilitates learning.

Figure 10.10 Comparison of blocked and random practice with a serial practice schedule.



Adapted, by permission, from T.D. Lee and R.A. Magill, 1983, "The locus of contextual interference in motor-skill acquisition," *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 9: 739. Copyright © 1983 by the American Psychological Association.

An important question is whether or not a practice schedule that represents some "middle ground" in terms of repetitiveness of practice might be beneficial to *both* performance and learning. Studies by Pigott and Shapiro (1984) and Al-Ameer and Toole (1993) support this possibility. In the Al-Ameer and Toole study, participants practiced a task similar to that used by Shea and Morgan (1979), under either random or blocked sequences. Results for both acquisition and retention replicated the Shea and Morgan findings. But Al-Ameer and Toole also added two groups that performed small, *randomized blocks of trials*, in which a participant would practice one task for two or three trials, then randomly switch to another task and practice that for two or three trials. This moderate CI condition, involving randomized blocks of either two or three trials, facilitated acquisition performance (relative to random practice), and was just as beneficial to learning as random practice. Landin and Hebert (1997) also found that serial alternation of blocks of trials was more effective than either blocked or random practice in the learning of basketball shooting skills.

These findings are important, as they suggest that it may be possible to reduce the acquisition performance decrement normally seen with random practice without sacrificing the long-term learning benefit as a consequence. The results are also important for applying the findings from these scheduling experiments to tasks involving daily activities. One obvious drawback with a completely random schedule is that constantly switching from one task to another may be impractical. For example, consider tasks that involve training a new worker on specific job-related skills. If these tasks are performed in separate locations in a plant, it is logical to do at least *some* blocked practice before switching to a new task. The findings previously discussed regarding a randomized-blocks schedule suggest that this condition combines the positive effect in acquisition performance of a blocked practice with the beneficial learning effect of a random practice schedule.

## Hypotheses on Contextual-Interference Effects

Before the first CI studies were published, learning researchers seemed to be quite satisfied with the general understanding that any practice variable that promoted effective performance in acquisition would also promote learning. The findings of Shea and Morgan (1979) caused many researchers to become much less comfortable with this general idea. How could a variable that slows improvement and retards the overall level of performance in practice be so potent in facilitating retention? This *performance-learning paradox* generated new thinking and debate, not only about why these scheduling effects occur but also with regard to the motor learning process in general. Several hypotheses have been advanced to explain the advantages of random over blocked practice for learning. Though they may seem to present competing views, they probably have much in common to say about the learning process.

### *Elaborative Processing Hypothesis*

One of these hypotheses, proposed by Shea and colleagues, holds that random practice forces the learner into more *elaborative* conceptual processing of the tasks to be learned (Shea & Morgan, 1979; Shea & Titzer, 1993; Shea & Zimny, 1983, 1988). During a random schedule, practice on one task is usually followed by practice on a

completely different task. Thus, the preparation for action before movement and the evaluation of performance afterward may be quite different from the preparatory and evaluative processing that was completed on the previous trial. According to the elaborative processing view, random practice promotes more *comparative and contrastive* analyses of the actions required to complete these tasks. As a result, the representation of each task following random practice is more *memorable* than in blocked practice, in which the opportunity for contrasting the different tasks is minimized because of the repetitive nature of the schedule. The advantages shown by random schedules in retention and transfer result from more *meaningful* representations of a given movement task and more elaborate distinctions between the various task versions (see also Kornell & Bjork, 2008).

Verbal reports from participants involved in these experiments provide one line of evidence in support of the *elaboration hypothesis*. Postexperiment interviews indicated that participants in the random condition understood the tasks in a qualitatively different way than did participants who performed blocked practice (Shea & Zimny, 1983). Compared to those who had blocked practice, participants in the random group reported a much larger number of elaborate mental representations for distinguishing the shapes of the various movement patterns (e.g., noting that one pattern was essentially a mirror image of another, or that a given pattern was the only one with a reversal in direction; Shea & Zimny, 1983). In contrast, participants in the blocked group reported that they tended to run the movements off without much thought, more or less “automatically.” Using a concurrent verbal report protocol, Zimny (reported in Shea & Zimny, 1988) found that participants who were engaged in random practice made comments about specific tasks, as well as between-task comparisons, about twice as often as those engaged in blocked practice (see also Del Rey & Shewokis, 1993). These verbal report data support the enhanced contrastive value of random practice as predicted by the elaborative processing hypothesis.

A different type of support for the elaborative view was provided in a study in which physical practice trials were interspersed with three imagery practice trials (Gabriele, Hall, & Lee, 1989, experiment 1). For two groups, these imagery trials were performed on the task that had just been practiced physically (blocked imagery). In the other two groups, participants imaged the three tasks, but these *had not* been performed on the preceding physical practice trial (random imagery). Regardless of whether the physical trials were practiced in a blocked or random order, random imagery facilitated retention more than blocked imagery, supporting the view that this contrastive processing during practice was beneficial for learning.

A more direct experimental manipulation of elaboration was examined in studies by Wright (1991; Wright, Li, & Whitacre, 1992). Using an arm movement task similar to that employed by Shea and Morgan (1979), four groups of participants engaged in blocked practice. One group performed no additional processing, while participants in the other groups performed selected cognitive activities between practice trials. After each practice trial, participants in two of the groups were asked to describe verbally the order of movements of one of the tasks—either the task just completed or one of the other tasks. In the fourth group, participants were asked to make specific comparisons between the task just performed and one of the other tasks. The prediction was that processing in this last condition would be most like the processing used by participants in random practice. The prediction was supported, as participants in the intertask processing condition were elevated in retention as compared to the other three groups. Interestingly, the additional processing in the other two groups with intervening cognitive descriptions did not improve retention at all, suggesting that the qualitative nature of the processing was more important than the quantity.

A more recent technique to study the elaboration hypothesis was introduced by Lin, Fisher, Winstein, Wu, and Gordon (2008; see also Lin, Winstein, Fisher, & Wu, 2010). They provided transcranial magnetic stimulation (TMS; see chapter 2) between blocked and random practice trials that was meant to prevent participants from conducting elaborative processing. The typical CI effect was found for the control, blocked, and random practice groups. However, the random practice advantage was eliminated when TMS was applied between random practice trials. Lin and colleagues provided a strong rationale to support the argument that TMS prevented participants in the random group from undertaking elaborative processing, thereby eliminating the CI effect.

### *Forgetting and Reconstruction Hypothesis*

A different explanation for the CI effect was proposed by Lee and Magill (1983b, 1985). According to the *reconstruction* view, the action planning that occurs just prior to a practice trial is influenced by what has been done in the previous trial. In chapter 6, we presented the notion that in order to produce an action, the generalized motor program (GMP) must first be retrieved from long-term memory; it must be parameterized and otherwise readied for execution in the response-programming stage of information processing. Presumably only one action plan can be in working memory at a time.

In blocked practice, “action plan A” is constructed for task A and remains available in working memory for future trials on task A. However, since tasks are ordered intermittently in random practice, “action plan A” is no longer useful for the next task (say, task B). Therefore, for the next trial, “action plan A” must be abandoned and “action plan B” must be prepared. When the random ordering determines that task A is to be performed again, the previously constructed “action plan A,” which was abandoned from working memory, must be *reconstructed*. According to the hypothesis, the value of a practice trial depends on the reconstructive processing that was undertaken. Remembering the “solution” (the action plan) from a previous trial (as in blocked practice) promotes performance in acquisition but does not promote the kind of processing that facilitates learning as measured in retention and transfer. In contrast, random practice causes a short-term “forgetting” of the action plan when a different task must be produced. This is detrimental to acquisition performance but beneficial to retention and transfer because it forces the participant to undertake reconstructive processing. Notice that this view of the CI effect is based on the same logic as a key explanation of the spacing effect in memory (see “When Forgetting Improves Remembering”).

One prediction of the reconstruction view that has been empirically tested in a learning paradigm relates to the cause of short-term forgetting. The idea here is that on a given task, *any* activity between practice trials that causes short-term forgetting should promote learning. Note that this prediction is different from the elaborative processing view, which suggests that distinctiveness *increases* as the similarity of different tasks in working memory increases. Several studies have examined this prediction; the evidence, though not strong, has been generally positive in support of the reconstruction hypothesis (Lee & Magill, 1983a, 1987; Magill, 1988; Young, Cohen, & Husak, 1993).

## When Forgetting Improves Remembering

One of the puzzles about working memory is the curious statement that “*forgetting helps remembering*” (Cuddy & Jacoby, 1982). This statement sounds strange because forgetting, which we will discuss in chapter 13, is usually thought of as a *reduction* in the capability to remember; saying that “forgetting helps remembering” sounds like nonsense. However, the evidence from experiments on the *spacing effect* in verbal memory suggests that this statement is not as bizarre as it seems. In these experiments, participants are typically given a long list of words that they are asked to study and recall some time later on a memory test. The list often comprises words presented only once, as well as words presented more than once. For the words presented more than once, they are sometimes repeated immediately (a zero “lag” condition) or at other times with a small or large number of words intervening between repetitions. The *spacing effect* refers to the finding that later recall of words that have been repeated with long lags is more effective than recall of words repeated with no lag or short lags.

Larry Jacoby (Cuddy & Jacoby, 1982; Jacoby, 1978; Jacoby & Dallas, 1981) proposed the idea that forgetting helps memory because the *processing* undertaken during study is determined by what is remembered about the material from the last processing of it. If the information is remembered well, then the material to be studied will not be fully processed on its second presentation. If the information has been forgotten, then the material will be more fully processed once again. The critical issue for Jacoby is that the value of a repetition lies in the degree to which it promotes full processing of the information on *each* presentation. Processing information is similar to solving a problem. The results of the processing

constitute a solution, much like the solution obtained by multiplying two numbers together “in your head.” If the same problem arises soon after the solution has been determined, then the mental arithmetic need not be undertaken again in order to solve the problem because the solution is readily available in working memory. However, if the solution has been forgotten, then full processing must be undertaken in order to solve the problem again. Memory, according to Jacoby, is a product of the processing activities. He summarized this idea when he wrote, “The means by which a solution is obtained influences subsequent retention performance: subsequent retention suffers when the solution is remembered” (Jacoby, 1978, p. 666).

A different approach to examining the reconstruction hypothesis was used in a study by Lee, Wishart, Cunningham, and Carnahan (1997). An important component of the prediction relates to the information in working memory when a trial is practiced. Instead of trying to induce short-term forgetting, Lee and colleagues attempted to introduce into working memory the information necessary for the upcoming trial’s action plan by means of a model. If the action plan was provided by the model, then the problem-solving activity normally undertaken during random practice would be unnecessary, and the beneficial effects of random practice would be eliminated or at least reduced. The experimenters used a timing task, with participants making patterns of key presses on a computer keyboard. The random and blocked practice groups performed in acquisition and retention as expected. A third, *random plus model* group also practiced in a random order; however, the computer generated a visual map of the task along with an auditory template of the timing requirements, presented three times before each action.

Two points of interest are noteworthy. First, even though practice was conducted in a random order, the performance of the group given modeled information was excellent. In fact, this random plus model group outperformed the blocked group on the very first block of practice trials. And, second, there was a strong negative influence of the model in immediate and delayed retention tests. The learning advantage normally seen following random practice was eliminated by the presence of the modeled information during practice. These findings were replicated and extended by Simon and Bjork (2002). In their study, the modeled information either matched the action plan requirements for the upcoming trial (as in Lee et al., 1997) or was inappropriate for the upcoming trial. The information provided by the inappropriate model was detrimental to acquisition performance but beneficial for retention, providing further evidence for the reconstruction hypothesis.

Another issue that is central to the reconstruction view deals with the nature of the planning activity. The hypothesis is that, for random practice, the action prepared for one task is inappropriate for a completely different task, and thus a new preparation is required. Experimenters have shown, for example, that more attentional capacity in general (Li & Wright, 2000) and motor programming time in particular (Immink & Wright, 1998, 2001) are required to prepare an action plan for an upcoming trial in random practice than in blocked practice. Measures of functional magnetic resonance imaging also show greater activity in the brain’s planning regions in random practice (Cross, Schmitt, & Grafton, 2007). Research suggests also that random practice is more beneficial than blocked practice if task variations require learning different GMPs, or parameter learning when all tasks belong to the same GMP (Hall & Magill, 1995; Lee, Wulf, & Schmidt, 1992; Wulf & Lee, 1993). However, the evidence also suggests that blocked practice is more beneficial than random practice for relative timing learning when only one GMP is practiced (Giuffrida, Shea, & Fairbrother, 2002; Lai & Shea, 1998; Lai, Shea, Wulf, & Wright, 2000; Shea, Lai, Wright, Immink, & Black, 2001). This latter result is inconsistent with the reconstruction view because it predicts that no differences between random and blocked practice should result. When only a rescaled action plan is required, the same relative timing can be maintained in memory on subsequent trials and little reconstructive process should be necessary (Magill & Hall, 1990; Lee et al., 1992).

Finally, Trachtman (2003) has used a paradigm that examines the benefit from the action planning per se. She used so-called “abort” trials, in which the action is planned and readied but at the last second is not executed. According to the reconstruction view, if the number of executed trials is held constant, additional abort trials should be beneficial to learning because of additional reconstructions provided. Trachtman’s data fail to provide any evidence for the benefits of abort trials, however, and thus offer no support for the reconstruction view.

## *Evaluating the Hypotheses*

On balance, there appears to be considerable support for both the elaborative processing account and the reconstruction view of the CI effect, although neither is able to explain all of the findings that now exist on the topic. One of the problems in comparing these hypotheses is that there are few situations in which different predictions can be contrasted. Thus, the hypotheses should not necessarily be seen as *competing* predictors of the CI effect, but perhaps rather as complementary theoretical views about the ways in which learners comply with the processing operations encouraged under different practice and task conditions.

## *Other Hypotheses*

Of course, it is possible that both the elaboration and the reconstruction views are wrong. Some researchers have suggested that the detrimental effect in retention occurs because of greater *retroactive inhibition*: The early tasks practiced by the blocked group are more difficult to recall because of the interference caused by practicing the other tasks in the interim (Del Rey et al., 1994; Shea & Titzer, 1993). Another view downplays the role of cognitive factors and suggests instead that CI effects reflect a “difficulty” arising from an interaction of factors that include the learner, the task, and the environment (Davids, Button, & Bennett, 2008; Ollis et al., 2005). Lastly, some researchers have modeled these effects using a *connectionist* approach (Horak, 1992; Masson, 1990; Shea & Graf, 1994).

## Practical Implications

Regardless of the theoretical explanation for these curious effects, it is clear that they are present in both laboratory and practical situations, that they lead to relatively large effects in learning, and that they should have important practical implications for the design of learning environments in sport, industry, and therapy. The “traditional” methods of continuous drill on a particular action (i.e., practicing one skill repeatedly until it is correct) are probably not the most effective way to learn. Rather, the evidence suggests that practicing a number of tasks in some nearly randomized order will be the most successful means of achieving the goal of stable retention and transfer. Of course, these findings highlight the learning–performance distinction discussed earlier in this and the preceding chapter. Here we have a situation for which the conditions in acquisition that make performance most effective (blocked practice) are *not* the most effective for learning—an important general consideration for those designing workable practice sessions (Bjork, 1994; Schmidt & Bjork, 1992). Although the application for these ideas is strongly implicated (Dempster, 1988; Goettl, 1996), much work remains to be done on these issues with more complex tasks (Wulf & Shea, 2002) and various training settings before we can be confident about how to effectively apply these principles.

## Two Caveats

If, indeed, beneficial effects of random practice are found to be useful for training settings, then another problem will need to be considered. In their research discussed earlier, Simon and Bjork (2001, 2002) asked their participants during practice and just prior to retention to predict their level of success in performance on the delayed retention test. If participants were aware that performance effects are misleading as predictors of retention, we would expect participants in a blocked practice group to realize that their expected performance in retention would be poor. However, Simon and Bjork (2001) found that this was not the case at all. Rather, blocked practice resulted in overestimated levels of retention—error in retention was more than *double* what had been predicted just prior to the retention trials (compare the open and filled circles in retention). This finding underscores a persistent illusion, that performance effects are often mistaken for learning effects (Bjork, 1994). Moreover, this illusion occurs not only in novice learners but in expert performers too (Abushanab & Bishara, 2013). As a result of this illusion, it is difficult to encourage students, instructors, and other training program organizers to use practice conditions that *appear* to be ineffective for learning during the training period. The implications are that some explanation *about* the learning process may be critical before the effects of CI and other practice-related

phenomena can be successfully employed in training settings.

But, let's consider one more conundrum before ending this section. Presumably, if learners were poor judges of their own learning, then allowing them to regulate their own practice schedules would probably result in considerable blocked practice and very little random practice. That seems to be true for some individuals. However, some tend to choose a more random schedule and some a series of "mini-blocks" of trials; still others choose a progression from blocked to random practice (Keetch & Lee, 2007; Wu, 2007). Regardless of the specific nature of the schedule that individuals choose, the very fact that they have self-regulated their own practice appears to provide a boost to learning when compared to yoked controls and experimenter-determined schedules. These findings offer a tantalizing suggestion that perhaps the optimal variability in learning multiple tasks occurs when it is self-determined by the learner (see also the section of self-regulated augmented feedback in chapter 11). Adaptive, or learner-contingent, schedules have also been explored recently as a means to tailor the schedule to the needs of the learner (Huang, Shadmehr, & Diedrichsen, 2008; Choi, Qi, Gordon, & Schweighofer, 2008; Simon, Lee, & Cullen, 2008). We predict that the success of these types of practice schedules will be determined when the participant's long-term (learning) interests are tailored to the schedule, rather than to the interests of immediate performance gains.

## Guidance

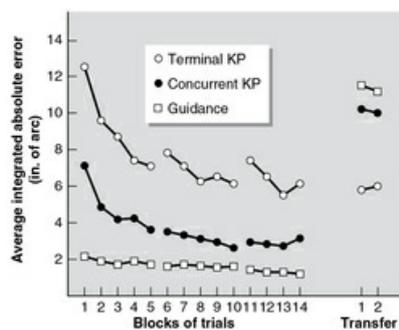
A technique frequently used in teaching and in rehabilitation involves *guidance*, whereby the learner is physically assisted through the task to be learned. Guidance refers to a variety of separate procedures, including physically pushing and pulling the learner through a movement sequence, preventing incorrect movements by means of physical limitations on the apparatus, or even verbally “talking someone through” a new situation. These guidance procedures tend to prevent the learner from making errors in the task.

What does the evidence on guidance suggest? Much of the early research on guidance by Holding (1970; Holding & Macrae, 1964; Macrae & Holding, 1965, 1966), Singer (1980; Singer & Pease, 1976; Singer & Gaines, 1975), and others (reviewed by Armstrong, 1970a), using various tasks and guidance procedures, showed considerable positive effects of guidance procedures on performance during acquisition. We should remember, however, that guidance almost certainly would usually have strong effects on *performance* during the trials in which it is administered. By its very nature, a guidance technique is a method that will prevent or severely limit the occurrence of errors. Of course, as we have discussed previously, performance gains during acquisition may not represent relatively permanent changes attributable to learning, and the important question is whether such performance gains will survive in a transfer test when the guidance is removed.

One of the definitive studies in this area was performed by Armstrong (1970b). He compared various forms of physical guidance in a task for which the learner was to make an elbow movement having a complex spatial-temporal pattern (see [figure 6.17](#)), with MTs of 3 or 4 s. Three of his groups are of specific interest here. One group practiced the task and received terminal, kinematic feedback (knowledge of performance, or KP) after each trial. In addition, after the last in a block of 15 trials, participants in this group were shown a plot of their last trial in combination with a template of the goal pattern. Another group was given concurrent, real-time visual feedback of the movement together with a perfect template of the goal movement. In a third group, the movement device moved by the participant was mechanically controlled such that deviations from the target path were physically restricted. Practice was conducted over three days, which also included a transfer test on the third day during which all participants performed the task with no augmented information.

The results, presented in [figure 10.11](#), were very dramatic. As can be seen, the guidance device restricted errors so that performance was nearly perfect throughout the entire practice period. The concurrent feedback was also quite effective in reducing performance error during practice but clearly not as effective as the guidance device (although much more so than the terminal feedback). But Armstrong’s results showed that the guidance effects provided only temporary boosts to performance. As can be seen on the right side of [figure 10.11](#), the transfer trials were performed most accurately by the terminal-feedback group and very poorly by both the guidance- and concurrent-feedback groups. In fact, the latter two groups performed the transfer trials at almost the same level of performance as had the terminal KP group early in practice. Together with other results (e.g., Domingo & Ferris, 2009; Schmidt & Wulf, 1997; Singer & Pease, 1976), Armstrong’s findings raise considerable doubt about the benefits of guidance techniques as learning aids.

Figure 10.11 Comparison of physical guidance with terminal- and concurrent-feedback effects on acquisition and transfer.



Adapted from T.R. Armstrong, 1970, "Training for the production of memorized movement patterns," *Technical Report 26*: 15.

There is research, however, suggesting that *some* guidance can be beneficial when interspersed with active practice trials (Hagman, 1983; Sidaway et al., 2008; Winstein, Pohl, & Lewthwaite, 1994) or when used with complex tasks (Tsutsui & Imanaka, 2003; Wulf & Toole, 1999). Still other research has used guidance that is less physically restrictive than many traditional types of physical guidance. For example, a computer-operated steering mechanism allowed participants in a study by Marchal Crespo and Reinkensmeyer (2008) to manipulate a wheelchair around a virtual environment under three training conditions: no guidance, fixed guidance, or a guidance-as-needed condition. This latter condition permitted participants to perform the task without restriction until a tolerance for error in performance was reached, at which time the computer provided haptic guidance as it physically corrected the tracking device. This condition also eased the tolerance limits as proficiency on the task improved over trials.<sup>3</sup> Marchal Crespo and Reinkensmeyer found that providing some guidance without eliminating all errors provided positive transfer performance when all guidance was removed, as contrasted with the fixed-guidance and no-guidance conditions. These findings offer strong promise for the use of computers and robots in the training of functional motor skills (Reinkensmeyer & Patton, 2008) and in rehabilitative settings (Reinkensmeyer, Emken, & Cramer, 2004).

These various findings permit a number of tentative generalizations about guidance. First, guidance may be effective in early practice when the task is unfamiliar to the learners. Much of the apparent contribution of guidance procedures is involved in getting the movement "into the ballpark" so that later refinements can be made. Second, guidance may be most effective for tasks that are very slow in time (e.g., matching some perceived state such as a force or a position). Presumably guidance gives the learner an indication of the nature of the state that is to be matched, so that movements may be adjusted to match this state later. Direct and indirect lines of evidence, however, suggest that guidance will be less effective for tasks that are rapid and ballistic or for tasks that involve the learning of motor programs (e.g., Armstrong's spatial-temporal pattern).

A final aspect of guidance that is rarely studied is the prevention of injury and reduction of fear. As with Marchal Crespo and Reinkensmeyer's "guidance-as-needed" robot, providing guidance that is relatively "loose" until the individual produces an error can also be an effective way to help people learn a dangerous task. Gymnasts use manual assistance and spotting belts regularly to ensure that a mistake will not result in a serious fall. Similar "techniques" are used by parents when their children begin to ride a bicycle without the training wheels. An adult running down the street beside the child, either with a guiding hand or without, is an easily recognizable image of "guidance as needed." Such procedures provide a great deal of confidence for learners and are highly effective in reducing the fear and potential disruptions in skill learning. The key feature is that guidance is minimal, while fear of injury is nearly eliminated. Even so, there remains the problem of the guidance serving as a "crutch," so that when it is removed there will be a marked reduction in the skill level. Gymnasts say that it is difficult to perform a risky new skill "out of the spotting belt" for the first time, as the performer knows that now a mistake could cause a serious injury. Even so, it would seem that there is no substitute for practicing the skill on your own as soon as it is safe to do so.



## Summary

This chapter deals with the major independent variables that affect the learning of motor skills and thus those variables that influence the design of instructional programs. Verbal instructions play an important role in the learning process. In particular, the learner's focus of attention that is induced by the instructions determines the effectiveness of learning. Instructions that promote an external focus have multiple benefits and speed the learning process. In recent years, it has also become clear that different practice conditions have different motivational consequences. Conditions that produce positive motivation by enhancing learners' expectancies for future performance and support their need to feel autonomous enhance learning. Conversely, conditions that do not consider these attentional and motivational influences result in nonoptimal learning.

Procedures involving mental practice or observational learning have been shown as effective methods that facilitate learning. The structure of practice also has important influences on learning. Distributed practice facilitates performance and learning more than massed practice does, although these effects seem to be stronger for the learning of continuous tasks. Practice sequences in which the task conditions are deliberately varied from trial to trial are slightly more effective than constant-practice conditions. Randomly ordered practice is detrimental to immediate performance as compared to blocked practice, but it facilitates retention and transfer. Guidance can be a useful aid in some situations, but overuse of guidance techniques can also be detrimental to learning.

### Student Assignments

1. Prepare to answer the following questions during class discussion:
  - a. Describe two examples related to which attentional focus a novice versus an expert performer might benefit from on a certain task.
  - b. Describe how a physical therapist might enhance the performance expectancies of a person who experienced a stroke.
  - c. How can a golf coach support his or her player's need for autonomy to facilitate learning?
  - d. Describe an alternative practice schedule that combines the benefits to performance and learning that are typical of blocked and random practice.
2. Find a recent research article that examines the effects of motivational influences on performance or learning of a sport skill and summarize the findings.

### Notes

<sup>1</sup> Although we are not in favor of change (pretest-posttest) scores to measure learning (see chapter 9), here these scores are similar to absolute retention scores because there were no differences between groups in the pretest. Thus, the change scores are essentially an absolute-retention score with a constant subtracted.

<sup>2</sup> Note that these variable-practice trials were conducted in a *random order*. This factor will become an important variable, as discussed in the next section.

<sup>3</sup> Note that this guidance-as-needed condition provides a type of bandwidth augmented feedback that is faded over trials, discussed in greater detail in chapter 11.

# Chapter 11

## Augmented Feedback

One of the most important features of practice is the information learners receive about their attempts to produce an action. Some of this information is inherent in the movement production; we have examined this kind of sensory information in chapter 5; we can also consider information that is presented in an “augmented” form from the instructor, therapist, or coach. This chapter deals with this latter form of information.

## Classifications and Definitions

Consider, as the broadest class, all the various kinds of sensory information that people can receive, including all those sources that have to do with the many diverse aspects of our lives. Of course, not all such information is related to our movements: the sound of wind in the trees as we walk through a forest is not relevant in this respect. Of the sources of information that are related to our movements, we can speak of those available (a) before the action, (b) during the action, and (c) after the action. Before the action, sensory information signals the position of your limbs, the sight of a ball flying toward you, the nature of the environmental setting, and so on. During the action, you receive sensory information produced by the movement, such as the way it feels, sounds, and looks. After the action is completed, information is available regarding the result that the movement produced in the environment (e.g., the actions of a ball that has been struck) and, for a brief time, a memory for the how the movement felt, sounded, and looked.

These types of information have been classified under the general term “feedback”, and can be further subdivided into two broad classes: *inherent* (sometimes called “intrinsic”) feedback and *augmented* (sometimes called “extrinsic”) feedback.

### Inherent Feedback

People can gain information about many aspects of their own movements through various sensory mechanisms. These forms of information are *inherent* to the individual during the action, and result from the movement’s execution. For example, you know that an error was made in a basketball shot because you saw that the ball did not go into the basket. Also, the stinging sensations as you land on your back in a pool after a faulty dive inform you that something probably went wrong. Just about every movement we can make has associated with it certain sources of inherent feedback that provide a basis for evaluating those movements. Such feedback is usually rich and varied, containing substantial information regarding performance. Depending on the nature of the movement and the source of inherent feedback, sometimes the performer knows that something has gone wrong before the movement is even completed. The information provided as the movement is executed is sufficiently useful that the movement outcome can often be predicted even before it occurs. At other times the nature of the movement and the source of feedback are such that the evaluation of the movement must occur after it is completed.

In many situations, *inherent feedback* requires almost no evaluation at all; one sees that the bat missed the ball or one can feel the fall while walking on an icy sidewalk. Thus, some errors seem to be signaled immediately and clearly. But other aspects of inherent feedback are not so easily understood, and perhaps the performer must *learn* to recognize their occurrence and evaluate what the feedback means. Examples might be the gymnast learning to sense whether or not the knees are bent during a movement, or a patient with a recent hip replacement who is learning to put partial weight through the leg while walking with canes. It is thought that inherent feedback is compared to a learned reference of correctness, with this reference acting in conjunction with the feedback in an error-detection process. Without such a reference of correctness, many forms of inherent feedback probably cannot be used to detect errors.

### Augmented Feedback

In contrast to inherent feedback, *augmented feedback* is information provided about the action that is supplemental to, or that augments, the inherent feedback. For example, you can receive information from a warning light or sound when your car’s engine exceeds a certain temperature—information that is not normally available to you without that augmented feedback. Augmented information can be provided verbally, for example in the presentation of one’s time after a 100 m race or the set of scores after a gymnastics or ice-skating routine. Even though these various forms of information are not strictly verbal, they are in a form that is capable of being verbalized.

A number of useful dimensions for augmented feedback are summarized in [table 11.1](#). First, one can distinguish between *concurrent* and *terminal* feedback. *Concurrent feedback* is delivered during the movement (e.g., the information about engine speed that the racing driver receives from the tachometer), while terminal feedback is postponed until after the movement has been completed (e.g., the gymnast's score). Another dimension of augmented feedback is the time at which it is delivered; it can be either *immediate* or *delayed* by some amount of time. The feedback can be verbal (or capable of being verbalized) or nonverbal (e.g., a light indicating that the car's engine is too hot). Also, the performance can be sampled for a period of time, with the *accumulated* feedback indicating the average performance for the past few seconds; or the feedback can be *distinct*, representing each moment of the performance (e.g., feedback from a speedometer). (See Holding, 1965, Annett, 1969, and Singer, 1980, for additional dimensions.)

Table 11.1 Dimensions of Augmented Feedback

<b>Concurrent:</b> Presented during the movement	<b>Terminal:</b> Presented after the movement
<b>Immediate:</b> Presented immediately after the relevant action	<b>Delayed:</b> Delayed in time after the relevant action
<b>Verbal:</b> Presented in a form that is spoken or capable of being spoken	<b>Nonverbal:</b> Presented in a form that is not capable of being spoken
<b>Accumulated:</b> Feedback that represents an accumulation of past performance	<b>Distinct:</b> Feedback that represents each performance separately
<b>Knowledge of results (KR):</b> Verbalized (or verbalizable) post-movement information about the outcome of the movement in the environment	<b>Knowledge of performance (KP):</b> Verbalized (or verbalizable) postmovement information about the nature of the movement itself

These various dimensions of augmented feedback should be considered independent of one another. For example, if the augmented feedback is terminal, it could be either verbal or nonverbal, and it might be delayed or immediate. These dimensions, then, should be thought of as separate descriptors of augmented feedback that define most kinds of feedback commonly used.

### *Knowledge of Results*

One of the important categories of augmented feedback is termed *knowledge of results (KR)*. Essentially, KR is verbal (or verbalizable), terminal (i.e., postmovement) feedback about the *outcome* of the movement in terms of the environmental goal. It forms one combination of the various possible dimensions of augmented feedback (verbal-terminal) shown in [table 11.1](#). Examples are seen when the instructor says “You were 2 m off target that time” or a computer screen presents the symbolic information “long 12” (meaning that the movement was 12 units too long). Knowledge of results can be highly specific, or it can be very general. Knowledge of results can also contain a rewarding component, such as “very good.”

It is important to be clear about the use of the term KR. First, note that KR is about movement *outcome* in terms of an environmental goal (“You missed the ball”). KR is *not* feedback about the movement itself (“Your elbow was bent”). Usually this distinction is easily made; in shooting a basketball, for example, the goal and the movement to produce it are clearly separable. But often these two aspects of feedback are difficult to distinguish—for example, in a situation in which the goal of a movement *is* the form of the movement itself, as in a gymnastics move. Occasionally, other terms have been used for KR as defined here, such as *information feedback* (Bilodeau, 1966), *extrinsic feedback*, or *reinforcement* (which implies a reward). Despite these inconsistencies, the tendency is to use the term KR as we have defined it here: *verbal, terminal, augmented feedback about goal achievement*. (See Salmoni, Schmidt, & Walter, 1984, for a review of additional distinctions.)

### *Knowledge of Performance*

As already mentioned, an additional kind of feedback information concerns the *movement pattern* that the learner has made (e.g., “Your elbow was bent”). Gentile (1972) called this type of feedback *knowledge of performance (KP)* to distinguish it from KR as defined previously (see [table 11.1](#)). Knowledge of performance is probably more related to the feedback that instructors give to their students, being directed toward the correction of improper movement patterns rather than just the outcome of the movement in the environment. Also, KP can refer to aspects of the movement about which the participant is only vaguely aware, such as the behavior of a particular limb in a complex movement.

## Research on Augmented Feedback

Research related to augmented feedback has a long history. Early models portrayed human performers as computer-like processors of information (e.g., Broadbent, 1958; Sternberg, 1969), and consequently the role of feedback for motor learning has long been viewed solely from an information-processing perspective. Augmented feedback has been seen as “neutral” *information* that the learner uses to correct errors. In this view, KR and KP guide the learner to the goal movement through repeated error-identification and error-correction processes. However, more recent findings have emerged that are difficult, if not impossible, to explain solely from an

information-processing perspective. It has become clear that this view is too narrow to explain all effects of feedback. Recent findings have highlighted the impact of feedback on the learner's *motivation*, which in turn has a direct effect on motor performance and learning. Moreover, augmented feedback tends to direct the learner's attention to certain aspects of the movement. Whether it directs the *attentional focus* to body movements, promoting an internal focus, or to the movement of an implement (e.g., ball, tennis racquet, discus), promoting an external focus of attention has important consequences for the effectiveness of feedback for learning (see chapter 10). In the subsequent sections, we discuss research concerned with the informational, motivational, and attentional focus functions of augmented feedback. This discussion also shows how the views of feedback have changed over time.

# Informational Functions of Feedback

How do scientists conduct research to understand feedback and learning? What forms of feedback are useful in motor learning, and how are these forms of feedback most effectively presented to the learner? A major problem for such research is that, in most natural situations, it is difficult to *control* the information received by a performer, so the situation is not easy to study. For example, there are many sources of feedback in the task of shooting a basketball, and it is difficult to know which sources are being used at any one time and how they are being used. A typical strategy used by many researchers in motor behavior has been to alter the environment or the task (or both) so that minimal feedback information is provided to the participant, and then provide augmented feedback information artificially (in the form of KR or KP) so that the effects can be studied directly. This technique usually involves experiments with tasks that are artificial and novel. It has been assumed that a basic understanding of the functioning of error information could result from that approach, although it certainly has limitations (Wulf & Shea, 2002, 2004).

## Paradigms for Augmented-Feedback Research

Although many definitions exist (Kuhn, 1962), a *paradigm* often refers to a standardized way of gaining knowledge through research. The study of KR variables<sup>1</sup> in motor learning research was directly influenced by research in experimental psychology, and these traditions remain today (see “Origins of the KR Paradigm”). Seldom stated explicitly is the assumption that the (augmented) KR provided in these artificial learning situations is fundamentally like the (inherent) error information a person would normally receive in a more natural setting. Is it correct to say that the information “You moved 2 cm too far” in a blindfolded linear-positioning movement works fundamentally in the same way as the information received by observing visually a shot missing the basket in basketball? Certainly different processes are involved, but it is entirely possible that the use of the error information is the same in both situations, in that the information provides a basis for changing the movement on the next attempt in order to make it more accurate. If this assumption is correct, then this general method provides a way to come to an understanding of the way in which inherent feedback works to produce learning in natural environments.

The other side of the argument is that such research, using tasks that are so simple and artificial, may have little to tell us about the ways in which the rich and varied sources of inherent feedback work in more natural settings. For now, our assumption will be that the study of KR is one means to understanding the operation of inherent feedback in natural environments. However, you should remember that the principles might not be quite the same in these two situations.

### Origins of the KR Paradigm

The classic learning theories of Pavlov, Watson, Thorndike, Guthrie, Tolman, Hull, and others during the first half of the 20th century established a framework for research that remains today. One of the dominant approaches was the instrumental conditioning paradigm, influenced largely by Thorndike. The main feature of this approach was the idea that if an animal’s behavior was followed quite soon by reward, the behavior was elicited more frequently under these conditions in the future. In theory, an association (“bond”) was formed between the situation and the behavior. The association was strengthened if the behavior was repeatedly “reinforced” (by the reward). Thus, the reward was considered instrumental to the occurrence of learning.

A key feature of the instrumental learning paradigm is the assessment of learning by means of experimental extinction—a phrase coined by Pavlov to refer to the *apparent* elimination of the learned

response. Extinction is studied in the instrumental learning paradigm during a period of time when the previously rewarded behavior is no longer reinforced. Strength of the conditioned response is measured by the *resistance to extinction*, defined as the continued behavior in the absence of the reward.

The instrumental conditioning paradigm in the study of motor behavior began with Thorndike (1927). Over a period of nine practice sessions, Thorndike's participants drew lines of 3, 4, 5, and 6 in. The first session was without KR. The next seven sessions saw performance improve steadily with KR. The last session, without KR, resulted in a marked deterioration in performance. In Thorndike's view, learning occurred through strengthening the connection between a stimulus (the movement goal) and a response to that stimulus (the movement), and KR was viewed as instrumental in strengthening that bond. The purpose of the no-KR trials was to study the "strength" of the bond via the resistance to extinction.

The rationale underlying Thorndike's line-drawing experiment was not to study the laws of motor learning, but rather to investigate the generality of his Law of Effect using a motor task. For our purposes, however, Thorndike's experiment is remembered for introducing the KR/no-KR paradigm to a later generation of researchers interested specifically in human motor learning. This influence may also be considered another one of Thorndike's legacies (cf. Adams, 1978).

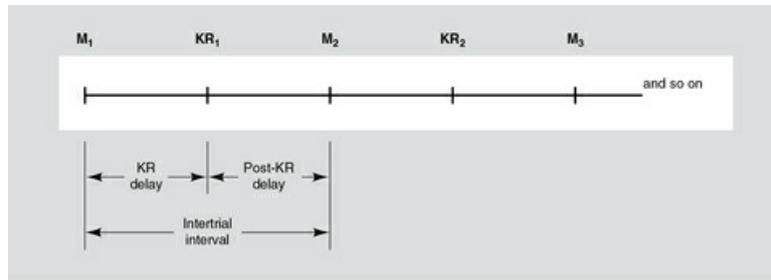
The dominant paradigm for understanding the functions of feedback information in learning is a legacy from the historical influences of experimental psychology (see "Origins of the KR Paradigm"). The KR paradigm frequently uses a movement task that is very simple; the most common task used in early research investigations was the linear-positioning task, for which the person must learn to move the arm to a given position, usually while blindfolded. In such tasks, the participant cannot evaluate performance outcome without some supplemental information because of the removal of the most potent source of inherent information (vision). If the instruction is to move the arm a distance of 20 cm, the participant cannot know for certain whether a given attempt to move that distance was correct or not on the basis of inherent information. True, the feedback from the limb is present to signal the movement details, but the individual likely does not have the reference of correctness against which to evaluate this source of inherent feedback. In some sense, the inherent feedback has not been "calibrated" to the environment. With this kind of task, one can study the use of feedback or KR by "augmenting" information to the participant in a systematic way. The most elementary of these experiments might involve the contrast between providing KR and withholding KR altogether. A more refined experiment might manipulate the time of presentation of the KR, the way in which the KR is presented (e.g., on a computer monitor or verbally, by an experimenter), or the qualitative aspects of the KR (e.g., imprecise or precise). In this way, experiments that vary the nature of the feedback given to the learner can be done in the same ways as experiments about any other independent variable. Thus, the task used must allow control over the relative usefulness of the sources of inherent feedback.

### *Temporal Placement of KR*

Many of the experiments on KR and motor learning are structured so that the temporal relation of the events in a trial is closely controlled. These events are shown in [figure 11.1](#). The participant performs movement 1 ( $M_1$ ); then, after a period of time called the *KR-delay interval*, the KR for that trial ( $KR_1$ ) is delivered by the experimenter. The period of time from the presentation of KR until the next movement is termed the *post-KR delay*, during which it is presumed that the person is processing the KR and planning the next movement. The sum of the KR delay and post-KR delay intervals is termed the *intertrial interval*. Usually the intertrial interval is on the order of 10 to 20 s, but of course these intervals can be practically any length to serve the purposes of a particular experimental situation.



Figure 11.1 Temporal placement of events in the knowledge-of-results (KR) paradigm.  $M_1$  refers to movement trial 1.  $KR_1$  refers to the augmented feedback provided about results of movement trial 1.



### Learning Versus Performance Effects

In the typical KR paradigm, the variables (such as amount of KR; absolute and relative frequency; length of, and activity during, the KR-delay, or post-KR-delay) are typically manipulated over a series of *acquisition* trials, just as we have discussed in chapters 9 and 10. After these trials, all the conditions of the particular KR manipulation (preferably involving separate groups of participants) are transferred to a common condition of KR for additional performance trials. By far the most common *transfer* test is a series of no-KR (or “KR withdrawal”) trials. Although other paradigms have been used, the no-KR transfer test has a long history of use in experimental psychology, upon which much of motor behavior research in this area is based (see “Origins of the KR Paradigm”).

Salmoni and colleagues (1984) provided a strong argument in support of the typical paradigm, in which a KR variable is manipulated during practice trials and the effects of that manipulation are evaluated in a common, no-KR transfer test. The authors argued that the two phases of the typical KR paradigm permitted a direct comparison of the effects of a KR variable on performance and learning (see chapter 9 for more explanation). Making a distinction similar to other distinctions between learning and performance (chapters 9 and 10), they argued that a KR variable that exerted an influence *only* while being manipulated was a *performance variable*. A KR variable that exerted an influence after the manipulation was withdrawn (and after the temporary influences had dissipated) was a *learning variable*.

Several arguments support the preference for the no-KR transfer test over other transfer tests in the assessment of KR effects on performance and learning. One argument is that learning can be addressed in a more steady state under no-KR than under KR trials, since continued improvements in performance are unlikely to occur in the absence of KR (Salmoni et al., 1984). A further contention is that a series of no-KR trials provides a more consistent estimate of performance capabilities and thus a more reliable account of learning effects, since performance is stabilized more in the absence than in the presence of KR (Rubin, 1978). Another argument is that the use of a no-KR test of learning is consistent with many practical applications: Augmented information supplied during training or rehabilitation is often unavailable when “real” performance is required (e.g., in a game situation or when a patient is away from the clinic).

### Evaluating the Effects of Augmented Feedback

The vast majority of the research on augmented feedback and motor learning has involved information about movement outcome (KR). For a person who has had extensive practice at a sport or occupational activity, it would seem far more effective to provide information about the movement itself, defined earlier here as KP. Why is the focus on KR when KP will probably be most useful for application? A significant reason is that experiments on KR can usually be measured easily and corrections on the next trial can be measured. But when the wanting to give KP, the experimenter has more difficulty in measuring the pattern of movement and then noting how the pattern changed on the subsequent trial. Until the 1980s or so, these procedures were quite tedious (using film analysis, strip-chart records, and so on), and many motor behavior workers chose not to use them. However, with the use

of computing technology and increased emphasis on biomechanical techniques, researchers have examined KP as a source of error information much more frequently. For now, we assume that the mechanisms involved when the learner receives any type of augmented feedback are essentially the same. We assume that what the learner does with these various kinds of information is identical; the major distinction is that these different kinds of information refer to different aspects of the movement. Thus, for example, the principles that have been discovered for KR would be applicable to situations when KP would be given. This idea could be incorrect, but until evidence appears to the contrary, the assumption is reasonable.

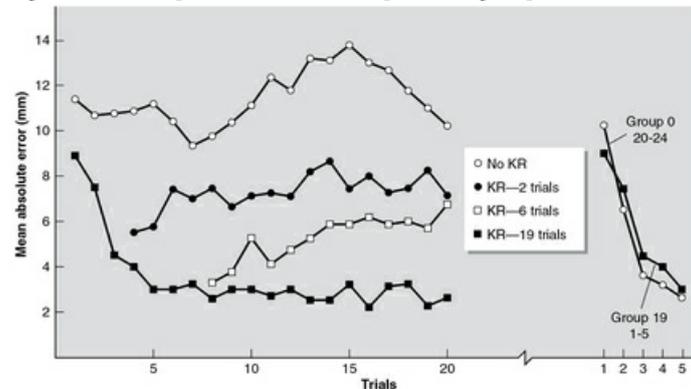
In this section, some of the fundamental principles of augmented feedback for motor learning situations are presented. A number of conclusions can be drawn from the literature, probably because this area has received a great deal of study in motor skills research (see Adams, 1987; Magill, 2001; Salmoni et al., 1984; Sigrist, Rauter, Riener, & Wolf, 2013; Swinnen, 1996; Wulf & Shea, 2004, for reviews). Also, the effects found are quite robust and large relative to those of other variables considered. First, we discuss a basic question: whether or not augmented feedback is a variable affecting performance, learning, or both. Then we discuss the research variables related to KP, and finally, we present the rather large and complex set of effects of KR variables on performance and learning.

Most of us probably suspect that KR has important effects on both performance and learning, so it is perhaps not crucial that we document these effects. But we have been fooled by our intuitions before, so we will review briefly some of the critical evidence on this issue.

### *Augmented Feedback Affects Learning*

Using the paradigm described in the previous section, Bilodeau, Bilodeau, and Schumsky (1959) employed an arm-positioning task with four groups of participants. One group had KR after the first 19 of the 20 acquisition trials, and a second group received no KR at all in the 20 trials. Two other groups received KR for two and six trials, respectively, before having KR withdrawn for the remainder of the 20 practice trials. The main findings are shown in [figure 11.2](#), where absolute error is plotted as a function of trials for these four groups. The group that had KR provided after trials 1 through 19 showed an initial sharp decrease in error, followed by a more gradual decrease. On the other hand, the group that had no KR at all showed essentially no change in performance over the 20 practice trials. For the remaining two groups, improvement occurred on trials that followed the administration of KR, but the improvement ceased when KR was withdrawn, with slight decrements in performance thereafter.

Figure 11.2 Absolute errors in a linear-positioning task as a function of knowledge of results (KR). (The group numbers indicate the number of presentations of KR received before KR withdrawal; group 0 switched to a KR condition shown at the right, where its performance is compared to group 19's first five trials replotted from left.)



Reprinted from E.A. Bilodeau, I.M. Bilodeau, and D.A. Schumsky, 1959, "Some effects of introducing and withdrawing knowledge of results early and late in practice," *Journal of Experimental Psychology* 58: 143.

Did KR affect the learning in this task? As with any other variable that could affect learning or performance, these data can be interpreted in at least two ways. First, we could conclude that the 19-trial KR group learned more than the no-KR group, as evidenced by the fact that they performed more effectively during the practice phase. But another possibility is that KR had affected performance only temporarily, perhaps through some kind of “energizing” process. Thus, it could be that when these temporary effects of KR are allowed to dissipate with rest (as with fatigue effects), the temporary effects of KR will vanish and performance will regress to the original level (see chapter 9).

Bilodeau and colleagues provided a partial answer to this question when they transferred their no-KR group to the KR conditions for an additional five trials. In the right portion of [figure 11.2](#), the absolute errors on these five trials are plotted together with those for the first five trials of group 19. The size of the errors, as well as the pattern of change with trials, was practically identical for these two sets of trials. That is, the no-KR group in this transfer condition performed nearly the same as group 19 at the beginning of their practice trials. Thus, we can say that the 20-trial no-KR practice sequence for this group did not produce any learning at all, and consequently that KR is a learning variable. And, KR is not just a variable that *affects* learning; rather, when KR is not present in such situations, learning does not occur at all. While Bilodeau and colleagues’ study uses a kind of transfer design, it does not use the typical transfer procedures we recommended earlier (see chapter 9). Similar conclusions, however, have come from a number of other studies in which relative amount learned was evaluated on no-KR transfer tests (Bennett & Simmons, 1984; Moran, Murphy, & Marshall, 2012; Newell, 1974; Trowbridge & Cason, 1932).

Knowledge of results does not always have such dramatic effects on learning motor skills, though, and the reasons often depend on the availability and usefulness of inherent feedback. For example, KR had only minimal effects on performance and learning for a tracking task in which KR was or was not provided after each trial (Archer, Kent, & Mote, 1956; Bilodeau, 1966). Similar effects have been found for learning an anticipation-timing task (Magill, Chamberlin, & Hall, 1991).

Does this mean that augmented information about errors is somehow not important for learning these tasks? Probably not. Rather, while practicing the task, participants are able to detect their own errors through the inherent feedback (visual feedback in these references) provided during the normal course of the trial. This visual information probably serves the same function as the verbal KR did in the linear-positioning experiment described earlier. This observation is in accord with the idea that the presentation of information about errors to the learner is more effectively studied in situations in which learners are unable to evaluate accurately their inherent feedback to detect errors.

### *Augmented Feedback Affects Performance*

The evidence clearly points to (temporary) performance effects of KR in addition to the learning effects we have just described. For example, KR can be “motivating” or “energizing” for the learners. Some early research shows that when KR is provided, participants report that they are more interested in the task, they seem to put more effort into practice, and they persist longer after the KR is removed, in comparison to practicing without KR (Arps, 1920; Crawley, 1926; Elwell & Grindley, 1938). In relatively boring situations such as *vigilance* tasks, in which participants are asked to spend hours monitoring a display for the appearance of a threatening object (e.g., in airport security monitoring), KR about the participant’s performance has an “alerting” (or energizing) effect, and it can act to counteract sleep loss (Poulton, 1973). All these phenomena exert strong influences on performance but weaker effects on learning (e.g., Szalma, Hancock, Warm, Dember, & Parsons, 2006).

Another temporary effect of KR is related to its informational properties, whereby KR informs the participant of the errors that have been made and then indicates what to do next. Thus, KR provides something like *guidance* for the learner. In chapter 10m we presented evidence that guidance is very effective for performance when it is present but that all or part of the beneficial effect can disappear when the guidance is removed (e.g., Armstrong, 1970a; see [figure 10.11](#)). In an analogous way, then, KR (acting as guidance) might provide strong informational support for performance when it is being administered, with the benefits disappearing as soon as the KR is removed or the task conditions are changed (Salmoni et al., 1984).

### *Untangling the Learning Versus Performance Effects*

As we have seen, variations in KR can have powerful effects on performance when KR is present, but there is good reason to question whether such effects are always “relatively permanent” to the extent that they can be thought of as learning effects. The scientific problem is to distinguish the variables that produce transient performance changes from those that produce relatively permanent changes. Transfer designs used as discussed in chapters 9 and 10 provide a good way to make this distinction in experiments on KR. However, except for a few studies (e.g., Annett, 1959; Griffith, 1931; McGuigan, 1959; Trowbridge & Cason, 1932), early feedback researchers did not take this learning–performance distinction seriously, apparently assuming that any variation of feedback that affected performance was automatically a learning variable. As we will see, there are many situations in which this assumption is simply incorrect.

## Knowledge of Performance

We begin our analysis of augmented-feedback variables by looking at studies of information that is provided to learners about the patterns of actions they make. It was Gentile (1972) who termed these kinds of feedback “knowledge of performance.” Many forms of KP are possible; they may range from rather casual comments about performance, made by a teacher or coach, to complex feedback generated by computer in a simulator and delivered to the learner online in computer-aided instruction. Some of these kinds of KP are discussed in the following sections.

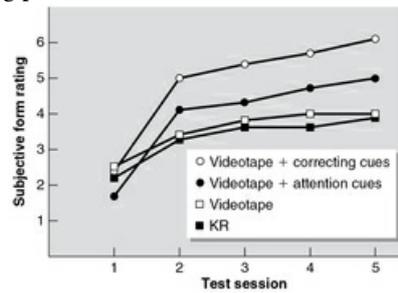
### *Video Feedback*

It would certainly seem reasonable to think of video feedback as a powerful mode in which to present KP. From a motor skills viewpoint, a video will contain a record of the entire performance, and the individual can detect errors directly and attempt to correct them on the next trial. However, for all the logic leading to the use of video feedback, as well as its use in many sport situations, the research evidence suggests that this method of presenting KP, *by itself*, is rather ineffective. Rothstein and Arnold (1976) and Newell (1981) have reviewed this work, finding that numerous experiments fail to show positive effects of these techniques for motor learning. Some evidence even suggests that video feedback might actually hinder learning (Ross, Bird, Doody, & Zoeller, 1985). One suggestion is that video feedback might provide *too much* information, especially if the skill is complex and the viewer does not know which of the many details are important. In support of this notion, Rothstein and Arnold pointed out that studies using *cuing*, in which participants were directed or taught to examine certain aspects of the display during a viewing, showed more positive effects of video feedback than did studies using

undirected viewing.

The benefits of cued or directed viewing of video feedback were shown clearly in a study by Kernodle and Carlton (1992) in which participants practiced throwing a sponge ball with their nondominant arm. After each throw, they were provided with KR regarding the distance thrown (participants closed their eyes on ball release, making the augmented feedback more important for learning) and were shown video feedback of the trial just completed. One group of participants was provided only KR, while another group watched a video replay of their own performance, with no additional augmented information. Previous research, however, had shown that combining verbal KP with other forms of augmented feedback can be quite beneficial to learning (Wallace & Hagler, 1979). So, another group received a verbal cue to watch one particular aspect of the movement during the video feedback (e.g., “Focus on the hips during the throwing phase”). A final group, before watching the videotape, was given additional augmented feedback in the form of specific error-correction information (e.g., “Rotate the hips from left to right during the throwing phase”). [Figure 11.3](#) illustrates the subjective ratings of throwing performance (or form) during no-feedback trials on five transfer tests over a four-week period.

Figure 11.3 Throwing performance under various conditions of videotape replays.



Data from Kernodle and Carlton 1992.

The results were clear: The strongest learning effects were seen when the video feedback was accompanied by error-correcting cues, although considerable gains were achieved with the attention-focusing cues as well. The video feedback alone was no better than simply providing KR. Similar results were obtained when measures of distance thrown were analyzed.

It is important to remember that video can also be used to present the performance of a model (see chapter 10). However, in both uses of videos as forms of augmented information, research has shown that they are most effective when supplemented with additional, attention-directing augmented information. Practically speaking, information provided in videos is most effective for learning when it is augmented by an instructor who can direct the learner's attention to important details and toward ignoring the irrelevant aspects. This is probably especially so if the learner is a novice, who has less knowledge than an experienced performer about what details in the video are important.

### *Kinematic Feedback*

Recall that the term *kinematics* refers to measures of “pure motion” without regard to the forces that produced them (see chapter 2). Feedback about kinematics involves various measures derived from movement such as position, time, velocity, and patterns of coordination. When coaches or teachers give information about movement patterning (e.g., “You bent your elbow that time”), they are really providing a (loosely measured) form of kinematic information, a form of KP. Expert music or dance instructors and sport coaches seem to be able to sense “what went wrong” and to provide verbal descriptors that can serve as suggestions for change in the movement. Of course, many different features of the movement can be described and used for feedback, and a major issue has been the discovery of what kinds of kinematic information would be most useful for learning and performance (e.g., Swinnen, 1996; Newell, 1991; Newell & Walter, 1981).

Early studies of kinematic information feedback were done by Lindahl (1945; see also Tiffin & Rogers, 1943), who analyzed patterns of foot-pedal actions in skilled industrial workers operating a cutting machine. Lindahl determined the most effective pattern of foot motion from measurements of highly skilled workers and then used this pattern as a “gold standard” for providing feedback about foot action to new employees. Such kinematic feedback greatly facilitated training; in as few as 10 weeks of practice, new trainees could be brought to the level of employees who had nine months of experience. Knowledge of performance about the most effective patterns of actions—not easily observable without additional measurements of the fine details of foot movements, and not easily verbalizable—was apparently critical to the establishment of proper actions in the new performers.

A key feature is that kinematic feedback informs learners about some aspect of the movement pattern that is otherwise difficult to perceive. In some cases, a whole pattern of multi-joint coordination is presented (e.g., by means of analog or digital video), showing important information about the movement of a particular joint in relation to another (e.g., Hatze, 1976). It is possible that learners could gain this information on their own, but it is unlikely that a learner would focus on the particular aspects that the instructor considers to be critical. Other kinds of information cannot be sensed at all, however, such as relative timing differences in two joints or subtle changes in velocity; and kinematic feedback can allow the learner to become aware of these features. Also,

feedback information about subtle aspects of the movement's goal has been shown to be useful; Phillips and Berkhout (1976) had participants learn gear-shifting and acceleration in a simulation of heavy truck driving and showed that computer-aided feedback about smoothness of acceleration produced marked gains measured later on a no-feedback transfer test.

But how effective is kinematic KP when compared with other types of augmented feedback? Several studies have been conducted on this issue, and the findings reveal some interesting principles. Most of this research suggests quite clearly that the effectiveness of kinematic feedback depends on the nature of the task goal. For example, participants were asked to draw geometric shapes on a tabletop in two experiments reported by Newell, Carlton, and Antoniou (1990). The task goal (a circle) was known in the first experiment, but in the second experiment, the task goal was an unknown, irregular shape. The participants were given one of three types of feedback: (1) KR about the error between their movement and the goal; (2) a digital image of the pattern plus the KR; or (3) a digital image of the feedback of the produced movement superimposed on a template of the task goal, plus KR. Learning (as measured in a retention test without any augmented feedback) was not affected by the nature of the feedback when the task goal was well known to the participants (the circle in experiment 1). However, when the task goal was unknown, there was a clear advantage for the group that received the KR plus the augmented feedback superimposed on the task goal. The benefit of augmented kinematic feedback may be optimized when its content specifies information that cannot otherwise be generated from sources such as inherent feedback or from other, less detailed sources of augmented feedback.

The role of task goal information and available sources of feedback may also be related to the findings reported by Swinnen, Walter, Lee, and Serrien (1993). Participants in this study practiced a discrete, bimanual-coordination task in which the actions of the two limbs were not the same. The left limb was to produce a unidirectional elbow flexion movement. At the same time, a flexion–extension–flexion movement of the right elbow was to be performed. Without practice, this coordination task is very difficult to perform, as there is a tendency to make the *same* actions with each arm (see chapter 8). Swinnen and colleagues (1993) found that the capability to perform each distinct limb goal improved little with practice in the absence of augmented feedback. Surprisingly, however, learning was facilitated equally well by KR (a simple outcome measure of coordination performance) and by the precise augmented kinematic feedback profiles of the two limbs. According to Swinnen and colleagues, the findings supported the idea that the limb coordination information provided by the KR was sufficient to enable participants to explore new strategies to learn the task. Thus, it seemed that practice—and strategies brought about by information sources that affected practice—combined to determine the value of augmented feedback.

In this research, the effectiveness of kinematic feedback was assessed in tasks in which the feedback was identical to the goal of the movement. For example, augmented feedback about a dive or an ice skating jump could be related directly to the movement, as the quality of the movement *represents* the task goal. However, in other skills, the outcome of an action may be quite distinct from the motions that produced it. Golfers, for example, understand that there are many different ways to get the ball into the hole.

How does kinematic feedback about movements affect the acquisition of skills in which the movements are not isomorphic with the task goal? A computer-controlled analog of a baseball-batting task was developed by Schmidt and Young (1991) to examine these issues. The task required participants to “strike” a moving-light “object” by passing a movement lever through a coincidence point as the light went by. The goal was to maximize distance, as defined by a combination of the velocity and timing accuracy at the coincidence point. On the basis of research suggesting that a particular movement pattern produced the best outcome scores (Schmidt & Young, 1991), Young and Schmidt (1992) conducted a study to assess what kinematic feedback variables facilitated learning when presented in relation to the optimal movement pattern. Their findings revealed that each kinematic variable manipulated (mean or variability of the reversal point; mean or variability of the time of the reversal) tended to facilitate the acquisition of that kinematic variable in the production of the movement. However, only the kinematic feedback about the mean reversal point was more effective than outcome KR in maximizing performance outcome. The effects of KP appear to be enhanced, however, when an optimal movement pattern is not used as a reference criterion, again suggesting that the kinematic information may be most useful when it promotes active, problem-solving activities in the learner (Brisson & Alain, 1996a, 1996b).

Similar findings reveal that kinematic feedback facilitates specific motor learning outcomes in rehabilitation. For example, Cirstea, Ptito, and Levin (2006) examined three groups of patients with hemiparesis as they practiced an arm-pointing task without vision over 10 sessions and in a one-month retention test. Compared to a control group, the individuals who received KR about movement end-point steadily learned and improved aiming precision but not speed. However, the participants who received KP about elbow and shoulder velocities mainly improved *these* performance outcomes. Thus, augmented information may contribute to specificity-of-learning effects.

In previous sections of the book we discussed findings regarding the impact of attentional focus instructions on performance and learning (see chapters 4 and 10). Similar effects are seen with respect to augmented feedback. Feedback that directs the learner's attention internally (e.g., Kernodle & Carlton, 1992) is not as effective as feedback that promotes an external focus of attention. Thus, the effectiveness of kinematic feedback might, to a large extent, depend on the type of attentional focus it promotes (see "Attentional Focus Functions of Feedback").

### *Kinetic Feedback*

Whereas kinematic measures are variables describing pure motion, kinetic measures are descriptors of the *forces* that produce the kinematic variables. We have long recognized that muscular forces and the durations over which they act are fundamental outputs of the central structures thought to organize movements; the impulse-timing theory discussed in chapter 6 is one statement of that basic view. As a result, researchers have often thought that feedback in terms of kinetics would be a "natural" kind of information for the motor system to use for learning.

Some early work supports this view. English (1942) utilized force feedback from a trigger squeeze to facilitate riflery training. Howell (1956) had participants learn a runner's sprint start and recorded forces applied against a strain gauge (a force sensor) that was attached to the foot plate in the starting blocks. The forces recorded during the time of the action provided a *force-time curve*, which was shown to participants after each trial as a form of kinetic feedback. Participants could use this information to *optimize* the form of the force-time curve (i.e., to produce a maximum impulse). Newell and Walter (1981) and Newell, Sparrow, and Quinn (1985) have provided similar examples with other tasks. The effects of this extra information are relatively permanent too, as they persist in a short-term no-feedback retention test (Newell et al., 1985), as well as in tests that occur after a long delay interval (Broker, Gregor, & Schmidt, 1993; van Dijk, Mulder, & Hermens, 2007).

Keep in mind that kinetic feedback might be confounded with attentional focus effects mentioned previously. If the provision of kinetic feedback encourages the learner to adopt an internal focus of attention, then the potential benefit of this rich form of augmented feedback might be overshadowed by the consequences of the ineffective attentional focus. In contrast, if the learner's attention is directed externally by the kinetic feedback, it may be quite effective.

## Knowledge of Results

We now turn our attention to the vast amount of research on KR—augmented information about the movement outcome. Experiments in this research area have frequently used very simple tasks, such as blindfolded limb-positioning tasks and timing tasks. The reason is that with these kinds of tasks, very little, if any, learning at all can occur in the absence of KR. In this way, the relative effectiveness of various manipulations of KR can be examined in terms of their impact on the learning process.

### *Bandwidth KR*

With the *bandwidth KR* method, the nature of augmented feedback is determined by a bandwidth about the movement goal. In most studies using this method, qualitative KR in the form of "correct" or "right" is provided to the participant when the performance outcome lies *within* the boundaries of correctness as defined by the bandwidth. However, when performance *exceeds* the bandwidth, the experimenter provides the learner with

specific KR that gives both the magnitude and the direction of error. This method is probably what many teachers and therapists do spontaneously—correcting relatively poor performance and rewarding relatively good performance.

Bandwidth KR has rather substantial effects on performance and learning. In fact, the research suggests that learning is facilitated as the bandwidth becomes *larger*. There is probably an optimal bandwidth size, although more research needs to be done to establish what this might be. Sherwood (1988) conducted one of the first studies in this area (see also Annett, 1959). Participants were to learn to achieve a rapid elbow flexion movement time as close to 200 ms as possible. Participants in a control (no bandwidth) group were told their exact movement time after each trial. In two other conditions, participants were given movement-time KR only if their outcomes exceeded a tolerance limit around the MT goal ( $\pm 5\%$  or  $\pm 10\%$ ). Performance inside the bandwidth received no *explicit* KR—which participants had been instructed to interpret as meaning that their MT had been correct. Although these bandwidth conditions had no differential effects on acquisition performance, the no-KR retention test performance was positively related to the size of the bandwidth.

Sherwood's experiment uncovered a number of important issues regarding KR and the learning process. For example, one consequence of the bandwidth KR procedure is that as the tolerance limits are increased (5%-10%), the proportion of trials supplied with *error* KR diminishes. As will be seen later in this chapter, less frequent error KR in acquisition also improves learning. So, one question is whether or not the bandwidth effect is more than just a reduced KR frequency effect. To examine this question, Lee and Carnahan (1990a) used bandwidth groups of 5% and 10% together with *yoked* control groups; the control groups received KR on the same trials as their yoked counterparts in the bandwidth groups. However, the key difference was that a bandwidth participant interpreted no KR to be feedback that the previous trial performance had been "correct." For the yoked controls, the absence of KR revealed nothing about the previous trial. Lee and Carnahan found that the bandwidth groups performed more effectively in retention than did their respective control groups, suggesting that the provision of the "correct" KR gave an additional boost to learning beyond that normally associated with less frequent KR. Similar results were reported by Butler, Reeve, and Fischman (1996) and Wright, Smith-Munyon, and Sidaway (1997). Moreover, bandwidth KR facilitated learning more than a yoked relative-frequency control group in an observational learning paradigm, supporting a high cognitive function to the provision of "correct" feedback (Badets & Blandin, 2005).

Another potentially strong learning effect that could have been going on in the Sherwood (1988) study is that the distributions of error KR and correct KR change as skill improves—the proportion of trials followed by error KR is reduced and the proportion of "correct KR" trials is increased. This seems to be an important component of bandwidth KR effectiveness, as methods of reducing the size of the bandwidth over the course of practice, keeping the proportions of error and correct KR relatively constant, have been ineffective (Goodwin & Meeuwssen, 1995; Lai & Shea, 1999).

As suggested earlier, these effects make considerable sense and have been replicated in experiments in which a golf chipping task was learned (Smith, Taylor, & Withers, 1997). The essence is that, when assisting people in learning a new skill, you might provide help when they are doing something wrong but not when they are correct (in other words, "If it ain't broke, don't fix it"). The key seems to be in deciding when is the best time to intervene and provide augmented feedback. If an optimal bandwidth exists for each person, its size would likely depend on a number of factors that may change with practice and task demands (Lee & Maraj, 1994). The effects of bandwidth KR relate closely to a class of KR-*scheduling* variables over which the experimenter has specific control, such as the frequency of KR, so-called summary KR, or average KR. As we will see, these variables also have profound learning and performance effects.

### *Relative- and Absolute-Frequency of KR*

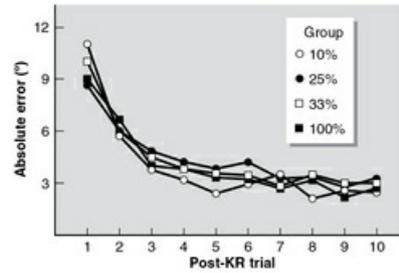
If error information is required for learning, we might reasonably expect that more KR will result in stronger learning. We can distinguish between two measures of the "amount" of KR that is provided: *absolute frequency* and *relative frequency* of KR. Absolute frequency of KR refers to the number of KR presentations received over the

course of practice. If 80 practice trials are given, and the person receives KR after every other trial for a total of 40 presentations, then the absolute frequency of KR is 40. On the other hand, relative frequency of KR refers to the *percentage* of trials on which KR is provided. It is the number of times KR is given divided by the total number of trials, multiplied by 100 for conversion to a percentage. In this example, the relative frequency of KR is  $(40 / 80) \times 100 = 50\%$ .

Which of these two KR-scheduling variables is the more critical for learning? Bilodeau and Bilodeau (1958) were the first to investigate this question, using a task in which participants turned a knob to a target position in the absence of vision. For the four different groups, KR was provided after (a) every trial, (b) every third trial, (c) every fourth trial, or (d) every 10th trial, producing relative frequencies of KR of 100%, 33%, 25%, and 10%, respectively. The number of trials performed by these groups, however, was adjusted so that all groups were presented KR after 10 trials; therefore, the group with 100% relative frequency received 10 trials, the group with 33% relative frequency received 30 trials, and so on. Thus, the experiment involved groups that had different relative frequencies but constant absolute frequencies (10) of KR.

The results for each of the four groups are presented in [figure 11.4](#). Only the trials *immediately following* the presentation of KR are plotted. This is, of course, every trial for the group with 100% relative frequency of KR, only one-third of the trials for the group with 33% relative frequency, and so on. The amount of error on each trial, as well as the pattern of change of the errors as trials progressed, was nearly the same for the four groups. Even though the groups differed greatly in terms of the relative frequency of KR, when the absolute frequency was equated, no difference in performance was found between groups. For performance, the critical feature of KR in this experiment was the number of times that KR was given; the relative proportion of trials followed by KR appeared not to be an important variable. Another way to think of this is that the no-KR trials were meaningless, neither contributing to nor detracting from performance of the task. Motor learning researchers initially took the equal performances of the various groups in [figure 11.4](#) to mean that absolute frequency is important for learning and that relative frequency is irrelevant.

Figure 11.4 Absolute errors in positioning for trials immediately following knowledge of results (KR). (Group numbers indicate the percentage relative frequency of KR.)

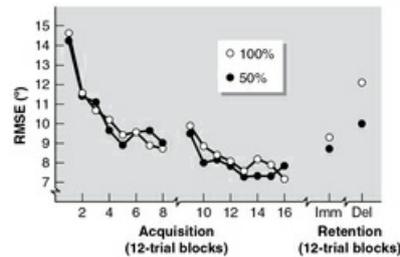


Reprinted from E.A. Bilodeau and I.M. Bilodeau, 1958, *Variable frequency knowledge of results and the learning of simple skill.* *Journal of Experimental Psychology* 55: 379.

But notice that the Bilodeau and Bilodeau study did not use a transfer design to separate the performance effects of relative frequency from the learning effects. Hence, we actually have no way of knowing whether varying relative frequency affected learning. More recently, experimenters have included these transfer tests, and the effects on learning have been mixed. Some studies showed that reduced relative frequencies of KR produced learning effects that were *as large as* those in 100% KR conditions (e.g., Lee, White, & Carnahan, 1990, experiment 2; Sparrow & Summers, 1992, experiment 1; Winstein & Schmidt, 1990, experiment 1). Yet, using similar tasks and slightly modified methods, other experiments showed that reduced relative-frequency conditions produced *more* learning than 100% KR conditions (e.g., Lee et al., 1990; Sidaway et al., 2008; Sparrow & Summers, 1992; Sullivan, Kantak, & Burtner, 2008, adults; Vander Linden, Cauraugh, & Greene, 1993; Weeks & Kordus, 1998; Weeks, Zelaznik, & Beyak, 1993). Similar effects have also been found when the provision of KR is reduced in an observational learning paradigm (Badets & Blandin, 2004; Badets, Blandin, Wright, & Shea, 2006).

An example is provided in [figure 11.5](#) (Winstein & Schmidt, 1990, experiment 2). Notice that there are no differences between the 100% and 50% relative-frequency groups in acquisition, as Bilodeau and Bilodeau (1958) had found. However, in 5 min and 24 h no-KR retention tests, a clear learning effect was shown that favored the 50% group. Thus, it seems that instead of being irrelevant for learning, reduced relative-frequency effects may be beneficial to learning!

Figure 11.5 Effects of 100% versus 50% relative frequency of knowledge of results (KR) in acquisition and retention.



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This general result has surprised many because it says that the no-KR trials, instead of being meaningless for learning as they appeared to be in the Bilodeau and Bilodeau (1958) study, contributed to the learning in some way. This contradicted a long-held suspicion that practice without feedback was useless for learning. Further, this contribution was not manifested during practice when the KR was present but was seen in a delayed retention test. Decreasing relative frequency certainly does not diminish learning and may actually facilitate it.

But there is one additional concern with these studies. When the relative proportion of trials that are followed by KR is reduced, a confounding variable arises. Compared to a 100% KR condition, if the total number of trials during practice is held constant, then reduced relative frequency of KR also results in reduced *absolute* frequency of KR. If the researcher decides to make the absolute frequency the same as in the 100% condition, then the total number of trials must be increased for the reduced relative-frequency group. In all the studies cited here, the total number of trials was kept constant. Thus, the effects of reduced relative frequency must be considered in light of the fact that fewer KR presentations were given. When we recall that learning increases with the number of KR presentations, perhaps it is not surprising that the effects of relative frequency are rather mixed. It may very well be that the positive effect of reducing the relative frequency has been offset by the negative effect of fewer KR presentations. This certainly contradicts the earlier conclusions that providing more feedback is all-critical for motor learning. And, note that delayed no-KR transfer tests were required in order to show these effects—further supporting the use of such transfer designs in motor learning research.

The effects of relative frequency appear to be clearer if the method used for reducing the presentations of KR is a "fading" procedure. Here, giving *fewer* KR presentations (trials constant) seems to greatly improve learning (Sullivan et al., 2008; Winstein & Schmidt, 1990; Wulf & Schmidt, 1989). The method usually involves providing KR relatively often during the initial stages of practice and then gradually withholding the presentation of KR more and more toward the end of practice. This method actually has an effect very similar to what naturally happens when using the bandwidth KR procedure, because skill improvements increase the likelihood that performance will lie within the bandwidth so that the provision of error KR will be withheld.

However, one further complication arises when we consider the effects of reduced relative frequency as a function of the task that is learned. Experiments have shown that when participants practice several versions of a generalized motor program, reduced relative frequency of KR facilitates the learning of invariances common to the movement pattern but not the parameterization characteristics (Wulf, Lee, & Schmidt, 1994; Wulf & Schmidt, 1989; Wulf, Schmidt, & Deubel, 1993).

A possible explanation for the relative-frequency effect in motor learning was suggested by Salmoni and colleagues (1984; see also Schmidt, 1991a; Schmidt & Bjork, 1992; Schmidt & Shapiro, 1986; Winstein & Schmidt, 1990). When KR is given on every trial (relative frequency of 100%), this condition is very effective for performance when KR is present, because of a number of temporary factors already discussed (e.g., guidance or energizing properties). However, the participant comes to rely too heavily on this information and fails to process information necessary for learning the task in a relatively permanent way; participants use KR as a "crutch." Participants in conditions of lower relative frequency, however, do not have such a strong performance enhancement from KR and so are "forced" to engage in other processes during the acquisition phase. These

processes result in the participants' learning something fundamentally *different*, such as the capability to detect one's own errors or to be consistent. Perhaps reducing the relative frequency also encourages one to make between-task comparisons, which might facilitate the abstraction of common movement attributes (Shea & Zimny, 1983; Wulf et al., 1994). This learning is not revealed during the acquisition phase because every-trial KR dominates performance, but it does contribute to performance on delayed no-KR transfer tests. According to this hypothesis, "too much" KR in acquisition is detrimental if the goal is to produce the movement without KR later, as it usually is. As we will see, this hypothesis can explain a number of seemingly contradictory findings in the KR literature and has been supported by some recent experiments to be discussed in sections that follow (e.g., Guadagnoli & Kohl, 2001).

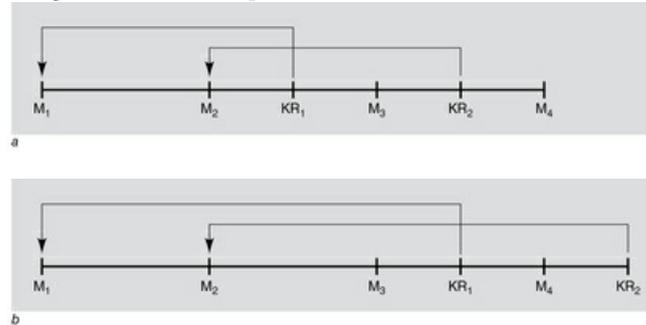
A few practical implications are possible. First, KR is certainly important for learning, as the results generally say that increasing the amount of feedback, other things being equal, is beneficial to performance and learning. But KR can be given too often; in these cases, learners come to rely too heavily on its guiding properties. This enhances performance during practice in which KR is present, but it is probably detrimental to learning as measured on a delayed test in which the learner must perform without KR. Also, relative frequency of KR should be large in initial practice, when guidance is critical; but then the instructor should systematically decrease relative frequency of KR as the performer becomes more proficient.

### *Trials Delay and Summary KR*

The literature discussed so far has involved situations in which KR for a given trial is presented before the next trial (i.e.,  $KR_n$  occurs before  $trial_{n+1}$  in [figure 11.1](#)). However, what happens if the KR from a given trial occurs *after* the performance of the next few trials? Such a procedure, at first glance, would appear to be extremely disrupting for performance; it would be difficult for the learner to know which KR to associate with which movement, particularly when KR is increasingly separated from the trial to which it refers. We can probably think of practical situations in which this effect might occur—for example, when a learner performs a number of trials in a series, *after which* the instructor or therapist gives information about each trial or maybe about just one of the trials in the series. In such situations, the first trial in the sequence is separated from its KR by the intervening trials.

This method of giving KR was given the term *trials delay* by Bilodeau (1956, 1966, 1969). In contrast to what occurs in the usual KR paradigm, we see in [figure 11.6](#) that one or more trials is interpolated between a given movement and its KR. In [figure 11.6a](#),  $M_1$  and  $KR_1$  are separated by  $M_2$ —there is a one-trial delay between a given movement and its KR. In [figure 11.6b](#) there is a two-trial delay, with two trials separating a given movement and its KR. You can probably think of many different variations of this type of KR paradigm.

Figure 11.6 The trials-delay technique, showing a trials delay of (a) one and (b) two. (A given movement and its knowledge of results [KR] are separated by other trials of the same task.)  $M_1$  refers to movement trial 1.  $KR_1$  refers to the augmented feedback provided about results of movement trial 1.



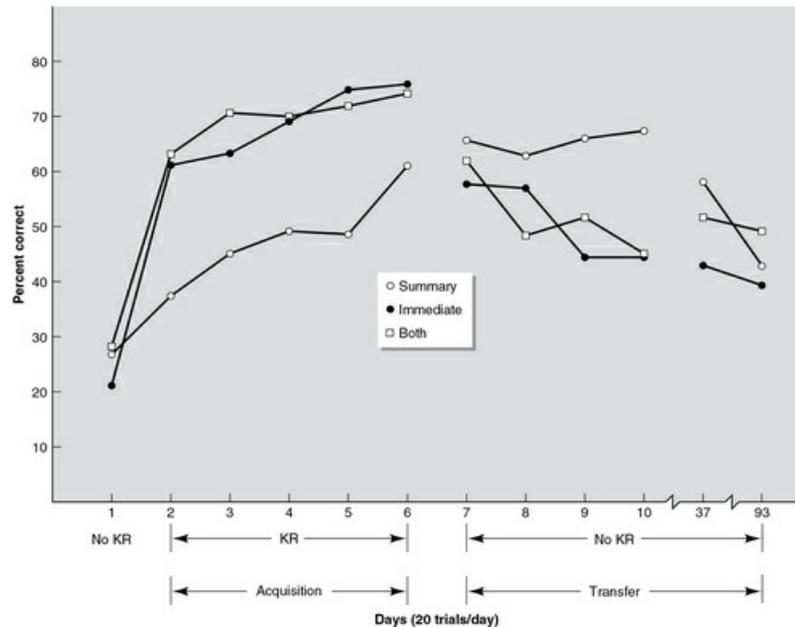
Bilodeau (1956) investigated the effects of trials delay using a lever-positioning task with blindfolded participants. In two experiments, she varied the number of trials by which KR was delayed. In experiment 1, Bilodeau used zero-, one-, two-, and three-trials delay; in experiment 2, she used zero-, two-, and five-trials delay. Participants were fully informed about this technique and were questioned to make certain that they understood how KR was being administered.

For both experiments, performance accuracy systematically decreased as the trials delay was increased. This can be seen both in the “rate” of approach to the final performance level and in the level of final performance. These findings differed somewhat from earlier ones by Lorge and Thorndike (1935), who had found that improvement in performance did not occur at all under the trials-delay method. But there can be little argument that trials delay is a variable that has drastic negative effects on performance. In the earlier literature (e.g., Bilodeau, 1966), the interpretation of these trials-delay effects was in terms of learning but these experiments did not use transfer designs to separate the temporary and relatively permanent effects. However, Lavery (1962; Lavery & Suddon, 1962) and others (e.g., Anderson, Magill, & Sekiya, 1994, 2001; Anderson, Magill, Sekiya, & Ryan, 2005) have used transfer designs in the study of this variable (and modifications of it), and their surprising results have had important influences on our thinking about how KR operates.

Lavery (1962) used several tasks in which a ball was propelled up a track to a target. Three methods were used to give KR. One was the usual condition in which KR is given after every trial, called “Immediate.” A second method was “Summary,” in which the performance on every trial in a 20-trial sequence was shown, but only after the 20th trial had been completed; no KR was given after each trial as in Immediate. This summary technique was more or less the same as the trials-delay technique, as the KR for trial 1 was separated from its trial by the other 19 movements in the block, trial 2 by the next 18, and so on. Finally, the third condition involved *both* the immediate postmovement KR and the summary, labeled “Both.” After an initial no-KR practice day, five days of practice were given under these conditions.

Performance on all the tasks averaged together is shown in [figure 11.7](#). In acquisition, the number of correct trials was far smaller for the Summary group than for the two groups with KR after each trial (i.e., Immediate and Both). The addition of the summary information to Immediate to create Both did not improve performance very much relative to providing the usual postmovement KR (Immediate), so it is clear that the major determinant of performance was the immediate KR. But we knew this before, as this pattern of results is similar to the pattern in the study by Bilodeau (1956) in that performance in acquisition (while KR was present) was hindered by the trials-delay technique.

Figure 11.7 Percentage correct trials for various summary knowledge-of-results (KR) conditions. (Immediate had KR after every trial; Summary had KR about every trial presented after each block of 20 trials; and Both had both forms of KR.)



Reprinted, by permission, from J.J. Lavery, 1962, "Retention of simple motor skills as a function of type of knowledge of results," *Canadian Journal of Psychology* 16: 305. Copyright © 1962. Canadian Psychological Association.

Now consider the measure of relative amount learned in this experiment—the performance on the transfer trials on days 7, 8, 9, 10, 37, and 93 for which no KR was provided at any time. The group that was formerly least accurate (i.e., Summary) was now the most accurate, and the other two groups, which had been the most accurate (i.e., Immediate and Both), were now the least accurate. Furthermore, the latter two groups appeared to have lost accuracy with each successive no-KR day, while the Summary group did not. The effects persisted to day 37 but were essentially gone by day 93.

Which group learned the most? Using the performance on the transfer/retention test as the measure of relative amount learned, as described earlier, we are forced to conclude that the Summary (trials delay) condition was more effective for learning than either the Immediate or the Both condition. Notice that this is yet another example showing that the most effective condition for performance in acquisition was the least effective for learning! The basic experiment was repeated by Lavery and Suddon (1962), but with the same trials-delay methods as used by Bilodeau (1956), and the results were nearly the same as the findings shown in [figure 11.7](#).

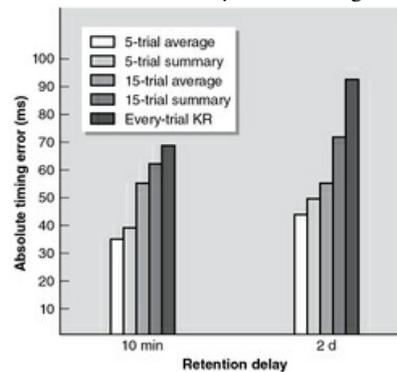
At first glance, we might be drawn to the interpretation that the summary KR per se was in some way effective for learning, providing a benefit over and above the normally useful immediate-KR condition. But look again. If summary KR was “good” for learning, then we should expect the Both group (which also had summary KR) to have benefited in a similar way. To the contrary, though, we see that the Both group performed almost identically to the Immediate group, both in the acquisition phase and in the no-KR transfer phase. One view is that, when KR was added to the normally effective summary-KR procedure to form the Both group, it *lowered* the level of learning to that of the Immediate group. In our interpretation (see Salmoni et al., 1984; Schmidt, 1991a; Schmidt, Young, Swinnen, & Shapiro, 1989), it was not that summary KR was necessarily responsible for the beneficial effect seen in learning, but that immediate KR was *detrimental* to learning! This interpretation is in keeping with the guidance hypothesis that immediate KR provides “too much” information for learners, causing them to rely on it too heavily; thus the participant is not forced to learn the information-processing activities critical for performance when KR is removed in the transfer test. Summary KR provides much less guidance, and presumably forces the participant to learn the task in a somewhat different way, perhaps by prompting the learner to gather information through alternative feedback sources (Anderson et al., 2005).

### *Optimizing Summary Length*

It would seem that summary KR could easily be overdone, with summaries of so many trials that the guidance properties of KR would be minimal. Such thinking leads to the idea that there could be an *optimal* number of trials to be summarized, and that this optimum might also vary with task complexity in some way. In an experiment by Schmidt and colleagues (1989), summary KR was provided as a graph of performance against trials and was given either after each trial (an immediate-KR procedure) or after 5, 10, or 15 trials. In a relatively simple movement-timing task, increased summary length systematically degraded performance in the acquisition phase when KR was present, as Lavery had found earlier. But surprisingly, in a delayed no-KR transfer test, the most accurate performance was achieved by the group that had (in acquisition) received the 15-trial summaries, with systematically increasing error as the acquisition summary length decreased. The effect appeared to be related to long-term retention, with systematically poorer retention as the summary length decreased. The longest summaries produce the most learning; no clear optimal summary length was evident. Similar findings were also reported by Gable, Shea, and Wright (1991), with participants in a 16-trial condition performing most effectively and no evidence for an optimal summary size.

In another investigation using a more complex, anticipation-timing task with KP provided rather than KR, summaries given after either 1, 5, 10, or 15 trials (Schmidt, Lange, & Young, 1990) were used as in the study just described. The study showed the performance in acquisition and on 10 min and two-day delayed no-KP transfer tests. Again, increasing the summary length degraded the performance in the acquisition phase, with systematically lower scores as the summary length increased. But in the no-KP transfer tests, the most effective summary length for learning was five trials; shorter (one trial) and longer (10 and 15 trials) summaries showed less effective learning. A similar set of results was also reported by Yao, Fischman, and Wang (1994); acquisition performance was least effective for conditions with the longest summary lengths (using summaries of 1, 5, and 15 trials). In the no-KR retention test, however, the five-trial summary condition was superior to both the every-trial and 15-trial summary conditions ([figure 11.8](#)).

Figure 11.8 Absolute timing errors for various summary- and average-KR (knowledge of results) conditions.



It seems clear from these studies that if optimal summary lengths do exist, these are likely to be task specific, perhaps in relation to the task's complexity. Such conclusions are supported in a clever experiment by Guadagnoli, Dornier, and Tandy (1996), in which participants learned simple and complex versions of a force production task. For the simple task, the largest (15 trials) summary condition produced the most learning; however, for the complex task, the smallest (one trial) summary group was optimal. These findings provide support for Schmidt and colleagues' (1990) suggestion that optimal summary-KR sizes are dependent on the amount of information provided in the summary, which is determined largely by the complexity of the task.

### *Statistical Summaries of KR*

In many summary-KR experiments, performance on a series of trials is presented to the participant in the form of a graph that organizes the augmented feedback about *all* of the trials in summary fashion. When multiple KR presentations need to be given, the information is more readily understood when given graphically than when given numerically (Cauraugh, Chen, & Singer, 1993), perhaps because the numeric information overloads the processing capabilities of the learner. However, there is an interesting variant of the summary procedure that has been called *average KR*. Here, instead of providing KR about a block of trials in the summary, the average of the block of trials is determined and this mean score is provided as KR. In this way, the average represents a *statistical summary* of the block of trials rather than a *graphical summary*. In the study by Yao and colleagues (1994) discussed in the previous section, two additional groups of participants received summary KR that was provided as a statistical average of either 5 or 15 trials. The results for a temporal measure of performance are presented in [figure 11.8](#) (the findings for a spatial measure were similar).

As described in the previous section, acquisition performance was related inversely to the summary size, and no-KR retention performance was most accurate for the five-trial summary group and least effective for the every-trial group. Of particular interest, however, was that the groups receiving average summaries performed similarly to the groups that received graphical summaries. This was consistent for both acquisition and retention and for both the five-trial and 15-trial summary conditions. These data suggest that the learning and performance effects of summary KR may be similar regardless of whether the summary is presented as a graph or as a statistical average (see also Weeks & Sherwood, 1994; Young & Schmidt, 1992). The similarity of effects of graphical and statistical forms of summary KR is also explained well by the guidance properties of KR, as the two methods work in similar ways to reduce the guiding properties of augmented feedback. But attempts to further tease apart the specific impact of KR summaries have had mixed success (Guay, Salmoni, & Lajoie, 1999; Guay, Salmoni, & McIlwain, 1992; Sidaway, Moore, & Schoenfelder-Zohdi, 1991; Wright, Snowden, & Willoughby, 1990).

### *Temporal Locus of KR*

The next two sections deal with the question of *when* KR is presented in the events prior to and following a practice trial. The question really concerns the three intervals defined in [figure 11.1](#)—the KR delay, the post-KR delay, and the intertrial interval—and the ways in which experimentally altering these intervals affects learning and

performance. The problem is complicated by the fact that when one of the intervals is lengthened experimentally (e.g., KR delay) and another is held constant (e.g., post-KR delay), then the third interval (in this example, the intertrial interval) must also increase. The effects of the KR delay and the intertrial interval are then *confounded*, so that any resulting change in learning cannot logically be attributed exclusively to either one of them. This fact sometimes makes it difficult to be certain about the particular roles these intervals have in the learning process, as we see in the following sections.

## KR-Delay Interval

The *KR-delay interval* is the amount of time KR is delayed after a movement. Many experimenters have examined feedback delays and motor learning, beginning with Lorge and Thorndike (1935). For a variety of reasons, scientists have always expected to find that increasing the KR delay degrades learning. One reason is that analogous effects in instrumental learning in animals are particularly strong (Lieberman, Vogel, & Nisbet, 2008). Delaying the reward (e.g., a pellet of food) slightly in time from the animal's bar-press movement has large effects on animal learning, and delaying the reward too much eliminates learning completely (Fantino & Logan, 1979; Tarpay & Sawabini, 1974). Scientists expected something like this for KR delay in human motor learning as well. A second reason is that because movement information is lost rapidly from memory (e.g., Adams & Dijkstra, 1966), learning should be less effective as the feedback delay from the associated movement is increased. This would seem to weaken the possibility for the learner to *associate* commands for the movement with its actual outcome—a concept critical to many early theoretical ideas about learning.

However, as reviewed by Salmoni and colleagues (1984), the experiments in human motor learning examining the delay of KR have almost uniformly *failed* to show that increasing the KR delay has any effect at all. For example, Lorge and Thorndike (1935) used delays of either 1, 2, 4, or 6 s and found no effect in an acquisition phase; but no transfer design was used here to evaluate effects on learning. Perhaps the delay was not sufficiently long. Other studies have used much longer delays ranging from a few seconds to a few minutes; one study even used a delay of one week! Whereas a few studies have shown small, somewhat inconsistent effects on performance, the majority of research has shown no effect (e.g., Schmidt & Shea, 1976). Recent work has used various transfer designs to assess the temporary versus relatively permanent effects of KR delay. There are numerous studies showing no effects, or at best very small effects, and we must doubt that delaying KR has a *detrimental* effect on motor learning.

In contrast, there is some evidence to suggest that detriments to learning can occur if the KR delay is *too short*. Swinnen, Schmidt, Nicholson, and Shapiro (1990) compared groups of participants who received KR after each trial—either at a short delay after performance was completed (3.2 s) or *instantaneously* upon completion of the trial. Acquisition performance was not affected on the first day of practice by the KR conditions. Performance improvements increased steadily for the delayed-KR group on a second day of practice but not for the instantaneous-KR group. Learning, as measured in no-KR retention tests after various time intervals, was also facilitated by having KR delayed for a short time. It seems that the instantaneous KR enhanced performance to a point but retarded both continued improvement and retention after that.

The degrading effects of instantaneous KR are strikingly similar to the effects of concurrent KR, discussed in the previous chapter, in the study by Armstrong (1970b). Take another look at [figure 10.11](#). In chapter 10 we discussed how guided practice degraded learning of a spatial-temporal pattern, relative to a terminal-feedback condition. Armstrong also included a condition in which augmented feedback was presented concurrently, as the participant performed the task. Although this concurrent feedback had a positive influence during practice, it severely degraded learning as seen in the transfer phase, suggesting that the concurrent feedback provided only a temporary boost to performance. These detrimental learning effects have been replicated often (Maslovat, Brunke, Chua, & Franks, 2009; Ranganathan & Newell, 2009; Schmidt & Wulf, 1997; Vander Linden et al., 1993); but they can be lessened by reducing the relative frequency of trials accompanied by concurrent feedback (Camachon, Jacobs, Huet, Buekers, & Montagne, 2007; Park, Shea, & Wright, 2000). This evidence supports the interpretation that frequent, concurrent feedback results in a learning effect that is highly dependent on maintaining the provision of concurrent information to support performance.

## Post-KR-Delay Interval

Next, consider the other portion of the intertrial interval—the post-KR-delay interval, or the time between the presentation of KR and the production of the next movement. In contrast to the hypothesis that the learner is trying to remember the aspects of the movement during the KR-delay interval, during the post-KR-delay interval it appears that other processes are occurring. In particular, KR has now been delivered, likely indicating that the movement was incorrect in some way. Now the learner must generate a movement that is *different* from the previous one, hopefully one that is more correct. So, in contrast to the hypothesis that during the KR-delay interval the learner is storing movement information, in the post-KR-delay interval the learner is thought to be an active and creative movement problem solver.

If the participant is actively processing KR to change the movement during post-KR delay, then shortening the post-KR-delay interval past a certain point should decrease learning in the task, as the person would not have sufficient time to develop an effective new movement. Some support for this view exists in the verbal learning literature using *concept-formation tasks* (e.g., Bourne & Bunderson, 1963; Bourne, Guy, Dodd, & Justesen, 1965; Croll, 1970; White & Schmidt, 1972). The literature on motor learning and performance, however, does not show close parallels to these findings for concept formation. In the acquisition phase, decreasing the post-KR-delay interval does have slight detrimental effects on performance accuracy in both adults (Weinberg, Guy, & Tupper, 1964) and children (Gallagher & Thomas, 1980), but no transfer designs were used in these studies to assess learning effects. When transfer designs are used, however, decreasing post-KR delay also degrades learning, but only when KR delay is held constant, not when the intertrial interval is held constant. Salmoni and colleagues (1984) argued, therefore, that it was the intertrial interval that seemed to be the important one for learning. But there is still some evidence that learning might be reduced when the post-KR delay is very short. Taken together, the evidence does not suggest that the length of this interval, per se, is very important for learning. But this is not to deny the role of processes that occur here, as they could occur quite rapidly for these very simple motor tasks, and varying the length of the interval might not severely limit processing.

## Intertrial Interval

The intertrial interval, or the sum of KR delay and post-KR delay (see [figure 11.1](#)), has been the object of considerable *indirect* study—mainly because it covaries when either one of the intervals composing it varies, and not because of much interest in the intertrial interval per se. According to a review by Salmoni and colleagues (1984), there are many conflicting results on intertrial-interval effects for performance during the acquisition phase, obtained from a variety of experimental procedures; little generalization seems possible. McGuigan (1959) and Dees and Grindley (1951) have shown, however, that increasing the intertrial-interval length increases learning as measured on no-KR transfer tests, similar to distributed-practice effects discussed in chapter 10. Perhaps longer intertrial intervals result in increased forgetting of the *solution* to the motor problem generated on the previous trial and thus require an active generation of the motor program again on the next trial. These forced generations could be very important for the learning process, as has been inferred from the contextual-interference literature discussed in the previous chapter.

### *Interpolated Activities During KR Intervals*

What is the effect of requiring the learner to perform various activities during otherwise “empty” KR intervals? This question is motivated by an information-processing viewpoint about KR according to which certain other activities could interfere with various processes that occur during these KR intervals and thus the effects should be seen in learning of the task. As we will see, however, various interpolated activities either have no influence, a positive effect, or a negative impact on learning, depending on the nature of the interpolated activity and the delay interval during which it is interpolated.

## Interference During the KR-Delay Interval

The influence of various activities during the KR-delay interval may be referred to as “interfering” if they distract the learner from processing the inherent feedback from the performance just completed. For example, Shea and Upton (1976) had participants perform linear-positioning movements, but *two* positions were to be practiced and learned on each trial rather than one. On a given trial, the participant would produce movement 1, then movement 2, then would engage in the performance of other movements (or would rest if in the other condition); then after 30 s the participant would receive KR about movement 1 and movement 2, then engage in the next trial, and so on. Filling the KR-delay interval increased absolute error on the acquisition trials, indicating that the extraneous movements had a negative effect on performance. And, in the no-KR transfer trials it seemed clear that the decrements in performance caused by the extraneous movements did, in fact, interfere with the learning of the tasks. Marteniuk (1986), Swinnen (1990), and Lieberman and colleagues (2008) provided similar results using more complex motor tasks.

What is happening here? One interpretation of these findings is that the participants usually engaged in various information-processing activities during the KR-delay interval and that the requirement of the extraneous movements in some way interfered with this processing, degrading learning as it did. What kind of processing might this be? Marteniuk (1986) argued that the interference is from relatively high-level planning processes. But it is also possible that the learner must retain in short-term memory the sensory consequences of the movement until the KR is presented so that the two can be compared. The retention of information is important in order to develop an *error-detection capability* (capability to detect errors based on inherent feedback sources). If other movements are required, then there will be either a blocked capacity to hold the information in short-term memory or a reduced precision of the inherent feedback, resulting in less effective use of KR when it is presented.

## Subjective Estimations During the KR-Delay Interval

Support for the interpretation just outlined is provided in situations in which learners are *encouraged* to undertake error estimation during the KR-delay interval. Hogan and Yanowitz (1978) asked some participants to estimate their own errors in a ballistic-timing task prior to receiving KR on each trial. In an acquisition session with KR present, there were essentially no differences between these participants and another group of participants who did not estimate their errors. But in a transfer test without KR, the participants who were estimating maintained performance nearly perfectly, whereas those subjects who did not estimate regressed systematically over trials. One interpretation is that the estimation conditions in acquisition forced the participants to attend to their own movement-produced (inherent) feedback to a greater extent than the no-estimation conditions did, thus enabling them to acquire an error-detection capability. This capability was not particularly useful in acquisition because of the powerful guiding properties of KR. But in no-KR transfer, learners who had gained this error-detection capability through estimation in acquisition were able to maintain performance, whereas the no-estimation participants were relatively unaware of their own errors and drifted off target. Swinnen (1990; Swinnen et al., 1990) extended and refined the Hogan-Yanowitz paradigm in various ways, using different tasks and transfer tests, in an attempt to understand these phenomena more completely. Overall, there continues to be support for the notion that asking for error estimation in acquisition is effective for learning as measured on no-KR transfer tests.

But some two additional experiments suggest that these effects might be more complex than originally conceptualized. Two recent studies have revealed this to be the case. In one study, Liu and Wrisberg (1997) investigated the effects of subjective estimations of movement form error in a throwing task by the nondominant limb (Kernodle & Carlton, 1992). Participants in two groups saw the outcome of their throw either immediately or after a 13 s delay. In two other groups, the participants provided subjective estimates of their throwing *form* either just after seeing the outcome of the throw or during the delay interval. The performance of these two subjective estimation groups was more accurate in retention than that of the two groups who did not estimate their movement form. From the perspective suggested earlier, this result is rather surprising because in the immediate + estimation group, the subjective estimation occurred after the KR, not during the KR-delay interval, which is typical of most studies of this type. One view of the results is that merely estimating something that will

be confirmed or corrected by the augmented feedback is not enough—perhaps one needs to estimate something about the performance itself, which is then supplemented by other augmented information and used in the problem-solving process.

Another study (Guadagnoli & Kohl, 2001) offers a related idea regarding the combined effects of subjective estimation and reduced relative frequency of KR. Participants performed 150 trials in a force-estimation task followed by a no-KR retention test one day later. Four groups were formed based on the factorial combination of relative frequency of KR (100% vs. 20%) and error estimation (every trial vs. no estimation). The 100% relative-frequency condition produced the most accurate retention, but only if accompanied by error estimation during practice. If KR was provided on every trial in the absence of any error estimation, then this condition produced the most error in retention. The performance of the other two groups showed that error estimation on every trial was only moderately effective when KR was presented on only 20% of the trials, but that reduced relative frequency was moderately effective even in the absence of error estimation (perhaps due to spontaneous estimation in this group).

These two experiments suggest that error estimation is an important factor in the use of augmented feedback in motor learning. The contribution of error estimation to learning appears to be diminished if it is not accompanied by augmented feedback (Guadagnoli & Kohl, 2001). Yet it also appears that estimating something about performance that encourages the learner to interpret the augmented feedback provides a boost to learning as well (Liu & Wrisberg, 1997).

The issues about error detection are important for theoretical reasons, but there is a strong practical application also. We can think of the self-detected error as a kind of substitute for KR, as it informs the participant about the size and direction of the error that was just made. It is unfortunate that nearly all the focus in learning environments is on performance and that there is almost no concern for the development of the learner's error-detection capacity (but see Schmidt & White, 1972). If procedures could be developed for increasing the strength of error detection, then learners could develop hypotheses about their performance that could then be checked against the objective information provided later in the form of augmented feedback from the teacher or coach. Effective teachers and coaches attempt to establish such error-detection capabilities that can be effectively used for self-evaluation when the teacher or coach is not present.

### Interference During the Post-KR-Delay Interval

The focus of processing activities during the KR-delay interval is on movement-produced inherent feedback. During the post-KR delay, however, the processing activities are likely focused on using augmented feedback to alter movement behavior on the next attempt. A number of early experimenters who interpolated activities in the post-KR interval showed that performance was degraded (e.g., Boucher, 1974; Rogers, 1974; but see Magill, 1973), but these studies did not use transfer procedures to assess learning (see Schendel & Newell, 1976, for a discussion). Later experimenters who used transfer tests produced mixed results. Swinnen (1990) and Benedetti and McCullagh (1987) found that interference during the post-KR delay was detrimental as measured in a no-KR retention test; Lee and Magill (1983a, 1987) found no detrimental effects of interpolated activities measured in a transfer test; and Magill (1988) found that such activities were actually beneficial. The rather equivocal nature of these findings makes it difficult to infer practical applications. However, given the comparative strength of these effects, it would appear that instructors should be more concerned about extraneous activities in the KR-delay interval than in the post-KR-delay interval.

# Motivational Functions of Feedback

As mentioned at the beginning of this chapter, the view of feedback as neutral information has a long history. Motivational influences of feedback were generally seen as being indirect, at best; it was assumed that feedback affected learners' willingness to practice. But it is easy to see that when a learner is given corrective feedback, especially when provided frequently, it may also have motivational consequences. Constant corrections could undermine the learner's confidence in his or her ability. Also, often a person already knows that he or she did not perform well on a given trial, so the feedback can be taken as adding insult to injury. Augmented feedback can also deprive the learner of a sense of autonomy if it is provided irrespective of the learner's desire to be informed, or not informed, about his or her performance. Since about 2010, research findings showing that feedback has an impact on the learner's motivation have amassed. These motivational influences are not simply side effects with indirect influences on learning. Rather, it has become clear that the performer's motivation has a *direct* impact on learning. Chapter 10 covered various motivational influences on learning. Here, we focus particularly on the role of feedback. Two types of feedback are of particular interest in this context, *self-controlled feedback* and *positive feedback*.

## Self-Controlled Feedback

In this experimental approach, participants perform a movement task and are presented with the option of receiving augmented feedback or not (e.g., Chen, Hendrick, & Lidor, 2002; Chiviacowsky & Wulf, 2002; Grand, Bruzi, Dyke, Godwin, Leiker, Thompson, Buchanan, & Miller, 2015; Huet, Camachon, Fernandez, Jacobs, & Montagne, 2009; Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997; Janelle, Kim, & Singer, 1995). For example, participants in a study by Janelle and colleagues (1997) practiced throwing a ball at a target with their nondominant arm. A control group received no KP, and another group received a summary-KP statement after every fifth trial. The group of most importance followed a self-controlled schedule, in which KP was provided only when participants asked to receive the augmented feedback. The final group was another control group that was *yoked* to the self-control group. The KP delivery schedule for each participant in this yoked group was matched to a member of the self-control group. In this way, the yoked control participants received the same number of KPs as the self-control participants, and on the same trials in the acquisition schedule sequence. The key difference was that the participant in the self-control group actively chose which trials would receive KP; the yoked participants did not.

The results of this study showed that augmented feedback was useful for learning, as all groups that received KP scored higher than the control group. More important, the self-controlled KP schedule produced more effective performance in acquisition and retention than did the yoked and summary-KP groups.

### *Other Findings and Explanations*

Subsequent studies have replicated the beneficial effects of self-controlled feedback (e.g., Chen, Hendrick, & Lidor, 2002; Grand et al., 2015; Patterson & Carter, 2010). For example, Chiviacowsky and Wulf (2002) used a task that required participants to press four keys on the numeric keypad of a computer keyboard in a prescribed timing pattern. Feedback consisted of the actual movement times, as well as the goal movement times, for each movement segment (between key presses). On a transfer test that involved novel goal movement times, the self-control group outperformed a yoked group, suggesting that the benefits of self-controlled feedback can also transfer to novel skill variations.

Self-controlled feedback has also been shown to lead to learning advantages relative to yoked control conditions in a study in which multiple tasks with different timing goals had to be learned (Patterson & Carter, 2010), in studies with children performing beanbag-tossing tasks (e.g., Chiviacowsky, Wulf, Medeiros, Kaefer, & Tani, 2008), in adults with Down syndrome learning a linear-positioning task (Chiviacowsky, Wulf, Machado, &

Rydberg, 2012), and many others. Overall, these studies provide converging evidence that giving learners the opportunity to choose feedback is more advantageous to learning than prescribed (yoked) feedback schedules. Further, the percentage of practice trials on which self-control learners requested feedback varied widely between studies, ranging from 11% (Janelle et al., 1997) to 97% (Chen et al., 2002), suggesting that the feedback frequency is less important than the learner's ability to choose or not to choose feedback.

Why does granting learners control over the feedback schedule have such a positive influence on learning?

Traditionally, the advantages of self-controlled feedback (or self-controlled practice, in general) for motor learning have been interpreted from a pure information-processing perspective. The assumption has been that self-control promotes a more active involvement of the learner and thus deeper processing of task-relevant information (e.g., Carter, Carlsen, & Ste-Marie, 2014; Chen & Singer, 1992; Chiviawsky & Wulf, 2005; McCombs, 1989).

While information processing is indeed likely enhanced when the learner is provided the opportunity to choose feedback, this explanation falls short. Converging evidence suggests that the root cause of the learning benefits is motivational in nature; self-control increases the learner's sense of autonomy (see also Grand et al., 2015). We elaborate on this view later in the chapter (see "Theoretical Issues: How Does Augmented Feedback Work?").

### *When Do Learners Want Feedback?*

A finding that aligns with the motivational interpretation of self-controlled feedback effects relates to when learners want to have feedback. Chiviawsky and Wulf (2002) used a questionnaire to find out when self-control learners decided to request (or not request) feedback. Two thirds of the self-control participants indicated that they asked for feedback predominantly after they thought they had "good" trials. In the yoked group, the majority of participants also indicated that they would have preferred to receive feedback after good trials. In fact, self-control learners asked for feedback predominantly after relatively successful trials, as demonstrated by a comparison of their error scores on trials for which they requested, or did not request, feedback. For yoked learners, the provided feedback was independent of their performance. These findings have been replicated in other studies (e.g., Chiviawsky et al., 2008; Grand et al., 2015; Fairbrother, Laughlin, & Nguyen, 2012; McRae, Patterson, & Hansen, 2015). One possible reason for the effectiveness of self-controlled feedback is that it has the potential to enhance learners' self-efficacy which, in turn, facilitates learning (see chapter 10).

## Positive Feedback

The findings by Chiviawsky and Wulf (2002) indicating that learners preferred feedback after good trials led to the question whether learning would actually benefit if participants were provided with feedback after relatively successful rather than poor trials. The issue whether learners might benefit more from positive than from negative feedback was first addressed in a study by Chiviawsky and Wulf (2007). In that study, feedback about task performance (accuracy of throwing an object at a target) was provided after each block of 6 practice trials.

However, it was provided on only half of those trials. Unbeknownst to the learners, one group of participants was given feedback about their 3 best trials in that block, whereas another group was provided feedback on their 3 worst trials. On a retention test without feedback, participants who had received feedback after their best trials during practice demonstrated more effective learning. Since then, the effects have been replicated in a series of other studies (e.g., Badami, VaezMousavi, Wulf, & Namazizadeh, 2012; Chiviawsky & Wulf, 2007; Chiviawsky, Wulf, Wally, & Borges, 2009; Saemi, Porter, Ghotbi-Varzaneh, Zarghami, & Maleki, 2012; Saemi, Wulf, Varzaneh, & Zarghami, 2011).

This issue is important from both theoretical and applied perspectives. The guidance hypothesis (Salmoni et al., 1984) does not speak directly to this point, but one of its implications seems to be that feedback is particularly important after poor trials (relatively large errors), when it is assumed to guide the learner back to the correct movement. After good trials (small errors), feedback is viewed as being of less importance. However, as discussed earlier, bandwidth feedback has been shown to enhance learning relative to yoked conditions (Lee & Carnahan, 1990a). If performance within a certain bandwidth is considered "good," it prevents the learners from receiving negative feedback about small errors. Thus, bandwidth feedback presumably gives the learner a sense of success,

which may be a reason why bandwidth feedback is so effective for learning.

In practical settings, coaches, music teachers, or other instructors are often inclined to correct mistakes rather than ignore them, and perhaps take movement success for granted rather than acknowledging it appropriately. Considering that learners often have a relatively good feel for how they performed (Chiviakowsky & Wulf, 2002), instructor feedback indicating errors may not only be superfluous, it may also be irritating or hamper learning by increasing learners' concerns about their ability. The implication of these findings is not that mistakes should be ignored and not corrected. Corrections can be made respectfully (Hooyman et al., 2014) and can speed the learning process, and sometimes they may be necessary for safety reasons. Rather, the implication is that highlighting good performances has important motivational consequences for learning.

Sometimes feedback involves video recordings of a learner's performance. Does it matter whether the video shows the learner performing well or demonstrates flaws in the movement pattern? Seeing oneself perform, especially when combined with augmented feedback or a video presentation of the goal movement, can be effective as it may lead to a better understanding of what one should be doing differently. Yet the benefits of videos showing good performances have likely been underestimated. In a few studies, the effects of edited video feedback about learners' best performance (self-modeling) were compared with video feedback about their actual or average performance, no video feedback (Clark & Ste-Marie, 2007), or verbal instructions (Ste-Marie, Vertes, Rymal, & Martini, 2011). Learners who watched the edited videos that showed their best swimming strokes or trampoline skills demonstrated enhanced learning relative to groups whose video feedback included both good and less-than-perfect (i.e., actual) performances, or who were provided only verbal instructions.

Verbal or video feedback that highlights good as opposed to poor trials increases individuals' confidence in their ability to perform well, and therefore increases learning. Various studies examining positive feedback have found increased perceptions of competence (Badami, Vaez Mousavi, Wulf, & Namazizadeh, 2011; Saemi et al., 2011) or self-efficacy (Badami et al., 2012; Saemi et al., 2012), greater satisfaction with performance, and higher intrinsic motivation (Clark & Ste-Marie, 2007). These motivational effects of positive feedback are not trivial (see chapter 10). The conviction that one is doing well, and the confidence in being able to perform well in the future, are preconditions for optimal performance and learning. They are also a key factor in the OPTIMAL theory of motor learning (see chapter 12).

## Attentional Focus Functions of Feedback

As discussed in chapter 10, instructions that direct attention to the intended movement effect (external focus) benefit performance and learning compared with instructions that direct performers' attention to their own movements (internal focus). Even though fewer studies have examined effects of attentional focus induced by feedback, the results are consistent with those induced by instructions (given prior to performance). The feedback studies have also revealed findings that seem to shed new light on how augmented feedback works. In particular, the effects of different *frequencies* of feedback seem to depend on the type of attentional focus they induce.

### External Versus Internal Focus Feedback

In the first study to examine the role of the learner's focus of attention promoted by feedback, Shea and Wulf (1999) found that feedback was more effective when it induced an external rather than internal focus. Although the feedback provided to different groups was actually identical, the learners' interpretation of that feedback differed. The authors used a stabilometer balance task and presented two groups of participants with the same concurrent feedback while they practiced to balance on the platform. The feedback consisted of two lines on a computer screen in front of them that mimicked the movement of the platform. One group of participants was informed that the lines represented their feet (internal focus), whereas the other group was told that the feedback represented two lines marked to the platform in front of their feet (external focus). When participants thought the feedback was representing lines rather than their feet, performance was enhanced not only during practice but also on a retention test without feedback one week later.

A couple of other aspects of this study are noteworthy. First, the concurrent feedback of the platform movement on the screen presumably did not provide augmented information beyond what the performer could derive from her or his intrinsic feedback. Yet relative to two additional groups that were simply instructed to concentrate on the lines or their feet, the two feedback groups outperformed the two instructed groups. Thus, the feedback generally provided an advantage, despite its apparent redundancy. Second, in previous studies that examined concurrent feedback (e.g., van der Linden, Cauraugh, & Greene, 1993), performance typically deteriorated when feedback was removed on retention tests. This was not the case in the Shea and Wulf study, though.

How can these results be explained? It is possible that the feedback itself produced a more distal external attentional focus. As discussed in chapter 10, a greater distance of the external focus from the body can increase the learning benefit (e.g., McNevin et al., 2003). In other words, the concurrent feedback on the screen might have served as a remote focal point (even when participants were asked to think of the feedback as representing their feet) that actually promoted an external focus. Also, the beneficial effects generalized to the retention test, suggesting that learners did not become dependent on the feedback. It is possible that dependency effects occur primarily in "artificial" laboratory tasks, where learners have to rely on the augmented feedback, because they are deprived of intrinsic feedback. The Shea and Wulf findings suggest that the function of augmented feedback is not only informational in nature but also directs the learner's attentional focus, with important consequences for learning.

A study by Hodges and Franks (2001) found similar effects. Even though the study was not specifically concerned with attentional focus effects, the two types of feedback compared in their experiment likely promoted an external versus internal focus. The task involved learning a new bimanual coordination pattern by simultaneously manipulating two levers. Continuous flexion and extension movements of the two arms were required, with one arm leading the other by a quarter of a cycle (90°). If the pattern was produced correctly, it created a circle on a computer screen. Two different types of feedback were compared, both of which were provided concurrently with the movement. In the "circle feedback" condition, participants were continuously shown the pattern they were creating on the screen. They were aware that the goal pattern was a circle, but they were never explicitly informed how to coordinate their arm movements in order to produce a circle. In the "limb feedback" condition, participants were informed about the required coordination pattern of their arms, and they were provided with

online feedback about the position of each arm at each point in time. In addition, after every fourth trial both groups received feedback about the actual pattern produced relative to the goal pattern of a circle. Thus, even though the two feedback conditions differed in various regards (e.g., the complexity of or the amount of information provided by the feedback), the “circle feedback” condition could be considered an external-focus condition, whereas the limb feedback condition could be considered an internal-focus condition. The results showed that circle feedback resulted in a more accurate bimanual coordination pattern than limb feedback during the practice phase, as well as on retention tests (with and without feedback). Apparently, simply providing learners with the goal pattern and feedback about the pattern they actually produced was enough to result in the learning of the correct coordination pattern. It was not necessary to inform them about how their arms needed to be coordinated in order to produce the pattern. In fact, instructing them and providing them feedback about the arm movement coordination pattern led to less effective performance and learning.

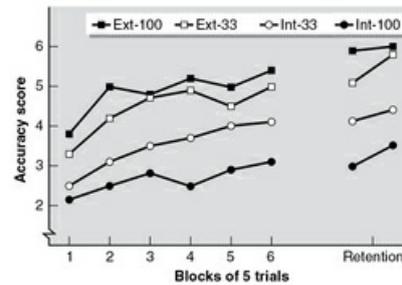
In contrast to the experimental technique in the Shea and Wulf (1999) study, which involved identical concurrent feedback provided by a computer, in practical settings, such as sports or clinical rehabilitation, coaches or instructors usually give verbal feedback after movement execution. Moreover, that feedback often refers to a certain aspect of the movement form. That is, based on what an instructor believes needs improvement, he or she gives feedback that is intended to help the performer make appropriate changes on subsequent attempts. Therefore, a study by Wulf, McConnel, Gärtner, and Schwarz (2002, experiment 1) was designed to simulate the feedback a coach would give. Arguably, that feedback often refers to body movements. Would verbal feedback that provided essentially the same information, but without references to body movements, be more effective? Novice and experienced volleyball players were asked to perform volleyball “tennis” serves, but different groups received slightly different feedback statements. For the internal-focus feedback group, the feedback statements referred to the performer’s body movements (e.g., “Shortly before hitting the ball, shift your weight from the back leg to the front leg”). For the external-focus feedback group, these statements were then “translated” so that they basically contained the same information but directed the performers’ attention more to the movement effects (e.g., “Shortly before hitting the ball, shift your weight toward the target”). The wording of the feedback indeed made a difference, and it did so for both novices and experienced volleyball players. Those who had received feedback that directed attention externally demonstrated greater accuracy of their serves, not only during practice but also on a delayed retention test.

## Feedback Frequency and Attentional Focus

Feedback is evidently more effective when it promotes an external rather than internal focus, and even concurrent feedback can result in learning advantages when it facilitates an external focus. Therefore, one might wonder if a high frequency of verbal external-focus feedback would be more effective for learning than a reduced frequency, even though such a finding would be at odds with the guidance hypothesis (Salmoni et al., 1984). This question was addressed in a couple of studies (Wulf et al., 2002, experiment 2; Wulf, Chiviacowsky, Schiller, & Ávila, 2010). Wulf et al. (2002, experiment 2) asked participants with soccer experience to perform lofted passes. Participants aimed at a target that was hung in the soccer goal. As in their volleyball study (experiment 1), the feedback statements given to internal-focus and external-focus groups were similar in information content. In this study, though, different internal and external focus groups were given feedback either after every third (33%) or every practice trial (100%), resulting in four groups: internal-33%, internal-100%, external-33%, and external-100%. When feedback was given, one of the five different feedback statements was selected, depending on which aspect of the skill needed the most improvement. The two external-focus feedback groups (external-100%, external-33%) had overall higher accuracy scores than the two internal-focus feedback groups (internal-100%, internal-33%) on a retention test conducted a week later. Also, while 100% feedback negatively affected learning, relative to 33%, in the internal-focus condition, the opposite was the case for the external-feedback condition where 100% tended to result in greater accuracy than 33% feedback ([figure 11.9](#)).



Figure 11.9 Accuracy scores of the external and internal focus feedback groups with 100% or 33% feedback.



Reprinted, by permission, from G. Wulf et al., 2002, "Enhancing the learning of sport skills through external-focus feedback," *Journal of Motor Behavior* 34: 171-182.

The overall results were essentially replicated in a subsequent study (Wulf, Chiviakowsky, Schiller, & Ávila, 2010). This study was designed after a previous one in which the authors examined the effects of different feedback frequencies on the learning of a soccer throw-in skill in 12-year-old children (Weeks & Kordus, 1998). In the Weeks and Kordus study, one of eight possible feedback statements was provided after every trial (100% group) or after every third trial (33% group) during practice. In line with many other feedback studies, the reduced feedback frequency resulted in a more effective learning. Ratings of movement form were higher in the 33% group compared with the 100% group. The findings were interpreted in terms of the guidance hypothesis. That is, it was assumed that the 100% feedback frequency created a greater dependency on the augmented feedback than did the 33% frequency. It is important to note, though, that the feedback statements in that study mostly referred to movements of various body parts (e.g., "The feet, hips, knees, and shoulders should be aimed at the target, feet shoulder-width apart;" "The back should be arched at the beginning of the throw;" "The arms should go over the head during the throw and finish by being aimed at the target"). Thus, the constant internal-focus feedback in the 100% group may well have been responsible for the detrimental effects on learning. Therefore, Wulf et al. (2010) added two groups (100% and 33% feedback) to the study design used by Weeks and Kordus, but otherwise used the same age group, task, and similar procedures. The added groups received feedback statements that were similar but induced more of an external focus (e.g., "The sneakers should point at the target; keep them apart;" "Produce a C at the beginning of the throw;" "Propel the ball forward and release it in front of you, aiming at the target"). Not only did external focus feedback result in better movement form, as seen on a transfer test with the target placed at a novel distance, the group with a 100% external-focus feedback clearly outperformed all other groups. The advantageous effects of a high frequency of external-focus feedback cannot be explained from a guidance perspective. In the next section, we try to make sense of these apparently contradictory findings and review what we currently know about how augmented feedback works.

## Theoretical Issues: How Does Augmented Feedback “Work”?

The previous sections have presented various findings in connection with the functioning of augmented feedback in motor learning situations. Augmented feedback used to be seen almost exclusively from an information-processing perspective; now, it is clear that feedback is more than neutral information. It can influence the performer’s motivation, which in turn can have a direct impact on learning. Moreover, how feedback directs the learner’s attentional focus has a decisive effect on motor performance and learning. In this section, we consider these various roles of feedback.

### Informational Role of Feedback

The research related to the informational role of feedback presented in this chapter suggests various ways in which KR and KP can affect learning.

In previous sections we have drawn attention to a number of features that are common to KR in human motor learning situations and reward in animal learning situations. Both KR and reward are presented contingent on the nature of the movement, and both are given after the movement. What is the evidence that KR and reward are really different?

That KR and reward might be similar is not a new idea at all, and it is the foundation of the Law of Effect (Thorndike, 1927; see Adams, 1978, 1987). This law states that the organism tends to repeat rewarded movements and to extinguish (or avoid) movements followed either by no reward or by punishment. For motor learning, according to this concept, KR indicating small errors or no error was thought to be a type of “reward,” and KR indicating large errors was thought of as “punishment.” In this way, the movements followed by non-reward were eliminated, and those followed by reward (i.e., zero or small error) tended to be repeated, leading to decreasing errors with practice.

However, numerous lines of evidence suggest that humans do not use KR as proposed by this interpretation of the Law of Effect. First, when KR is not presented (on no-KR trials), participants tend to *repeat* the given movements rather than to eliminate them. Only when KR is presented do participants change their movement behaviors, and then quite clearly in the direction of the target. It would seem that participants are not using the KR as a reward, but rather as *information* about what to do next. In addition, even a short delay of reward in animal learning severely retards acquisition, and delaying reward by 30 s or so can eliminate learning. Of course, we do not find these effects at all in humans, as the delay of KR seems to have no effect on motor learning. Thus, reward in laboratory rats and KR in humans seem to involve fundamentally different principles of operation.

For these major reasons, the current belief about augmented feedback is that it produces learning more by the provision of *information* about what was wrong with the previous trials—and by *prescriptive* means to improve performance (Newell, 1991)—than through the rewarding of correct movements and the “punishment” of incorrect ones. This interpretation would seem to contradict the findings from manipulations of bandwidth KR; in these experiments, information conveying to the learners that performance was correct gave an additional boost to learning in comparison to the learning in no-KR trials (Lee & Carnahan, 1990a). We suggest that the boost to learning came from the information content provided by this “no error” type of feedback. That learners resist making changes to performance on the basis of what could be “noise” might be a way of avoiding the negative influences of too-frequent augmented feedback (see “Inducing Maladaptive Corrections”).

One further suggestion is that KR has *optimal* informational value when the learner is *uncertain* about the reliability of his inherent sources of information. A dictionary provides a useful analogy here. The dictionary is like KR in that it is an externally available, objective, and reliable source of knowledge, providing augmented information such as the spelling or meaning of a word. The decision to consult a dictionary arises because we have questioned the reliability of our inherent knowledge; we do not consult the dictionary otherwise. Thus, the

dictionary provides the means for assessing (and improving) the reliability of our spelling knowledge. One hypothesis arising from this analogy is that augmented feedback can be optimally useful when the learner asks for it—which has been demonstrated in numerous studies (see “Motivational Functions of Feedback”).

### *Guidance Function*

Another view of how KR works is that it guides the learner to making the correct movement. Thus, when the learner makes a movement, KR informs the person about how the movement was inadequate, and the learner then changes the movement to one that (hopefully) will be more adequate. Augmented feedback thus carries inherent “instructions” about which aspects of the movement should be changed, as well as about the directions those changes should take. According to this position, KR does not provide any direct strengthening of the movement but creates it indirectly by guiding the person to the proper action. Once the proper actions are being produced, other processes take over to help the person learn the task.

This view is fundamental to Adams’ (1971) learning theory, which says that KR presented after each trial of a slow positioning movement guides the person toward the correct location. Then, as the learner achieves positions close to the target, he or she also receives kinesthetic feedback associated with the proper position, and this feedback forms an internal representation of being at the target (a reference of correctness). This internal representation becomes stronger with each successive trial near the target and thus provides an increasingly effective means for detecting errors. Thus, according to Adams, KR has a guidance role in driving the learner closer and closer to the target so that a reference of correctness can be formed.

Considered in this way (as envisaged by Adams, 1971), the guiding influences of augmented feedback on learning should always be positive. As we have seen, however, in some experiments the KR effects showed that increased guidance *degraded* learning (leading to doubts about Adams’ theory; see chapter 12). We consider reasons why feedback can degrade learning in the next sections (see also Salmoni et al., 1984; Schmidt, 1991a; Schmidt & Bjork, 1992).

### *Blocking Other Processing Activities*

When augmented feedback is provided frequently, immediately, or otherwise in such a way that various processing activities are not undertaken, then there will likely be a decrement in learning. One of the negative influences of augmented feedback may be to *block* the processing of inherent sources of feedback, which then leads to the failure to learn error-detection capabilities for this task. Augmented feedback is often a very salient source of information. The presentation of instantaneous KP (Swinnen et al., 1990), which was discussed earlier, is an example of a case in which the saliency of the augmented feedback is maximized. We interpret results of this type as suggesting that the augmented feedback blocked the processing of alternative sources of information and reduced the learning effectiveness of the practice session as measured in retention.

### *Inducing Maladaptive Corrections*

One of the fundamental views about the directive function of augmented feedback is that it tells the learner what went wrong and how to fix it. When each trial is followed by information about errors, there is a tendency for the learner to make a change for the next trial based on that error. The problem is that motor performance is variable, and a change meant to correct a very small error might actually make the error larger on the next trial. The idea is that KR induces movement variability, not all of which is adaptive in producing improved learning. Sometimes augmented feedback can have maladaptive corrective properties (R.A. Bjork, personal communication), in which case withholding feedback (and stabilizing performance) seems to be beneficial for learning. Presenting information that encourages a learner to correct an action that was essentially accurate may have a detrimental impact on learning (Schmidt, 1991a; Schmidt & Bjork, 1992).

Bandwidth KR effects illustrate how maladaptive corrections may be avoided. Under bandwidth KR conditions,

there exists a zone of acceptable error within which movement is considered correct. Defining the actual width of the band of correctness, as well as what would be considered maladaptively corrective and what would be considered too imprecise, is a challenge for future research. However, we suspect that an *optimal KR bandwidth* may be closely related to the precision of an individual's motor control capabilities, although even within an individual this is likely to change (e.g., with learning and aging).

## Motivational Role of Feedback

Chapter 10 included discussion on different motivational influences on learning, specifically those that affect performers' expectancies and their perceptions of autonomy. Practice conditions that enhance learners' expectancies for future performance or provide them with a sense of autonomy have been shown to positively affect learning, whereas conditions that highlight errors or poor performance or are controlling in nature result in nonoptimal learning. These principles also apply to feedback. When feedback is provided on relatively successful rather than unsuccessful trials, learning is enhanced (e.g., Chiviawosky & Wulf, 2007). Similarly, video feedback showing good performance as opposed to actual (good and poor) performance facilitated learning (e.g., Clark & Ste-Marie, 2007). Those findings cannot easily be explained with differences in information processing between conditions. In fact, one might argue that, if the main function of feedback is to provide error information, feedback after poor performance should have been more valuable and effective for learning. However, that is not the case. What can explain these findings?

Allowing learners to choose feedback has consistently led to more effective learning than (yoked) control conditions without choice. These benefits have also been attributed to differences in information processing between self-controlled and yoked feedback conditions (e.g., Carter, Carlsen, & Ste-Marie, 2014; Chen & Singer, 1992; Chiviawosky & Wulf, 2005). However, it has become clear that a bigger picture is being missed by such a narrow view. As stated earlier in this chapter, enhanced information processing is likely a consequence of having choices, but it is not the root cause of the beneficial learning effects of self-controlled feedback. Recall that many other conditions in which learners are given choices—even incidental choices—have been found to enhance learning (see chapter 10). Overall, those findings strongly suggest that the support of learners' need for autonomy is the underlying cause of the effect. It has also been shown repeatedly that self-controlled learners tend to request feedback after trials with relatively small errors (e.g., Chiviawosky & Wulf, 2002; Chiviawosky, Wulf, Medeiros, Kaefer, & Tani, 2008; Patterson & Carter, 2010; Patterson, Carter, & Sanli, 2011). Thus, one reason for the effectiveness of self-controlled practice conditions may be that they have the potential to enhance learners' self-efficacy, a factor that is predictive of learning (e.g., Stevens et al., 2012) and is also a key variable in the OPTIMAL theory of motor learning (Wulf & Lewthwaite, 2016; see chapter 12).

Self-efficacy may also play a role in other feedback-related contexts. Learning is typically assessed by delayed retention or transfer tests without feedback, based on the premise that potential temporary effects of different feedback frequencies that may be present during practice have a chance to dissipate during the retention interval (Salmoni et al., 1984; Schmidt, 1991). An alternative explanation may be that, after having been provided with constant feedback (100%) during practice, learners' confidence in being able to perform the task completely without feedback, especially after a longer delay, may be lower than that of learners who have experience performing the task without feedback (e.g., on 50% of practice trials). Considering the influence of self-efficacy on learning (e.g., Holladay & Quinones, 2003; Stevens et al., 2012), self-efficacy might well play a mediating role in different feedback conditions as well. This includes summary or *average feedback* conditions, which seem to have similar effects as reduced feedback frequencies. *Bandwidth feedback* (e.g., Lai & Shea, 1999; Lee & Maraj, 1994; Sherwood, 1988), which involves no feedback within a certain performance range (learners know that their performance is "good" if they are not provided feedback), may have an additional benefit. No feedback will be interpreted as positive feedback, with concomitant motivational and perhaps attentional focus effects. In future studies, researchers will need to unravel the various effects of different feedback manipulations and determine the extent to which motivational or attentional focus influences contribute to the learning effects seen under different feedback conditions.

## Attentional Focus Role of Feedback

The effects of the attentional focus that is induced by feedback have revealed additional limitations of the guidance explanation of feedback (Salmoni et al., 1984). In fact, several of those findings seem to be at odds with the guidance notion. First, it cannot explain the learning benefits of external relative to internal focus feedback (e.g., Shea & Wulf, 1999; Wulf, Chiviacowsky, Schiller, & Ávila, 2010; Wulf et al., 2002; experiment 1). More important is that interactions of feedback frequency and attentional focus (Wulf, Chiviacowsky, Schiller, & Ávila, 2010; Wulf et al., 2002; experiment 2)—with frequent external-focus feedback enhancing learning and frequent internal-focus feedback degrading learning—partially contradict the guidance idea. Furthermore, failures of frequent internal-focus feedback to produce a benefit during practice (Weeks & Kordus, 1998; Wulf et al., 2002; experiment 2) cannot be explained by the guidance hypothesis. How can the apparently contradictory findings in the feedback literature be reconciled?

Recall that the guidance hypothesis was developed based on findings from experiments that used relatively simple laboratory tasks. In these situations, participants are often deprived of natural sources of feedback in order to examine various manipulations of experimenter-provided feedback. It is therefore likely that they indeed developed a dependency on augmented feedback when it was provided frequently. Furthermore, simple laboratory tasks are perhaps particularly prone to inducing an internal focus, or a focus on their movements may be participants' default focus in experimental and other social settings. This would explain the detrimental effects of frequent feedback. In contrast, frequently provided external-focus feedback helps learners maintain an external focus. Thus, these findings suggest that more of a good thing (i.e., frequent reminders to adopt an external focus) is good, as is experiencing less of a detrimental influence by way of limited use of an impairing internal focus.

How a person's focus of attention affects performance and learning has already been discussed in chapter 4. Because of the importance of an external focus induced by instructions or feedback, it is also a major factor in the OPTIMAL theory of learning (Wulf & Lewthwaite, 2016), which is described in the following chapter.

## Summary

Feedback is that class of sensory information that is movement related, and it can be classified into two basic categories—*inherent* (intrinsic to the task) and *augmented* (supplementary to the task). Two major classes of augmented feedback include KP, which is information about the form of the movement, and KR, which is verbal postmovement information about performance outcome. Much research suggests that the provision of feedback is one of the most important variables for motor learning.

Information about the learner's movements (KP) can be given through video feedback, recordings of the force-time characteristics of the movement (kinetics), or representations of the movement trajectories (kinematics); and all these appear to have positive effects on performance and perhaps on learning. The impact of KP on learning appears to be strongest when it precisely specifies information that is critical for movement efficiency and that cannot be obtained from other sources of feedback.

Presenting combinations of qualitative and quantitative KR, based upon a goal-related bandwidth of correctness, has strong beneficial effects on learning. Early research indicated that the *relative frequency* of KR (the percentage of trials on which KR was given) was irrelevant for learning, whereas the absolute frequency (the number of KR presentations given) was the critical determinant. Later studies using transfer designs contradicted this position, indicating that both were clearly important. Trials on which no KR is given appear to contribute to learning in the task, but not as much as the KR trials do. The trials-delay and summary-KR procedures, in which the KR for a given movement is separated from the movement by other trials, were shown to produce detrimental effects on motor performance but positive effects on learning.

The effect of delaying KR, that is, the effect of the interval from the movement until KR is presented, has been found to be negligible for learning most motor tasks, as long as KR is not presented too soon after performance. Filling this interval with activities not related to the task degrades learning. However, filling this interval with activities related to the task, such as subjective estimation processes, enhances learning. If the post-KR-delay interval—the interval from the KR until the next movement—is too short, participants appear to have difficulty generating a new and different movement on the next trial. However, filling this interval has uncertain effects on learning.

Augmented feedback appears to have several possible mechanisms for enhancing learning. It acts as *information* and also acts to form *associations* between movement parameters and resulting action. Within its informational role, augmented feedback has a guidance property that can enhance performance but degrade learning.

Feedback also has an important motivational role. In line with other findings showing that enhanced expectancies for future performance are critical for optimal motor learning, feedback that highlights good performance facilitates learning. Another motivational influence is seen when learners are in control of the delivery of feedback. Self-controlled feedback is one way of satisfying learners' need for autonomy. In addition, it gives learners the opportunity to choose feedback after presumed successful trials, contributing to their confidence in their future task performance.

Feedback directs the learner's attention. The attentional focus significantly impacts performance and learning. Thus, the wording of feedback—whether it refers to body movements (internal) or directs attention more to the intended movement effect (external)—determines its effectiveness. When feedback induces an internal focus, less of it is less detrimental. External-focus feedback results in more effective learning, especially when given frequently (or even concurrently), relative to internal-focus feedback. Future studies should examine to what extent beneficial learning effects of reduced feedback are, in fact, due to enhanced processing of intrinsic feedback and to a greater independence from augmented feedback—or to less frequent (and maybe unwanted) error feedback, which may direct learners' focus to their movements, possibly undermining their self-efficacy.

### Student Assignments

1. Prepare to answer the following questions during class discussion:
  - a. Choose any sport skill, and provide examples for augmented feedback that could be useful in learning this skill. Keep in mind the effects of attentional focus promoted by feedback.
  - b. Describe how an occupational therapist may use feedback to enhance patients' performance expectancies.
  - c. Discuss the various roles of feedback (informational, motivational, attentional focus) and how they might be related.
2. Find a research article published in the past 5 years that examines the influence of augmented feedback on the performing or learning of a motor skill.

## Notes

<sup>1</sup> Although we have distinguished between various types of augmented feedback, of which KR is one, we will generally refer to many aspects of this work in relation to the term KR. However, exceptions will be made when a clear distinction is necessary.

# Chapter 12

## The Learning Process

So far in the discussion of motor learning, our major concern has been the most important empirical findings about the acquisition of skills. It is time now to consider the underlying reasons for these findings and to ask about the nature of the motor learning processes that cause the motor system to behave in the ways identified in previous chapters. A part of this process is theoretical, in that we search for a fundamental understanding—stated as theories—of how the system “works” when it learns. But part of it is practical, in that a solid understanding of the system’s function provides suggestions for practical application to situations that have not actually been studied; there is nothing as practical as a good theory (Kerlinger, 1973).

In this chapter, we consider the many ways in which various people have conceptualized the motor learning process. All these theoretical perspectives have as their basic goal an understanding of the changes in skill that occur with practice. However, we will see that a phenomenon as broad and common as this can be explained in various ways and at a number of levels of analysis (biomechanical, cognitive, and so on). At the same time, we will see that the concepts basic to these various theoretical ideas are already familiar from previous chapters, having to do with such notions as the building of new motor programs, changes in attentional requirements, the development of error-detection processes, and the like.

The chapter is divided into four major sections. The first section presents some fundamental ideas about the learning process. With this information in mind, together with information from the previous two chapters, we then present various theoretical views about motor learning. Two of these, which were considered major theoretical advances in the history of motor learning research, are presented in the second section of the chapter. The third section presents different perspectives on the learning process—perspectives that in one form or another can be considered major hypotheses about learning. The last section discusses the most recent motor learning theory, which explains the motivational and attentional focus influences on learning outlined in chapters 4, 10, and 11.

## Stages of Motor Learning

Without a doubt, the most notable thing that happens when people practice is that they demonstrate increased proficiency in the task. Sometimes this is so obvious that it hardly needs to be mentioned, while in other cases the changes are more subtle and require special methods, observation, and rationale in order to be examined. In this section we describe how the learning process has been characterized.

Many have noticed that learners appear to pass through relatively distinct stages (or phases) as they practice a skill. Bryan and Harter (1897, 1899) were among the first to study the acquisition of skill in considerable detail (see “Bryan and Harter’s Hierarchy of Habits”). Learning was defined as a two-stage process by Snoddy (1926). Participants in Snoddy’s research learned to make hand movements but saw their hand only in a mirror—a task that requires abilities needed by a dentist, for example. According to Snoddy (1926), the *adaptation* stage involved acquisition of the neuromuscular pattern required to perform the task. Once the pattern was learned, the *facilitation* stage involved improving the efficiency of the pattern. Other two-stage views were later suggested by Adams (1971) and Gentile (1972). A three-stage view of learning was suggested by Fitts (1964; Fitts & Posner, 1967) and later Anderson (1982, 1995). These three stages, referred to as the *cognitive*, *fixation*, and *autonomous stages*, are discussed in more detail in this section. As you read these explanations, however, remind yourself that these stages are not discrete and fixed stages, but have “fuzzy” borders (see Anson, Elliott, & Davids, 2005, for an excellent discussion of Fitts’ stages of learning).

### Bryan and Harter’s Hierarchy of Habits

A fascinating early set of studies regarding the perceptual and motor changes that occur with learning was conducted by William Lowe Bryan (a psychologist) and Noble Harter (a telegrapher and student of Bryan’s). The result of their shared interests was two landmark papers regarding the acquisition of telegraphic skills (Bryan & Harter, 1897, 1899). In these papers, Bryan and Harter presented the results of experiments that compared novice and expert telegraphers, as well as data they obtained by charting the acquisition of telegraphy skill over many months of practice. These papers present many interesting findings (Lee & Swinnen, 1993), but we will focus on one in particular.

Skill, in Bryan and Harter’s view, was a process of achieving a *hierarchy of habits*. At the most basic level, telegraphy involves the ability to discriminate (perceptually and motorically) between *units* of time. A dot is one “unit” of continuous auditory signal. A dash is three “units” of continuous time. One unit of no signal occurs between dots and dashes within a letter (e.g., the letter *G* is a dash-dash-dot). Three continuous units of no signal denotes that a new letter is beginning, and six units marks a new word. This “language” of telegraphy lent itself well to Bryan and Harter’s view of learning as a hierarchy of habits. The discrimination of time was learned quickly.

The alphabet became the next challenge. This, too, is usually learned quickly, and performance in sending and receiving code improves rapidly. However, Bryan and Harter then noticed something peculiar about the practice curves of some of their participants: Periods of time would go by during which little or no improvement occurred at all, which were followed later by rapid improvements. They called these periods *plateaus* in performance that occur prior to the formation of a new, advanced capability. They proposed that rather than hearing dots and dashes, with learning, the telegraphers “hear” letters. With further practice they then “hear” words, and, for the most skilled, “hear” even larger units of a sentence. Presumably, the plateaus in performance occur because the maximum performance capability of one habit places a limit on performance, which is then lifted when a higher-order habit is formed. Although some of Bryan and Harter’s views have been challenged at times (e.g., Keller, 1958), many of the basic concepts of progression through stages and to higher orders of skill have been retained in a number of conceptualizations of skill acquisition that remain popular today.

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## Stage 1: Cognitive

When the learner is new to a task, the primary problem to be solved concerns *what is to be done*—that is, what actions need to be taken in order to achieve the goal of the task? Naturally, considerable cognitive activity is required so that the learner can determine appropriate strategies to try to get the movement in the “ballpark.” Effective strategies are retained, and inappropriate ones are discarded. As a result, the performance gains during this stage are dramatic and generally larger than at any other stage in the learning process. Performance is usually very inconsistent, perhaps because the learner is trying many different ways of solving the problem. The use of instructions, models, augmented feedback, and various other training techniques (discussed in chapters 10 and 11) is most effective during this stage because they assist the learner in this problem-solving process. Most of the improvements in the cognitive stage can be thought of as verbal–cognitive in nature, the major gains being in terms of what to do rather than in the motor patterns themselves. Adams (1971) termed this stage the *verbal–motor stage*.

## Stage 2: Fixation

The second stage of motor learning begins when the individual has determined the most effective way of doing the task and starts to make more subtle adjustments in *how the skill is performed*. Performance improvements are more gradual, and movements become more consistent in the fixation stage. This stage can persist for quite a long time, with the performer gradually producing small changes in the motor patterns that will allow more effective performance. Many writers (e.g., Adams, 1971; Fitts, 1964) think that the verbal aspects of the task have largely dropped out by this stage, with the performer concentrating on *how to do* the action rather than on which (of many) movement patterns should be produced. This stage and the next (autonomous) are equivalent to what Adams called the *motor stage*.

## Stage 3: Autonomous

After many months, perhaps years, of practice, the learner enters the autonomous stage, so named because the skill has become largely *automatic* in the sense discussed in chapter 4. That is, the task can now be performed with almost no interference from other ongoing activities. It is easy to find examples of high-level performers engaging in secondary tasks without interference—for example, the concert pianist who can shadow digits or do mental arithmetic without interference while sight-reading and playing the piano (e.g., Allport, Antonis, & Reynolds, 1972; Shaffer, 1971, 1980). Automaticity is usually evidenced with respect to particular kinds of simultaneous tasks, primarily those that we could class as verbal–cognitive; some other motor task could in fact interfere with a performance in the autonomous stage, as discussed in chapter 4 in detail. Even so, the performer gives the impression that he or she is performing without having to “pay attention” to the actions. This stage has the benefit of allowing the person to process information from other aspects of the task, such as the strategy in a game of tennis or the form or style of movement in ice skating or dance.

A major problem for motor behavior research is that this stage, which is of immense importance for understanding high-level skills, is only rarely studied in experiments on motor learning. The reasons are probably obvious. In paradigms in which participants practice on laboratory tasks, such practice should continue for months before even approaching the levels of skill shown by high-level musicians, athletes, and industrial workers. It is very difficult to convince participants to devote this kind of effort in experiments. Alternatively, we could use other, more natural tasks that learners are practicing anyway; but it is difficult to manipulate and control the many variables that would need to be used for a scientific understanding of the learning processes.

Some efforts at understanding the principles of automaticity have been made in this direction by Schneider and colleagues (Schneider & Fisk, 1983; Schneider & Shiffrin, 1977) in reaction-time (RT) tasks, and by Logan

(1985, 1988) using speeded-decision tasks. Unfortunately, research involving more complex motor tasks is rarely taken to this stage of learning (but see Jabusch, Alpers, Kopiez, Vauth, & Altenmüller, 2009, for a recent exception).

## Closed-Loop Theory

Adams (1971) developed his closed-loop theory of motor learning using a well-established set of empirical laws of motor learning, most of which were based on slow, arm-positioning movements. He believed that the principles of performance and learning that applied to these movements were the same as for any other kind of movement, and that using a well-established set of empirical laws from positioning movements would produce a solid basis for theorizing.

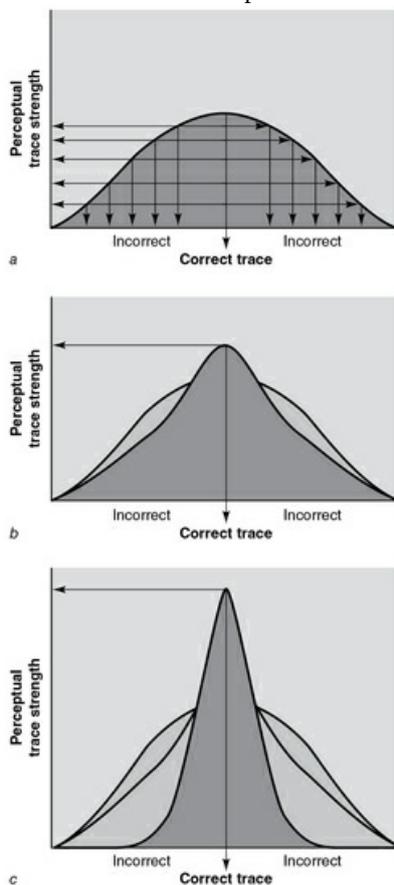
### A Feedback Emphasis

Adams believed that all movements are made by comparing the ongoing feedback from the limbs to a *perceptual trace*—the reference of correctness, stored in memory, which is learned during practice. When the person makes a positioning movement, inherent feedback is produced that represents the particular locations of the limb in space. These stimuli “leave a trace” in the central nervous system (hence the name *perceptual trace*). With repeated practice, the person comes closer and closer to the target over trials; and on each trial another trace is laid down, so that eventually a distribution of traces develops. With practice (and KR), the learner’s movements become increasingly closer to the target and with increasing consistency. Therefore, each trial provides feedback that tends to represent the *correct* movement with increasing frequency. In turn, the collection of perceptual traces comes to represent the feedback qualities of the correct movement. Then, on subsequent trials, the learner moves to that position in space for which the difference between the ongoing (inherent) feedback produced and the perceptual trace is minimized. Because the perceptual trace associated with the correct movement becomes stronger with each KR trial, the errors in performance decrease with practice.

Adams’ theory assumed a guidance role for KR (although his writings do not use this term). Learners, according to Adams, are not passive recipients of reward, but rather are actively engaged in verbalization and hypothesis formation about the task to be learned. To Adams, KR provides information to solve the motor problem. After a trial, KR is given that provides information about how the next movement should be adjusted to more closely achieve the task goal. In early learning, the learner uses KR in relation to the perceptual trace to make the movement more precise, so that KR guides the movement to the target on successive trials. In such a view, KR does not produce learning directly. Rather, it creates the appropriate situation (i.e., being on target) so that the actual learning processes can operate. The movement’s feedback produces an increment in “strength” for the perceptual trace.

We created the graphs in [figure 12.1](#) to illustrate the learning process in *Adams’ theory*. In the early stage of learning ([figure 12.1a](#)), the participant produces some correct movements but produces many incorrect movements, too. Thus, the movement feedback provides not only an increment to learning of the correct perceptual trace but also strengthens many incorrect traces as well. In this stage of learning, performance is likely to be inaccurate and variable because of the spread (wide relative distribution) of trace strengths among correct and incorrect perceptual traces. With the guidance of KR, the learner produces more and more correct movements, which has the effect of strengthening the correct perceptual trace and reducing the *relative* strength of incorrect perceptual traces, as illustrated in the middle and bottom graphs ([figure 12.1, b and c](#)). The reduction in relative strength of these incorrect perceptual traces improves the likelihood that the correct perceptual trace will guide the limb to the goal position with increasing frequency (i.e., less variability).<sup>1</sup>

Figure 12.1 Adams' theory, represented as a growth in perceptual trace strength. As skill develops (from top to bottom panel), the correct perceptual trace accumulates proportionally more repetitions, and the shape of the distribution becomes more peaked at the mode.



One of the interesting implications of Adams' theory is that errors produced during the course of training will be harmful to learning. This is the case because when an error is made, the resulting feedback is necessarily different from the feedback associated with a correct movement, and thus will increment the strength of an incorrect perceptual trace. Consequently, the *relative strength* of the correct perceptual trace will be degraded a little bit as well. One prediction, then, is that guidance should be particularly useful as a training method, as it prevents errors and therefore, develops the relative strength of the correct perceptual trace.

Adams also sought to explain how learners develop error-detection capabilities. He argued that after the movement was completed, the individual could compare the feedback received against the perceptual trace, the difference representing the movement error that the person could report to the experimenter or use as self-evaluation in the form of subjective reinforcement. Presumably, this subjective reinforcement could be used to keep the movement on target without KR; and, according to the theory, keeping the movement on target can provide gains in learning because the feedback continues to add to the correct perceptual trace, again without KR in later learning.

Contrary to earlier closed-loop theorists, Adams realized that in order for the system to have the capacity to detect its own errors, two memory states must be present—one to produce the action and one to evaluate the outcome. What if the same state that produced the movement also evaluated it? If the movement were chosen incorrectly, the feedback from the movement and the reference of correctness would always match, producing a report of no error on every attempt. In Adams' theory, the movement is selected and initiated by another memory state that Adams called the *memory trace*—a “modest motor program” responsible for choosing the direction of the action, initiating it, and giving it a “shove” toward the target. The perceptual trace then takes over the control of the movement to stop it at the final target location.

## Limitations and Contradictory Evidence

One characteristic of a good theory is that there should be no contradictions among the logically derived predictions. Contradiction does appear to exist in Adams' theory, though, regarding subjective reinforcement for *slow* positioning movements. Adams viewed the perceptual trace as providing (a) the basis for placing the limb at the correct target location and (b) a basis for the performer to detect how far that movement was away from the target location after the movement has been completed. Schmidt (1975b) argued that, if the perceptual trace is used to position the limb, then no additional information can be available about the amount of actual error produced. Schmidt and Russell (1974; Nicholson & Schmidt, 1991) provided evidence that no error-detection mechanism exists after the completion of slow positioning movements, even after 100 trials of practice, contrary to Adams' predictions. However, Schmidt and White (1972; Nicholson & Schmidt, 1991) found strong error-detection mechanisms after *rapid* movements, for which the perceptual trace presumably cannot be used to guide the limb during the movement. Adams did not make a distinction between these fast and slow movements, yet the evidence shows that they develop and use error-detection mechanisms very differently (e.g., Newell, 1976b).

Certainly one of the most damaging lines of evidence with respect to Adams' theory is the work on deafferentation in animals (Taub, 1976) and humans (Lashley, 1917). Organisms deprived of all sensory feedback from the limbs can move reasonably skillfully, and they can even learn new actions (e.g., Taub & Berman, 1968). If the only mechanism for controlling skilled actions involved feedback in relation to a perceptual trace, then these animals should not have been able to produce the actions they did. Adams (1976b) has countered this argument by saying that the animals may have shifted to some other source of feedback, such as vision, to substitute for the lost sensations from the responding limbs. This may be the case for some of these studies, but it does not apply to all of them (e.g., Polit & Bizzi, 1978, 1979; Taub & Berman, 1968). Also, Adams' theory does not account for the data from various species showing the existence of central (spinal) pattern generators—structures apparently capable of generating complex actions without feedback from the responding limbs (see chapter 6). The failure to recognize the role of open-loop processes in movement control is a serious drawback for Adams' theory.

A second line of evidence that weakens the Adams' theory was provided by the literature on variability of practice. Because the perceptual trace is the feedback representation of the correct action, making movements *different* from the correct action (in variable practice) should not increase perceptual trace strength. Thus, Adams' theory predicts that variability of practice should be less effective for learning the criterion target than is practice at the target itself. In chapter 10 we reviewed this literature and found no clear evidence that variable practice was less effective than practice at the transfer target; and often the evidence said that variability in practice was superior to practicing the transfer target itself (e.g., Shea & Kohl, 1991). Because Adams' theory explicitly claims that experience at the target location is critical for the development of the perceptual trace, this evidence is quite damaging to his position.

Lastly, the role of KR in Adams' theory was to guide the learner to making the correct movement. However, as we reviewed in chapter 11, there is clear evidence that, when KR serves a guidance role, it has a degrading influence on learning, not the enhanced effect as would be predicted by Adams' theory.

## Summary

At the time Adams' theory was proposed, it represented a major step forward for motor learning, as it presented a plausible, empirically based theory for researchers to evaluate. We believe that such evaluations have shown the theory to have a number of limitations, as outlined here, and that it no longer accounts for much of the currently available evidence on motor learning. But the theory served its intended purpose. It generated substantial research and thinking, and it paved the way for newer theories that account for the older data together with newer data. Thus, it remains as a key legacy in the growth of motor learning research.



# Schema Theory

Largely because of dissatisfaction with Adams' theory, Schmidt (1975b) formulated a theory that was considered an alternative to Adams. The primary concern with the Adams position was the lack of emphasis on open-loop control processes, and the schema theory has a strong open-loop component. Yet, at the same time, many aspects of Adams' theory are very appealing, such as the emphasis on subjective reinforcement, the concern for slow movements, and the need to have one memory state that is responsible for producing the movement and another state that is responsible for evaluating it. Thus, schema theory borrowed heavily from Adams and others by retaining the most effective parts and replacing, changing, or eliminating defective ones. Also, the new theory was based heavily on knowledge about motor control and used these concepts in conjunction with ideas about learning processes to attempt to explain the learning of both rapid and slower movements (see also Schmidt, 1980, 2003).

## Recall and Recognition Memory

Schema theory holds that there are two states of memory, a *recall memory* responsible for the production of movement and a *recognition memory* responsible for movement evaluation. For rapid, ballistic movements, recall memory is involved with motor programs and parameters, structured in advance to carry out the movement with minimal involvement from peripheral feedback. Recognition memory, on the other hand, is responsible for evaluating the inherent feedback after the movement is completed, thereby informing the participant about the amount and direction of errors. Such a two-memory state system satisfies the goal of having a memory that produces the action be different from a memory that evaluates its correctness, also one of the strengths of Adams' theory.

According to schema theory, recall memory is not thought to have an important role in slow positioning movements. The major problem for the learner is the comparison between movement-produced feedback and the reference of correctness. In these movements, the recall state merely pushes the limb along in small bursts, with the person stopping when the movement-produced feedback and the reference of correctness match. Here, in these slow movements, the agent that produces the action is the same as the agent that evaluates it; hence no postmovement subjective reinforcement can exist as is the case for rapid movements.

## Schema Learning

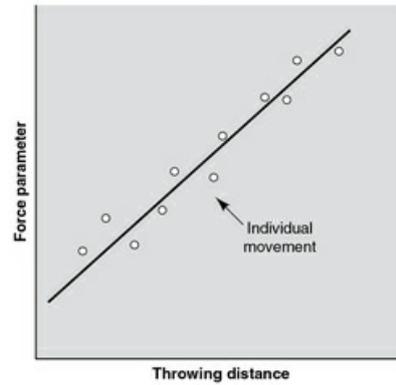
The *schema* concept is an old one in psychology, having been introduced by Head (1926) and later popularized by Bartlett (1932). For these researchers, the schema was an abstract memory representation thought of as a rule, concept, or generalization. Schmidt (1975b) attempted to use the basic idea of the schema (or rule) to form a theory of how motor skills are learned.

At the heart of Schmidt's view of schema learning is the idea that movements are made by first selecting a generalized motor program (GMP), structured with invariant features (such as relative timing), then adding parameters as required in order to specify the particular way that the program is to be executed for any one particular instance (see chapter 6). After a GMP is selected and a movement is made by adding the parameters, four types of information are available for brief storage in short-term memory: (1) information about the initial conditions (bodily positions, weight of thrown objects, and so on) that existed before the movement was made; (2) the parameters assigned to the GMP, (3) augmented feedback about the outcome of the movement; and (4) the sensory consequences of the movement—how the movement felt, looked, sounded, and so on. These four sources of information are stored only long enough that the performer can abstract information to update two schemas. These abstract rules of how the sources of information are interrelated are called the recall and recognition schemas.

### *Recall Schema*

The first of these relationships is termed the *recall schema* because it is concerned with movement production. [Figure 12.2](#) represents the kind of process that occurs, according to the recall-schema idea. On the horizontal axis are the outcomes in the environment, such as the distance a ball traveled after being thrown. On the vertical axis are the parameters that an individual assigned to the GMP. The co-occurrence of the parameter and the movement outcome produces a data point on the graph. With repeated movements using different parameters and producing different outcomes, other data points are established. As the number of throws accumulates, a *relationship* between the size of the parameter and the nature of the movement outcome is established; this relationship is represented by the *regression line* drawn through the points.<sup>2</sup> With each successive movement using the program, a new data point is produced and the relationship is refined slightly. After each new movement, the various sources of information are lost from working memory, so all that remains of the movement is the updated rule, termed the recall schema in LTM.

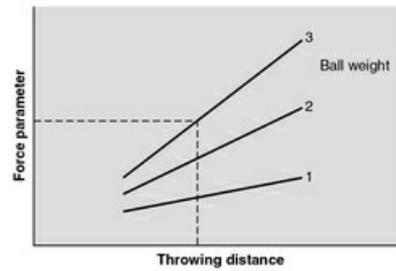
Figure 12.2 The hypothetical relationship between throwing distance movement outcomes in the environment and force parameters.



Adapted from Schmidt 1982.

But this is not the entire story. The relationship also includes information about the initial conditions of the movement, shown in [figure 12.3](#). Here, the relationship between the parameters used and the outcome produced will depend on the nature of the initial conditions, such as the weights of the balls to be thrown. These different initial conditions are represented as different regression lines in [figure 12.3](#).

Figure 12.3 The hypothetical relationship between throwing distance movement outcomes in the environment and the force parameters that were used to produce them for various ball weights (initial conditions): the recall schema.



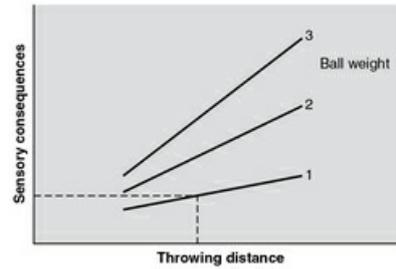
Adapted from Schmidt 1982.

How does the individual use the recall schema? On a future trial using this GMP, the person sets as a goal the desired environmental outcome, for example the throwing distance. Also, the particular initial conditions are noted (e.g., the weight of the object to be thrown), which might fit into the category represented by line 3 in [figure 12.3](#). Then, with use of the relationship established by past experience, the rule is employed to select the parameter that will come closest to accomplishing that goal. The value of this parameter is then applied to the GMP to produce the action.

### *Recognition Schema*

The recognition schema, for movement evaluation, is thought to be formed and used in a way similar to the recall schema. Here the schema is composed of the relationship between the initial conditions, the environmental outcomes, and the *sensory consequences*. This relationship is represented as the three lines shown in [figure 12.4](#). Before the movement, the individual selects a movement outcome and determines the nature of the initial conditions. Then, with the recognition schema, the person can estimate the sensory consequences that will occur if that movement outcome is produced. These, called the *expected sensory consequences*, serve as the basis for movement evaluation. The expected sensory consequences are analogous to Adams' perceptual trace.

Figure 12.4 The hypothetical relationship between throwing distance (movement outcomes in the environment) and the sensory consequences produced for various ball weights (initial conditions): the recognition schema.



Adapted from Schmidt 1982.

## Some Predictions About Schema Learning

The theory says that we acquire skills, at least in part, by learning *rules* about the functioning of our bodies—forming relationships between how our muscles are activated, what they actually do, and how those actions feel. Thus, movements for which any of the four stored sources of information are missing will result in degraded learning of the rules. One of the most critical of the sources is movement outcome information (augmented feedback, such as KR); if the person does not receive augmented information about the movement outcome, then even if the other sources of information are present, no strengthening of the schema can occur because the location on the horizontal axis will not be known. Similarly, if sensory consequences are missing (e.g., as in temporary deafferentation), then no recognition schema development can occur. In passive movements, no parameters are issued to the GMP (indeed, no GMP is selected to be run off), so no recall schema updating can occur.

Also, note that, according to schema theory, there are positive benefits from the production of movements whether they are correct or not. This is so because the schema is the rule based on the interrelatedness of all stored elements, and this relationship is present just as much for incorrect movements as for correct ones. Adams' theory, you may remember, views errors as disruptive, as they degrade the relative strength of the correct perceptual trace (see [figure 12.1](#)).

### *Variability of Practice*

The theory predicts that practicing a variety of movement outcomes with the same program (i.e., by using a variety of parameters) will provide a widely based set of experiences upon which a rule or schema can form. When the range of movement outcomes and parameters is small, all the data points are clustered in one place, and less certainty exists about the placement of the line.<sup>3</sup> When a *new* movement is required, greater error will occur in estimating the proper parameters, expected sensory consequences, or both. Shapiro and Schmidt (1982) found considerable evidence that practice variability is a positive factor in motor learning reviewed in chapter 10.

### *Novel Movements*

Schema theory also predicts that a particular movement outcome (specified by a particular value of the parameter) need not have been produced previously in order to be produced in the future. This is so because the basis for producing a new movement is a *rule* about parameter selection based on the performance of earlier similar movements. Research has shown that, after varied practice, novel movements can be produced about as accurately as they can be if the novel movement had been practiced repeatedly, and sometimes *more* accurately (see the section on variability of practice in chapter 10). This evidence suggests that motor learning may be primarily rule learning and not the learning of specific movements. Such ideas have been used for a long time in movement-education situations with children, where the pupils are presumably developing a set of rules or schemas about their motor behaviors and consequently being helped to be more proficient performers in novel situations in the future (Nicholson & Schmidt, 1991; Schmidt, 1976b, 1977).

## Especial Skills

The *set shot* in basketball provides an interesting “test” of schema theory. The set shot is characterized as a deliberate shooting motion in which the player’s feet never leave the ground. The set shot is not typically used in game action because it is relatively easy to block. However, it is the type of shot that is used for a free throw and is executed many, many times in practice, almost exclusively from the free throw line. An interesting question, then, is this: Do years of free throw practice establish a GMP, in which time and force parameters appropriate for the free throw distance must be generated when a free throw is to be performed (as predicted by schema theory)? Or does this practice result in a motor program that is specific for the free throw? Or do both processes occur? Keetch, Schmidt, Lee, and Young (2005) examined this question using skilled players from college basketball team participants who probably had performed many thousands of free throws in practice and games. The players were asked to perform set shots at distances of 9 to 21 ft (the official free throw distance is 15 ft) from the basket, from locations on the floor 2 ft apart. Several key predictions were of interest, based on the combined predictions of schema theory and the principles of force variability (see chapters 6 and 7; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). First, a negatively sloped regression line that relates the success of the shot to the distance from the basket was expected. The GMP would need to be parameterized with increased levels of force as the distance increased, thereby increasing the force variability in the movement output and increasing error. Second, schema theory predicts that the accuracy between 9 and 21 ft would fall on or very close to this negatively sloped regression line, because of the principles reviewed earlier in this section about the recall schema.

The findings of the study support all but one of the predictions: The regression line nicely fits four of the five data points. However, the key finding, which does not support schema theory, occurred at the distance of 15 ft from the foul line. From this distance, the players’ success was considerably higher than predicted based on the schema regression. A similar effect of distance has been found in skilled baseball pitchers who were much more accurate (than predicted) at the regulation pitching distance compared to other distances, including distances *just one foot* closer or farther from home plate than the normal pitching distance (60.5 ft; Simons, Wilson, Wilson, & Theall, 2009). But, when these basketball skills were performed by novices (Breslin et al., 2010) or by experts using jump shots (where the feet do leave the floor), all of the data points fit nicely on the regression line, as predicted by schema theory. There was no advantage for a jump shot taken from the foul line, presumably because jump shots are not practiced more frequently at the foul line than at any other location as set shots are.

What do these results suggest? For the set shots, something specific and unique to the free throw distance had been learned through many years of practice at this distance. This specific capability facilitated performance only for the set shot and only at the 15 ft distance taken at an angle straight on to the basket, making it an “especial” skill rather special skill existing within a class of basketball set-shot skills. Note that this particular finding is not consistent with the schema view, as the theory gives no specific preference for any particular parameterization, regardless of the number of specific practice instances that have been executed. This study illustrates many questions of practical interest that have been discussed at a theoretical level in this and previous chapters, such as force-variability principles, variable practice, schema theory, and *specificity of learning*. The results from these free-throw shooting studies are similar to results found in handwriting research. When signing your name with your nondominant hand, the signature looks like yours and is spatially similar to your dominant-hand signature. However, the nondominant-hand signature does not look as nice as your usual signature. Thus, there is a specific component to practice that is outside of the purview of schema theory.

Schema theory predicts that there should be no capability for error detection after a slow movement, whereas such capability should exist after a rapid movement. This is the case because the error-detection capability is actually used to produce the slow movement, leaving behind no capability with which to detect errors. Based on the information about closed-loop processes presented in chapter 5, if the movement was rapid (as was the case in the Schmidt & White, 1972, study), the participant would compare the feedback from the movement to the reference of correctness to define an error after the movement was completed. The error-detection process is not responsible for producing the action, and it evaluates the correctness of the action only *after* the movement has been completed. For reasons discussed before, there is insufficient time for the performer to take in the feedback, evaluate it, and make corrections before the movement is completed. According to the theory, the recall schema is thought to produce the movements, and the recognition schema is responsible for comparing the movement-produced feedback with the learned reference of correctness for evaluating the movement afterward. Empirical evidence supports this prediction (Schmidt & Russell, 1974; Schmidt & White, 1972).

## Limitations and Logical Problems

The emphasis of schema theory on the GMP concept represents both a major strength and major limitation of the theory. While we believe that the evidence strongly supports the GMP view (see chapter 6), the theory is mute in terms of how the program is formed in the first place, and this deficiency is readily acknowledged as a major problem with the theory (Schmidt, 2003). The following sections highlight other limitations.

### *Knowledge-of-Results Frequency*

Strengthening of the schema depends on the learner's knowledge of the movement outcome, so higher levels of KR relative frequency would be expected to enhance schema learning as compared to lower levels. When relative KR frequency effects on overall learning were evaluated in chapter 11, the results appeared to contradict this schema theory prediction because reduced frequencies either had no effect on learning or in some cases enhanced it, rather than degrading it, especially so if the KR was "faded" over trials (Sullivan, Katak, & Burtner, 2008; Winstein & Schmidt, 1990). These findings are further complicated by KR variables that appear to influence the learning of parameters and invariances in different ways, which is also contrary to schema theory (Shea & Wulf, 2005).

### *Contextual Interference and Cognitive Operations*

One key prediction of schema theory is that variable practice would result in stronger rule learning than nonvariable (or constant) practice, and evidence supports that general prediction (but see the discussion in "Especially Skills"). However, schema theory makes no prediction about *how* the variable practice should be scheduled. Recall from the discussion of random versus blocked practice effects in chapter 10 that the amount of variable practice in these studies was equal. Because they share a common breadth of practice variability, schema theory fails to predict the learning differences that occur between random and blocked practice (Lee, Magill, & Weeks, 1985). The explanations for contextual-interference effects stress the importance of cognitive operations during practice, which highlights a more general limitation of schema theory, as the theory provides no rationale for learning effects due to cognitive operations such as imagery, mental practice, and observational learning (Shea & Wulf, 2005; Sherwood & Lee, 2003).

## Summary

Schema theory has provided an alternative to Adams' closed-loop theory of motor learning. Compared to Adams' theory, it has the advantage that it accounts for more kinds of movements; it seems to account for error-detection capabilities more effectively and seems to explain the production of novel movements in open-skills situations. Some logical problems need to be solved, and it is not clear that this can be done without discarding the entire theoretical structure (Petrynski, 2003; Schmidt, 2003; Shea & Wulf, 2005). There are some apparent failures of

the evidence to agree with the theoretical predictions as well (e.g., Klein, Levy, & McCabe, 1984; Keetch et al., 2005). While the theory was a step forward, it should be clear that it does not provide a complete understanding of the data on motor learning. Even so, the theory provides a useful framework for thinking about skill learning because it is consistent with the literature on the GMP.

## Differing Theoretical Perspectives of Motor Learning

The ideas presented next are probably best described as hypotheses about the learning of motor skills. They really do not satisfy the basic criteria for consideration as *theories* for a number of reasons. First, many of them are directed at only certain kinds of tasks, such as continuous tasks, positioning tasks, and *tracking*; and more generality is usually required for a theory. As well, some of these theoretical perspectives concern only a few experimental variables, and theories (such as closed-loop theory and schema theory) are usually thought to have more complete structures that are capable of explaining the effects of a variety of independent variables. Further, an important ingredient of a theory is that it makes testable predictions that can be falsified by experimental testing. Nevertheless, the theoretical perspectives that we consider next represent important advances in furthering our understanding of the complex interaction of processes involved in motor learning.

### Cognitive Perspectives

Although both closed-loop theory (Adams, 1971) and schema theory (Schmidt, 1975) emphasized the role of memory structures in skill, the learning process depended on movement repetition and feedback. The development of the perceptual trace in Adams' theory and the recall and recognition schema in Schmidt's theory were mechanistic processes. Research conducted since these theories were published, on learning variables such as the contextual-interference effect (see chapter 10) and various augmented-feedback effects (see chapter 11), suggests that the role of cognitive processes in learning might be more complex than originally conceptualized in Adams' and Schmidt's theories.

Both of the major hypotheses regarding the contextual-interference effect suggest that cognitive processes play a key role. In the elaboration hypothesis, explicit contrasts and comparisons of the tasks to be learned were thought to benefit learning. In the reconstruction view, it was the process of planning a different action to be performed that boosted learning. In both hypotheses, learning was more effective if the elaboration or reconstruction was made more *difficult* (i.e., in random practice), suggesting that the *effort* with which the cognitive processes were undertaken had a critical impact on learning (Lee, Swinnen, & Serrien, 1994; Sherwood & Lee, 2003; Vickers, Livingston, Umeris-Bohnert, & Holden, 1999).

This cognitive emphasis suggested that something more was occurring during learning than executing movements and receiving inherent feedback, which could not explain the differences between random and blocked practice. In both practice conditions the participants received the same amount of practice on the same tasks. The effects on learning of augmented-feedback variables, such as concurrent feedback (see chapter 11), also fit a cognitive perspective well. Movements that are produced with the assistance of concurrent feedback experience the same efferent commands and intrinsic feedback as nonguided movements. However, as argued in the KR-guidance hypothesis (Salmoni, Schmidt, & Walter, 1984; Schmidt, 1991), such variables tend to *minimize* the learner's need for evaluation of subjective information and other cognitive operations that are ordinarily undertaken in the preparation for the next trial.

The effects of these practice variables on the learning process are complex, however—they appear to have a strong dependence on the nature of the task and the experience level of the participant (Wulf & Shea, 2002). Some of these complexities were conceptualized in a theoretical framework by Guadagnoli and Lee (2004), who suggested that cognitive processing during practice is affected by the degree to which the participant is *challenged* during the practice period. The nature of the task, the conditions of practice, and the experience level of the learner interact to determine the amount of challenge present during acquisition trials. For example, random practice is considered more challenging than blocked practice and therefore should benefit learning. But, driving on a busy highway would be more challenging than driving in a deserted parking lot—and certainly much more challenging for the novice learner than the semiskilled driver. The framework suggests that variables such as random practice and concurrent feedback are effective to the degree that they challenge the cognitive processes of the learner. The framework suggests, however, that there exists a *point* at which these cognitively challenging practice conditions

may not be needed. Indeed, they may be detrimental to learning if used for tasks that are already inherently challenging. Similarly, learning may be sufficiently challenged in individuals whose performance capabilities are put to the test merely by the demands of the task. In such cases, nonchallenging practice conditions (e.g., blocked practice or concurrent KR) would be expected to facilitate, rather than be detrimental to learning.

Although the Guadagnoli and Lee framework has provided an explanation for some of the complex relationships for learner, task, and practice variables that exist in the literature, it has limitations. Certainly, the concept of *task difficulty*, though frequently discussed as an important factor in the motor learning literature, remains a construct with an elusive definition. As well, the framework stops short of identifying exactly what cognitive processes are being challenged and how these processes change over the course of learning. Nevertheless, it is clear from the many studies conducted in the past several decades that the effects on learning of practice and augmented-feedback variables are much more complex than at first believed. The challenge-point framework represents an attempt to characterize the complexity of these relationships within a cognitive perspective. Some empirical explorations of the framework support its explanatory power, especially with individuals who have a compromised motor system (Lin, Sullivan, Wu, Katak, & Winstein, 2007; Onla-or & Winstein, 2008; Sullivan et al., 2008).

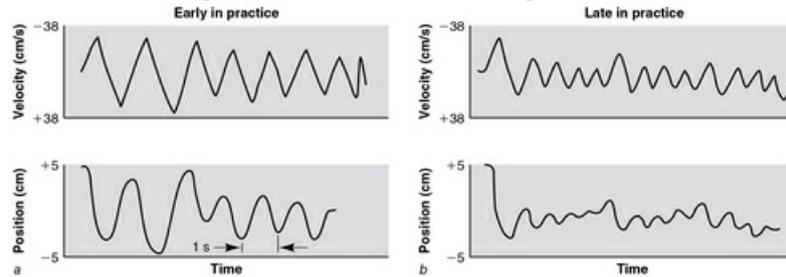
## Hierarchical Control Perspectives

As people learn, at least with some tasks, a change occurs such that motor control is shifted to progressively “lower” levels in the nervous system. The idea that motor behavior is hierarchical means that some “higher” level in the system is responsible for decision making and some “lower” level is responsible for carrying out the decisions. With respect to the information-processing analysis, the decision-making processes of the system are considered to be at a “higher” level in the hierarchy than the motor programming level. The hierarchical control perspective suggests that with practice, control is *shifted* from the “higher” to the “lower” levels in the system.

A good example that demonstrates research in this perspective was a study by Pew (1966), who used a tracking task in which the participant controlled the movement of a dot on a monitor by pressing one or the other of two buttons. Pressing the right button caused the dot to accelerate to the right, and the acceleration could be halted and reversed by pressing the left button, which caused the dot to accelerate to the left. If no button was pressed, the dot accelerated off the screen in one direction or another. The participant’s task was to keep the dot in the center (this is called a compensatory tracking task).

A record from one of the participants, with the velocity and position of the dot shown for early and late practice, is presented in [figure 12.5](#). In early practice ([figure 12.5a](#)), the participant was making about three button presses per second, and the dot was never positioned near the center of the screen for very long. In this mode of control the participant pressed the button, waited for the visual feedback from the screen, decided that the dot was accelerating off the screen, then planned a movement to reverse it, pressed the other button, and so on. Here, the participant is using the executive (e.g., the information-processing stages) level predominantly, so that the “highest” level in the system is consistently involved in the production of every movement.

Figure 12.5 Performance records from a button-press tracking task in (a) early and (b) late practice. (Top records show instantaneous velocity, and bottom records show position with target represented as zero; responding is more rapid and more accurate in later practice.)



Reprinted, by permission, from R.W. Pew, 1966, "Acquisition of hierarchical control over the temporal organization of a skill," *Journal of Experimental Psychology* 71: 768. Copyright © 1966 by the American Psychological Association.

Compare [figure 12.5a](#) to [figure 12.5b](#), which is from the same participant but later in practice. Here the motor behavior is quite different. First, the rate of responding is much faster, about eight movements per second. Next, the dot is much closer to the target because the button was pressed to reverse the direction of the dot before the dot was very far away from the target. Although we cannot be absolutely certain, the mode of control appears to have changed. It appears that now a long string of movements is prestructured as a unit, perhaps governed by a motor program. Thus, a separate decision from the executive level is no longer required for the control of each button press. Pew viewed this finding as evidence for the hypothesis that with practice, the participant shifted the control from an executive-based level to the lower-level control of the motor program, freeing the decision mechanism for other activities and making the movement more effective. Now, instead of controlling every button press, the executive level was controlling *groups* of button presses. With some participants, the durations of the right and left buttons were adjusted, perhaps as a kind of "parameter" of the programmed activities.

It is easy to see the advantages of shifting the control from the decision-making level to the motor program level. Foremost is the freeing of the attentional mechanisms for use on higher-order aspects of the task (e.g., strategy), for doing other simultaneous tasks, or for simply resting so that the organism does not become fatigued. This freeing of attention is one of the major events that occur when people learn, and it is discussed further in later sections of this chapter.

### *Progression–Regression Hypothesis*

Of particular relevance to tracking tasks is a hypothesis presented by Fitts, Bahrck, Noble, and Briggs (1959) about how changes in motor behavior occur with practice. In many tracking tasks, both in the laboratory and in the outside world, the movements of the track to be followed are made up of a number of components that can be described according to the physical principles of motion. At the simplest level is the position of the track at any moment. The next most complex aspect of the track is its velocity at any moment. A third and yet more complex aspect of the track is its acceleration at any moment. In designing servo systems to regulate some mechanical system, engineers can devise a simple system that responds to (a) only the position of the track, (b) the position and velocity, or (c) the position, velocity, and acceleration. With each increase in the number of components being tracked, progressive increases are required in the complexity (and expense) of the mechanical or electronic devices that are to track them.

The *progression–regression hypothesis* for humans presented by Fitts and colleagues (1959) holds that, when the learner practices a tracking task, a progression develops in the learner's behavior in the direction of acting more and more like a complex tracking system. Early in practice, the person responds only to the simplest elements of the display (position). With increased practice, the learner becomes able to use velocity information, and even later comes to use information about acceleration as well. The regression portion of the hypothesis refers to what happens to the learner under stressful conditions or when forgetting of the movement has occurred (perhaps as a result of a long layoff). According to the hypothesis, the person regresses to a simpler level of control (from acceleration to velocity, or from velocity to position), with systematically reduced tracking performance as a

consequence. Thus, the hierarchical nature of learning involves progressing to levels of more complex information, although performance effects may show reversals in the shift between levels in the hierarchy (regressing to less complex information).

A number of experimenters have studied learning in tracking tasks with respect to the progression–regression hypothesis. Fuchs (1962) found that the role of position cues in tracking decreased with practice, while the role of acceleration cues increased; and these effects were reversed when a secondary task was added to induce stress (see also Garvey, 1960). More recently, researchers have improved on the methods used in the earlier work and have provided additional evidence for a shift in movement control consistent with the hypothesis (Hah & Jagacinski, 1994; Jagacinski & Hah, 1988; Marteniuk & Romanow, 1983).

At least for tracking tasks, learners appear to respond to systematically different aspects of the track with practice and to reverse these trends with stress. We should be careful not to go too far with these conclusions, because we have no independent way of knowing exactly which stimuli were being used here. But the evidence is certainly consistent with the progression–regression hypothesis, and it contributes to an understanding of the hierarchical nature of the underlying changes in motor control when skill is achieved with practice or reduced under stress or with forgetting.

### *Creating Motor Programs*

Of course, we know that many changes occur in our movements when they are subjected to practice, with actions tending to become more consistent, smoother, less effortful, and more routine or automatic with experience. These are all powerful changes, and in the next sections we consider some of the experimental evidence for them.

### Acquisition of Movement Pattern Consistency

One important change in movement behavior with practice is that the movement outcomes tend to become more consistent, predictable, and certain with experience. Recall that variable error and other measures of variability (see chapter 2) were devised to capture this aspect of motor behavior. In the study of these phenomena, the patterns of movement are measured by various kinematic procedures (e.g., video analysis, position–time records, computer simulation). Changes in the trial-to-trial consistency of these measures have been noted in an impressive variety of tasks, such as driving (Lewis, 1956), throwing (Stimpel, 1933), handwheel cranking (Glencross, 1973), table tennis (Tyldesley & Whiting, 1975), tracking (Darling & Cooke, 1987; Franks & Wilberg, 1984), keyboarding (Salthouse, 1986), bimanual coordination (Lee, Swinnen, & Verschueren, 1995), and many others. Such generalizations perhaps seem to be particularly appropriate with respect to the acquisition of closed skills, which have as a major goal the production of a consistent action in a stable (or predictable) environment—the kinds of skills for which stable motor programs are most highly suited. These changes in movement pattern consistency probably represent some of the most persistent phenomena in the motor learning area.

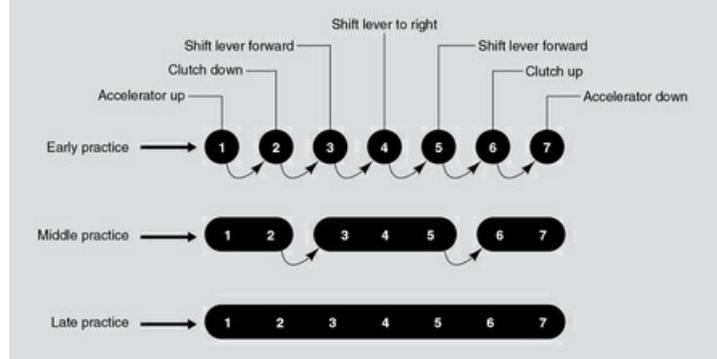
### Acquisition of Sequencing: The Gearshift Analogy

Another hierarchical change in movement control with practice involves the ways in which movements are sequenced. MacKay (1976, personal communication) suggested that motor programs might be generated by stringing together smaller programmed units of behavior so that eventually this string of behavior is controllable as a single unit—such as in learning to shift gears in a car.<sup>4</sup> The act of shifting gears for a first-time learner is a slow, jerky, step-by-step process; the learner lifts their foot from the accelerator, then depresses the clutch, and then moves the shift lever (probably in three distinct movements as well), until the entire act is completed (or until the car rolls to a stop going up a hill). Contrast this behavior to that of a race car driver, who appears to shift gears in a single, rapid action. Not only does the movement occur much more quickly, but also the elements of the action are performed with precise timing, and the actions of the hands and both feet are coordinated in relatively complex ways. In relation to the behavior of the early learner, the action seems to be controlled in a very different

way, perhaps as a single programmed unit.

MacKay suggested that the various elements are learned in a progressive way to form the entire action. [Figure 12.6](#) is a diagram of how this might work. Assume there are seven elements in the entire sequence and that these are at first controlled one at a time, each by a separate motor program. With some practice, the first two elements might come to be controlled as a single unit; the next three elements could compose another unit, and the last two could compose a third. Finally, with considerable experience, the entire sequence might be controlled as a single unit. This view is of a type of hierarchical control in that it specifies how the program is structured from the beginning, progressively growing in length by adding parts. Other possibilities exist as well (Marteniuk & Romanow, 1983).

Figure 12.6 The gearshift analogy. (Initially, seven elements are each controlled by separate programs; later, they become grouped so that they are organized into a few units or even into a single unit.)



Adapted from MacKay 1976, personal communication.

We should be able to see evidence of the changes in these structures by using a fundamental principle of variability: The variability (inconsistency) of the elements *within* a unit should be considerably smaller than the variability between units. In [figure 12.6](#) (middle practice), if we were to measure the interval from the end of element 2 to the beginning of element 3, the relative variability of this interval (expressed as the SD of the interval divided by the mean interval length) from trial to trial would be greater than the variability from the end of element 3 to the beginning of element 4. This is the case because the first two elements (2 and 3) are in different units (controlled by different programs), while the latter two (3 and 4) are supposedly controlled by the same program. Turning this logic around, if we found intervals in the sequence in which temporal variability was very high, this could be taken as evidence that the behaviors occurring at the opposite ends of this interval of time are members of different motor programs. This is similar to the method used by Young and Schmidt (1990, 1991) and Schmidt, Heuer, Ghodsian, & Young (1998) to investigate the acquisition of new bimanual coordination skills (see also chapter 8).

## Combinations of Reflexes

Another way that motor programs are thought to be formed in practice is through the combination of fundamental reflexes (Easton, 1972, 1978). According to this viewpoint, higher levels in the motor system are capable of tuning or adjusting lower spinal levels so that the existing reflexes (e.g., the stretch reflex) can be controlled in ways that result in skilled actions. Thus, rather than hypothesizing that the motor system builds a set of commands that come to exist as a stored motor program, Easton held that the “commands” are really ways of controlling the preexisting reflexes. Such emphases on reflexes are also seen in the views of Fukuda (1961) and Hellebrandt, Houtz, Partridge, and Walters (1956), as discussed in chapter 5; but here, while the reflexes are thought to be of assistance to the overall programmed action when increased force or speed is required, they are not the fundamental basis of it. But Easton’s viewpoint also has a great deal in common with the ideas of Greene (1972), Turvey (1977), and others, all of whom argue that rapid movements consist of controlling structures that are constrained to act as a single unit, perhaps by tuning of spinal systems or by utilization of reflexes. These ideas share much in common with the theoretical perspectives of the Russian physicist Bernstein (see “Nikolai A. Bernstein” in chapter 1), whose ideas on learning are presented next.

## The Bernstein Perspective

Suppose you were asked to throw a ball overhand with your nondominant arm. In all likelihood, your performance would look quite clumsy—the movements of the body would lack the fluid motion that characterizes a throwing motion with the dominant arm. The motions of the nondominant arm would probably be described as much more fixed and restricted in the range of motion. This example characterizes an important concept of learning initiated by the work of Bernstein (1967). The concept is that learning involves a process of *solving the*

*degrees of freedom problem*—discovering ways in which the independent parts of the moving body can be organized in order to achieve a task goal. In Bernstein’s perspective, learning occurred in three stages, although the stages that he proposed were different than the stages discussed earlier in the chapter (Adams, 1971; Fitts, 1964). According to Bernstein (1967), the stages of learning involve (a) freezing degrees of freedom, (b) releasing and reorganizing degrees of freedom, and (c) exploiting the mechanical and inertial properties of the body.

### *Stage 1: Freezing Degrees of Freedom*

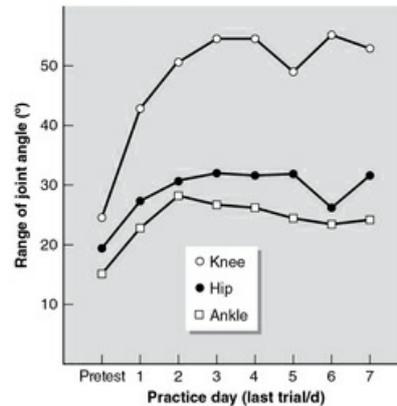
Bernstein suggested that early in practice the learner attempts to “freeze” as many of the degrees of freedom as possible, allowing as few as possible of the body parts to move independently. With practice, more and more of the degrees of freedom are “thawed out”—individual body parts appear to move either with more independence or with a different dependency. In the earlier example of throwing with the nondominant arm, one possible strategy for the performer would be to *fix* or limit the degrees of freedom involved in the act. This is done in order to reduce the contribution of their independent variability, and hence reduce the complexity of the action. In this way, the performer can achieve a relatively crude level of success at the task by reducing the number of ways in which things can go wrong. In a nice demonstration of this stage of learning, Southard and Higgins (1987) showed that people who learned a racquetball shot initially restricted the motion of the elbow and wrist and performed the shot with a more whole-arm action. A similar set of findings was reported by Hodges, Hayes, Horn, and Williams (2005) over 10 days of practice in a soccer-chip task. Participants gradually achieved more initial successes at the task as the range of motion at the hip was reduced with practice.

### *Stage 2: Releasing and Reorganizing Degrees of Freedom*

According to Bernstein’s arguments, in stage 2 of learning, the *constraints* on the degrees of freedom are loosened, allowing both for greater independent motion and for a higher level of success. Bernstein’s introspections about the learning process have received support in a study by Vereijken, van Emmerik, Whiting, and Newell (1992), for example. Participants practiced a ski simulator task that required whole-body movements to move a platform from side to side over curved metal rails (see [figure 2.8](#)). The sides of the platform were anchored to a frame by rubber springs; when the springs were subjected to force from the “skier,” the platform would oscillate from one side of the frame to the other. Participants practiced this task over seven days, attempting to produce large-amplitude displacements of the platform.

Changes in some of the kinematic measures of performance are presented in [figure 12.7](#). In this figure we can see that in the pretest, the platform movements were made with quite *restricted* angular movements of the hip, knee, and ankle. At this early stage of learning, participants seemed to “freeze” the range of motion of the lower limb and trunk, perhaps just to get *any* movement of the platform at all. By the end of the first day, the range of motion of each of the joints had been extended considerably, resulting in much larger amplitudes of the platform but with reduced frequency. By the end of the seventh day, oscillation frequency had increased dramatically, along with further increases in amplitudes and joint ranges of motion. Thus, greater success in displacement and frequency of platform oscillations was achieved with greater range in the motion of the lower limbs and trunk—supporting Bernstein’s suggestion that practice results in a release of the degrees of freedom (Vereijken, Whiting, & Beek, 1992; see also Arutyunyan, Gurfinkel, & Mirskii, 1968, 1969; Newell, van Emmerik, & Sprague, 1993).

Figure 12.7 Changes in the frequency and amplitude of movements during practice of the ski simulator task.



Note, however, that the concept of releasing degrees of freedom has not received universal acceptance among researchers. For example, a study of violinists by Konczak, vander Velden, and Jaeger (2009) revealed that shoulder motions of the bowing arm were actually *reduced* as a function of practice, indicating that the degrees of freedom underwent freezing, not freeing, as a function of practice. We can hypothesize at least two other exceptions. First, in learning to windsurf, the performer gradually learns to freeze the degrees of freedom in the knees and hips, so that most of the controlling actions are in the shoulders and arms—actions used to manipulate the sail’s orientation to the wind. Second, in learning to do a handstand on the still rings, the learner comes to freeze the degrees of freedom in the knees, hips, and trunk, so that balance control is ultimately achieved primarily by movements of the wrists. Unfortunately, very few studies have addressed this stage of Bernstein’s perspective on learning, revealing a gap in empirical evidence.

Overall, we think that these ideas (about freezing and freeing degrees of freedom) form a useful description of learning’s effect on movement control in *some* tasks. However, the counter-examples described here indicate that this does not provide a universal account of all motor learning.

Another key concept suggested by Bernstein was that independent degrees of freedom are assembled into functional units that act together. When two or more independently moving degrees of freedom “combine” to perform as one functional movement, the independent parts are said to be coupled—they act as *coordinative structures* (or *functional synergies*) to coordinate the independent parts to work as if they were a single unit. This is perhaps exemplified by the gear-shifting concepts presented earlier in this chapter (see [figure 12.6](#)).

Another good example of coupling independent degrees of freedom occurs when you try rubbing your stomach while patting your head. In this task you are asking the two limbs to perform two different actions. How does your motor system deal with each limb when performing this task? Most likely, if you have never practiced the task before, you will find it difficult because of the strong tendency to perform similar actions with each limb—either patting both the head and the stomach or rubbing both (see chapter 8). However, research suggests that with practice, you can overcome the tendency to couple these parts as a coordinative structure.

A series of studies that demonstrated the effects of practice on bimanual coordination was conducted by Walter and Swinnen (1990, 1992, 1994; Swinnen, Walter, Lee, & Serrien, 1993; Swinnen, Walter, Pauwels, Meugens, & Beirinckx, 1990). Participants initiated rapid, discrete actions of the left and right limbs simultaneously. The left arm moved a lever toward the body with a single, rapid elbow flexion movement. The right arm also moved a lever toward the body. However, midway through the movement the right arm was required to reverse the direction of its movement twice. Thus, the participant’s task was to produce a unidirectional, flexion movement of the left arm and a flexion–extension–flexion movement of the right arm, the arms starting and moving simultaneously (see [figure 8.9](#)).

As with the task of rubbing your stomach while patting your head, Walter and Swinnen found that participants tended to perform similar actions with the two limbs: There was a *less* pronounced reversal for the limb that the participant intended to reverse, and there was evidence of a reversal in the limb that the participant did *not* intend

to reverse (Swinnen, Walter, & Shapiro, 1988). Thus, neither of the limb movements was performed as intended. Rather the functional unit was of two limbs performing similar, albeit hybrid, actions of the individual goals; this was seen via high (within-participant) correlations in the kinematics of the two limbs. Learning was viewed in terms of the success with which each limb performed its own goal with practice. Learning was enhanced if it was supplemented with augmented feedback (Swinnen et al., 1990, 1993), as we would expect from our understanding of feedback effects in chapter 11.

Learning was also enhanced under *adapted* conditions, whereby the actions were performed slowly at first and then were gradually increased in speed (Walter & Swinnen, 1992). Related findings have been provided in experiments involving the acquisition of handwriting skills (Newell & van Emmerik, 1989) and dart throwing (McDonald, van Emmerik, & Newell, 1989), as well as in bimanual aiming tasks involving asymmetric amplitudes (Sherwood, 1990; Sherwood & Canabal, 1988).

One interpretation of these findings is that, by overcoming the existing coupling of degrees of freedom, the limbs are somehow *uncoupled* in a way that allows them to move more or less independently. This interpretation has some controversy, however, as others have shown that learning a new bimanual pattern actually results in an *increased* dependence between the hands: that learning results in the development of new bimanual GMPs involving tight, complex linkages between the limbs (Schmidt et al., 1998). This controversy is complicated by the evidence that the duration of the movement task (e.g., discrete vs. continuous skills) has a large role in the control and learning of coordinated actions (see chapter 8).

### *Stage 3: Exploiting the Mechanical–Inertial Properties of the Limbs*

The final stage of Bernstein's perspective on learning is the alteration of movement control so that the motor system can take advantage of (or exploit) the built-in mechanical–inertial properties of the limbs. This notion is tied strongly to mass–spring control, discussed in chapter 7, in which certain spring-like properties of the limb system can be used to the performer's advantage to reduce the need for complex computations and information processing, to reduce energy costs, or to make the movement faster and more forceful.

Schneider, Zernicke, Schmidt, and Hart (1989) studied this question using film analysis of rapid three-joint arm movements together with a biomechanical analysis that allowed the estimation of torques in each of the participating joints. Near the middle of this maximum-speed movement, the participant was to reverse his hand movement at a target, at which the arm was briefly extended upward at about 45°. Early in practice, the participants tended to use a shoulder flexion torque at the target (reversal point), as if they were holding their arm up against gravity. But later in practice, the shoulder flexion torque tended to drop out, to be replaced by an *extension* torque. Now the limb appeared to be “thrown” at the target, to be “caught” by the shoulder *extensors* in order to reverse its direction and bring it back down quickly. Certainly, the structure of the GMP had changed markedly across practice, employing systematically different muscle groups for essentially the same set of positions early and late in practice. There were many other changes in movement trajectories and in the forces produced as well (see also Spencer & Thelen, 1999).

A different type of analysis was performed by Gray, Watts, Debicki, and Hore (2006), who reported on the differences between the baseball throwing motions of the dominant (skilled) and nondominant (unskilled) arms. Their analyses revealed evidence of restricted ranges of motion for the movements of the unskilled arm, providing additional support for Bernstein's stage 1 (freezing degrees of freedom). However, one of the strengths of Gray and colleagues' (2006) study was the comparison of the unskilled arm mechanics and the mechanics of the skilled arm, thereby revealing the effects of practice and learning. Their analyses showed that, compared to the unskilled arm, the skilled arm tended to exploit interaction torques at various joints to achieve higher arm velocities.

The interpretation of these studies was that the motor system learned to use various passive inertial properties of the system, and that the benefit could be realized not only in terms of increased speed but also in terms of decreased energy costs. These studies clearly support Bernstein's hypothesis and reveal many interesting changes that occur in the movement control processes during the third stage of learning (see also Newell & Vaillancourt,

2001a).

## Haken-Kelso-Bunz Model

The HKB model of movement coordination was presented in chapter 8. As mentioned there, the performance of discrete tasks appears to be fundamentally different when compared to performance of continuous tasks. We have discussed several times in previous chapters that discrete skills are dependent on a motor program for their execution. In contrast, continuous motor skills are more dependent on interactions with the environmental stimuli for their regulation. Therefore, it should not be surprising that perspectives on the learning of continuous motor tasks differ in many respects from those constructs developed to explain the learning of discrete tasks.<sup>5</sup>

In chapter 8 we presented evidence that there are two preferred coordination patterns by which continuous oscillations of two limbs or fingers can be reliably produced—*in-phase* and *anti-phase* coordination (the observed coordination pattern is measured in terms of the relative phase lag between the individual cycles; 0° or 180° in these two instances; for review see chapter 2). Much of the research conducted on coordination dynamics uses the Haken-Kelso-Bunz (1985) model as a basis (see chapter 8). Basically, the HKB model states that intrinsic stabilities of the motor system attract moving degrees of freedom to perform in accordance with one of the system's naturally stable states. For the oscillating-fingers research presented in chapter 8, the strong tendency was to coordinate the fingers in an in-phase or an anti-phase pattern. Of course, theoretically, there are an infinite number of bimanual coordination patterns that can be produced. However, if the system were not amenable to change, then we would forever be locked into performing only these two patterns. But research suggests that new patterns can be learned, leading to a number of important issues about the learning process as a consequence (Swinnen & Wenderoth, 2004).

Recall from chapter 2 that studies of motor learning often devised experimental tasks that were as unique as possible to the learner. The reasons for this were straightforward—if participants came into the laboratory with skills already learned (e.g., typing skills), then it would decrease the skill that could be gained during the earliest stages of learning. Traditional motor learning tasks such as the pursuit rotor (see [figure 2.5a](#)) satisfied these criteria because it was highly unlikely that participants had ever learned skills that were remotely similar to the skills required to perform these “novel” tasks. These advantages however, must be weighed against the major disadvantage that learning does not occur against the background of a “blank slate”—we can never know how learning this new task is influenced by the skills that the learner possessed prior to practice.

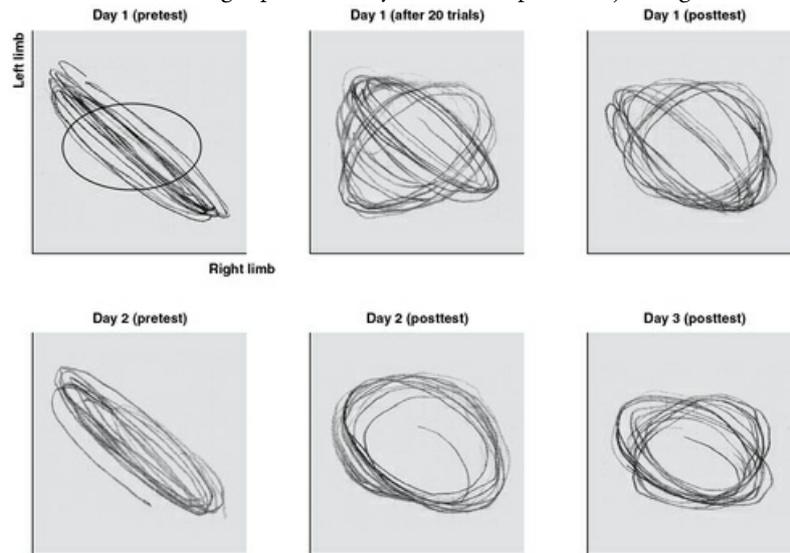
The self-organization approach, which was critical in the development of the HKB model, overcame some of the problems associated with “novel tasks” and provided many advantages for the study of motor learning. The approach both exploited the requirements for a learning task and provided a unique window into the influence of previously acquired skills on new learning (see also Kelso & Zanone, 2002; Schöner, Zanone, & Kelso, 1992; Zanone & Kelso, 1994, 1997). Because in-phase and anti-phase coordination are known and measurable *stable* patterns that exist prior to practice, the performance of new bimanual coordination patterns could be evaluated over the course of practice trials and compared to the performance of these existing skills.

In one experiment (Zanone & Kelso, 1992; see also Kelso & Zanone, 2002; Zanone & Kelso, 1997), participants attempted to coordinate the relative phasing of the index fingers on both hands by rhythmically oscillating them in time to two blinking lights, which alternated in 90° relative phase. Before, during, and after each of five days of practice, Zanone and Kelso had participants perform a type of transfer test in which the visual metronomes started by blinking simultaneously (in 0° relative phase) and then increased in phase offset by 15° after every 20 s until 180° relative phase had been reached. The main finding was that the 90° pattern was learned and became relatively stable with practice. An unexpected finding, though, was that some participants showed a *reduced* stability for the anti-phase (180°) pattern as practice trials accumulated on the 90° pattern. This finding provided support for Zanone and Kelso's argument that learning does not involve simply adding a new skill to a participant's repertoire. Rather, learning occurs against the background of an individual's existing skills, resulting not only in the acquisition of new patterns but also in a change in the previously stabilized patterns. This latter finding is a controversial one, however, as it implies that new learning may result in the *unlearning* of previously acquired

skills. Other studies suggest that the destabilization of the anti-phase pattern is only a performance bias, not a permanent destabilization in performance (Fontaine, Lee, & Swinnen, 1997; Lee et al., 1995; Smethurst & Carson, 2001), reminiscent of our previous discussions on the learning–performance distinction.

Another finding with use of this approach is also of interest. In the study by Lee and colleagues (1995), which used many of the same methods as Zanone and Kelso's (1992), when learning a 90° pattern, participants showed strong influences of the existing stable patterns. As an example, the progress in learning for one participant is illustrated in [figure 12.8](#). The panels in this figure represent a plot of the relative motion of the right limb together with the relative motion of the left limb. Recall that plots of this type were presented in chapter 2, for in-phase and anti-phase coordination (see [figure 2.11](#)).

Figure 12.8 Effects of practice on the development of a novel bimanual timing skill. The goal is to produce a relative timing represented by an oval-shaped Lissajous figure.



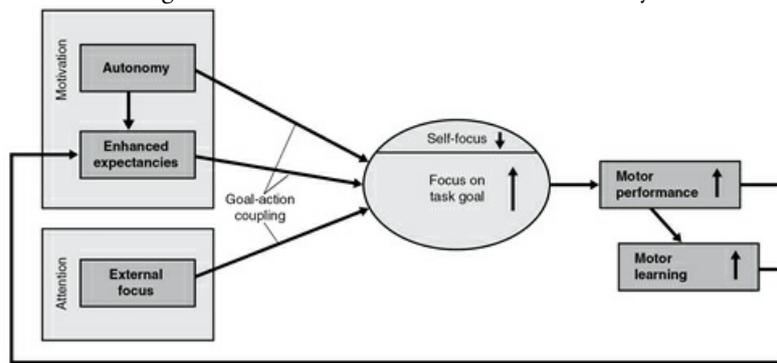
For the 90° pattern investigated by Lee and colleagues, the “correct” plot was represented as an ellipse (overlaid in the top left panel of [figure 12.8](#)).<sup>6</sup> All participants practiced the ellipse pattern during three days of practice. There are two observations in particular to note in this figure. First, for most participants the initial performance trials were performed in anti-phase; much of the initial stages of learning involved “breaking away” from the attraction to perform this bimanual task as a previously acquired stable pattern. This process was revealed over the practice trials on day 1, with fewer and fewer anti-phase cycles being produced and coordination moving toward 90°. A second important finding concerned the initial trial on day 2, illustrated in the lower-left. Here, the participants showed a short-lived performance bias that reverted to anti-phase. This result is interesting because it showed an effect that was very much like that predicted by the progression–regression hypothesis (regression to a previously mastered level of learning). It also is consistent with a phenomenon to be discussed in chapter 13 termed *warm-up decrement*, in which retention loss has a dramatic impact on performance. But, note here that the decrement was very specific, as performance reverted to a previously stable pattern, not to an *unstable* state.

The application of the HKB model and new experimental paradigm to the study of motor learning by Zanone and Kelso (1992) has generated considerable interest. Investigators have studied the role of many different variables with the purpose of discovering how new coordination patterns develop as a function of practice. For example, an existing coordination pattern may help to either stabilize or destabilize a new pattern (Fontaine, Lee, & Swinnen, 1997; Hurley & Lee, 2006; Kostrubiec & Zanone, 2002; Wenderoth & Bock, 2001; Wenderoth, Bock, & Krohn, 2002) in ways that are different than the retention of that pattern (Tallet, Kostrubiec, & Zanone, 2008). The acquisition of a stabilized new pattern appears to be greatly accelerated if movements are unpaced (Kovacs, Buchanan, & Shea, 2009) or when the discrepancies in augmented feedback and action can be readily detected and corrected (Shea, Buchanan, & Kennedy, 2016). Learning bimanual skills also appears to provide a window into important factors on the role of aging in motor learning (Maes, Gooijers, Orban de Xivry, Swinnen, & Boisgontier, 2017). And other factors, similar to those seen with more traditional approaches to the study of practice (chapters 10 and 11) and transfer (see chapter 13), have been recast within a self-organization framework (Faugloire, Bardy, & Stoffregen, 2009; Lay, Sparrow, & O’Dwyer, 2005; Ronsse, Miall, & Swinnen, 2009), broadening the conceptual approaches to viewing these more traditional ideas.

## OPTIMAL Theory

As described in chapters 4, 10, and 11, a significant amount of evidence demonstrates strong motivational and attentional focus influences on motor performance and learning. In addition to these insights, advances in neuroscience related to structural and functional brain changes, and the role of neuromodulators (e.g., dopamine) in the learning process, have led Wulf and Lewthwaite (2016) to propose a theory of motor learning. It is called the OPTIMAL (Optimizing Performance Through Intrinsic Motivation and Attention for Learning) theory of motor learning. In this theory, two key motivational variables are *enhanced expectancies* for future performance and learner *autonomy*. In addition, an *external focus of attention* is considered critical for optimal motor performance and learning. The theory provides explanations as to how these factors contribute to skill learning. A schematic of the theory is provided in [figure 12.9](#).

Figure 12.9 Schematic of the OPTIMAL theory.



*Psychonomic Bulletin & Review*, "Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning." Vol. 23, 2016, pg. 1391, G. Wulf and R. Lewthwaite, Copyright 2016. With permission of Springer.

## Motivation

Motivation is generally related to the direction and intensity of behavior. Expectations for the future and perceptions of autonomy play prominent roles in different theoretical perspectives of motivation. Humans are motivated to act when they expect positive outcomes, and perhaps particularly when they believe they will play a role in bringing about these positive outcomes. Thus, it is perhaps not surprising that practice conditions that enhance learners' expectancies or allow them to act autonomously also facilitate motor learning.

### *Enhanced Expectancies*

According to the OPTIMAL theory (Wulf & Lewthwaite, 2016), high expectancies for future performance prepare the learner for successful movement at various levels, including cognitive, motivational, neurophysiological, and neuromuscular levels. Goals are effectively coupled with intended actions (see "Goal-Action Coupling"). While planning the action, being confident that one can achieve the desired movement outcome may protect from thoughts, in particular self-related thoughts (e.g., internal focus of attention), that would hinder optimal performance. Lack of confidence tends to act as a self-invoking trigger (McKay, Wulf, & Lewthwaite, 2015). Concerns about one's ability, fear of failure, and the like result in counterproductive neuromuscular activity, and subsequent attempts at *self-regulation* that reduce attentional capacity and detract from a goal focus. Thus, as indicated in [figure 12.9](#), high performance expectancies have a dual role for goal-action coupling, namely, maintaining a focus on the task goal and preventing a self-focus (or other off-task activities such as mind wandering).

Practice conditions that make movement success likely support a psychological or biological need for competence (Deci & Ryan, 2008; Leotti, Iyengar, & Ochsner, 2010). They also tend to be experienced as rewarding and to elicit dopaminergic responses (Schultz, 2013). Dopaminergic systems subserve brain activity relevant to motor, cognitive, and motivational functioning (Wise, 2004). For example, the mesolimbic dopaminergic system is related to reward or motivation. The nigrostriatal dopaminergic system is associated with response selection and motor planning. The fact that this latter system receives projections from the former system (e.g., Schmidt, Lebreton, Clery-Melin, Daunizeau, & Pessiglione, 2012) is consistent with behavioral findings demonstrating motivational influences on motor activity.

While dopaminergic activity is predominantly associated with expected success or reward, some dopamine neurons seem to be sensitive to negative events. Thus, occasional risks to movement success, or challenges, can temporarily dampen dopamine levels. However, challenges amplify the impact of subsequent positive experiences, thereby strengthening the learning effect (Schultz, 2010, 2013). Thus, *success with challenge* is likely more important for learning than challenge or task difficulty per se (e.g., Lee, Swinnen, & Serrien, 1994; Schmidt & Bjork, 1992).

### *Autonomy*

As discussed in chapter 10, practice conditions in which learners have a certain degree of autonomy, such as those in which they are given choices, facilitate learning relative to more controlling conditions. In the OPTIMAL theory (Wulf & Lewthwaite, 2016), learner autonomy is assumed to contribute to enhanced expectancies (see arrow from autonomy to enhanced expectancies in [figure 12.9](#)). The sense that one will be in control enhances expectations for future success. It in turn aligns thoughts, attention, motivation, and neuromuscular activity to the performer's goals (i.e., *goal–action coupling*). Opportunities to act autonomously seem to be related to activation in brain regions that are associated with a sense of agency (Lee & Reeve, 2013). Having a sense of agency is associated with dopamine release (Aarts, Bijleveld, Custers, Dogge, Deelder, Schutter, & Haren, 2012). This may be the reason why autonomy not only results in longer-term learning benefits (see chapter 10) but can also have immediate benefits for performance (e.g., Halperin, Chapman, Martin, Lewthwaite, & Wulf, 2016; Iwatsuki, Abdollahipour, Psotta, Lewthwaite, & Wulf, 2017).

Performer autonomy, or lack thereof, may also have a more direct impact on motor performance and learning (see arrow from autonomy to self-focus/focus on task goal in [figure 12.9](#)). Controlling conditions, in which learners do not feel autonomous, tend to be stressful (Reeve & Tseng, 2011). The stress hormone cortisol has a downregulatory effect on the brain's reward network (Montoya, Bos, Terburg, Rosenberger, & van Honk, 2014), which might contribute to degraded learning under those conditions (Hooyman et al., 2014).

The rewarding nature of optimal motivational conditions (enhanced expectancies, autonomy) is assumed to make dopamine available for the establishment of neural connections that are critical for successful performance and learning. Those conditions are also important for the effective processing of error information. A study by Legault and Inzlicht (2013) showed that autonomy was associated with greater sensitivity to task errors relative to controlling conditions, and it resulted in enhanced performance. Similarly, Grand, Bruzi, Dyke, Godwin, Leiker, Thompson et al. (2015) found enhanced information processing, higher intrinsic motivation, and more effective motor learning under autonomy-supportive practice conditions (self-controlled feedback) relative to a yoked control condition. Thus, differences in information processing seen between self-control and yoked conditions (e.g., Carter & Ste-Marie, 2016) are a *consequence* of the motivational impact of those conditions.

## External Focus of Attention

In the OPTIMAL theory, an external focus of attention is another important contributor to goal–action coupling. By concentrating on the intended task goal and away from the self (see [figure 12.9](#)), an external focus is assumed to facilitate neural connections that are critical for optimal performance. The result is greater automaticity (Wulf, McNevin, & Shea, 2001), effective and efficient movement patterns, and enhanced performance and learning (see Wulf, 2013).

In fact, an external focus on the task goal is likely the default focus for the production of skilled movements. It is hard to imagine a monkey leaping to another tree branch focusing on extending its limbs. In contrast to other animals, humans often revert to an internal focus on body movements, perhaps as a result of previous instructions or other conditions that act as a self-invoking trigger (McKay et al., 2015), such as pressure to perform well. The inefficient muscular activation and disruption of automaticity, termed *microchoking* episodes by Wulf and Lewthwaite (2010), are evident, for example, when a golfer leaves a putt short. In a study by Perreault and French (2015), children practiced basketball free throws and were given feedback that promoted either an external or internal focus of attention. At the end of the experiment, participants in the internal focus group reported having had more self-evaluative thoughts (36%–57%) than did participants in the external focus group (7–21%). Thus, aside from keeping concentration directed at the task goal, an external focus has the additional advantage that it directs concentration *away* from the self.

## Goal–Action Coupling

Motor learning is associated with structural brain changes, as well as in functional connections across brain regions (Taubert, Lohmann, Margulies, Villringer, & Ragert, 2011). *Functional connectivity* refers to task-specific neural

connections across distinct brain regions that are seen in skilled performers (Bernardi, Ricciardi, Sani, Gaglianese, Papasogli, Ceccarelli, Franzoni, Galetta, Santoro, Goebel, & Pietrini, 2013; Milton, Solodkin, Hluštík, & Small, 2007). Practice under optimal motivational and attentional focus conditions facilitates the development of functional connectivity, as well as *structural connectivity*, and enhances motor performance and learning. Linking goals to movement actions readies the motor system for task execution. The switching to neural networks that are necessary for successful task performance—and away from the default mode network, which supports self-referential processing and mind wandering (Buckner, 2012)—is facilitated by the so-called salience network (Menon, 2015). Lack of a clear task focus (e.g., internal focus) or nonoptimal motivational conditions (e.g., no autonomy) would prevent efficient switching to task-related functional networks or goal–action coupling. The salience network may be an important site for future investigations into goal–action coupling.

## Predictions and Practical Implications

The OPTIMAL theory makes a number of predictions, most of which have already been mentioned in this section. While some support already exists for a number of the predictions, others—in particular those that require brain imaging or measures of dopaminergic activity—will have to await additional studies.

### Predictions of the OPTIMAL Theory

- When temporally associated with skill practice, conditions that enhance expectancies for positive outcomes trigger dopaminergic responses and thereby benefit motor performance.
- Enhanced expectancies and autonomy support contribute to efficient goal–action coupling by readying the motor system for task execution.
- Autonomy support facilitates performance by enhancing expectancies.
- An external focus of attention directs attention to the task goal, enhancing goal–action coupling.
- An internal focus of attention impedes performance by directing attention to the self.
- Movement success resulting from an external focus enhances expectancies for future success.
- Enhanced expectancies and autonomy support facilitate motor learning by making dopamine available for memory consolidation and neural pathway development.
- Challenge, in the context of prevailing success, elicits a potentiating dopaminergic response that contributes to learning beyond success or challenge alone.
- Higher expectancies facilitate efficient switching from the default mode network to motor networks associated with the movement skill.
- An external attentional focus facilitates efficient switching from the default mode network to relevant motor networks.
- An internal attentional focus impedes efficient switching from the default mode network to motor networks associated with the movement skill.
- Generally, conditions that optimize performance facilitate learning.

*Psychonomic Bulletin & Review*, “Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning,” Vol. 23, 2016, pg. 1391, B. Wulf and R. Lewthwaite, Copyright 2016. With permission of Springer.

The findings that inspired the OPTIMAL theory have important implications for practical settings in which motor skills are learned or taught, be it in sports, physical or occupational therapy, surgery, the performing arts, military or law enforcement, or other fields. Imagine a typical scenario, in which an instructor selects the tasks to be performed, gives instructions that refer to body movements, and provides corrective feedback. Learners’ lack of autonomy, internal focus of attention, and low expectancies for future performance would likely result in nonoptimal learning. Moreover, poor performance or slow progress may further decrease self-efficacy and increase a self-focus, essentially resulting in a vicious cycle. Ultimately, the result may be a lack of interest in practicing or learning new skills.

In contrast, imagine an instructor who gives learners small choices, highlights positive aspects of performance, and directs their attention externally. Enhanced expectancies and perceptions of autonomy would likely increase the learners’ self-efficacy. Combined with external-focus instructions, successful movement outcomes are much more

likely. These in turn will further promote self-efficacy, perhaps resulting in a virtuous cycle with positive consequences for further learning and motivation.

Practitioners might wonder whether it is necessary to include each of the three factors (enhanced expectancies, autonomy, external focus) in practice or training protocols. While numerous studies have shown that each factor individually enhances learning, would it be even more effective to incorporate two or all three factors? Initial studies have demonstrated that this indeed seems to be the case. Studies that examined combinations of enhanced expectancies and autonomy support (Wulf, Chiviakowsky et al., 2014), enhanced expectancies and an external focus (Pascua, Wulf, & Lewthwaite, 2015), or autonomy support and an external focus (Wulf, Chiviakowsky, & Drews, 2015), all found additive benefits relative to one factor or none. Finally, combining all three factors yielded even more effective learning than combinations of two (Wulf, Cardozo, Lewthwaite, & Chiviakowsky, 2017). These findings suggest that enhanced expectancies, autonomy support, and an external focus are all important contributors to optimal learning.

## Summary

The empirical laws of motor learning presented in previous chapters are the focus of hypotheses or theories that are directed at explaining them, and this chapter presents some of the more important of these formulations. Learners appear to pass through various stages (or phases) when they practice a skill: a *cognitive stage* in which emphasis is on discovering what to do, a *fixation stage* in which the concern is with perfecting the movement patterns, and an *autonomous stage* in which the attentional requirements of the movement appear to be reduced or even eliminated.

Two major theories of motor learning are *closed-loop theory* and *schema theory*. Closed-loop theory holds that the learner acquires a reference of correctness (called the *perceptual trace*) through practice and that the improvements in skill result from the increased capability of the performer to use the reference in closed-loop control. Schema theory is based on the idea that slow movements are feedback based, with rapid movements being program based; with learning, the learner develops rules (or schemas) that allow for the generation of novel movements. Both theories can claim a number of lines of experimental support, but neither is capable of explaining all the evidence on motor learning.

Several other theoretical perspectives have spawned a number of hypotheses about the learning process. The *cognitive perspective* suggests that processes involved in the planning and evaluation of movement affect learning, especially so when performance difficulties challenge these cognitive processes. The *hierarchical control perspective* holds that the control of the skill is systematically shifted from higher-level control processes to lower-level processes involving motor programming. Motor programs are assumed to be constructed through practice, but it is not known how such structuring occurs. In the progression–regression hypothesis, learning to track is viewed as a progression toward higher-order control, with regression to a previously achieved level of skill the result of stress or forgetting. The *Bernstein perspective* addresses his three stages of learning, in which, at least for some tasks, degrees of freedom are initially frozen, then later released and reorganized with learning. In a later stage of learning, the mechanical–inertial properties of movement can be exploited for movement control that is more precise, faster, or more efficient (or some combination of these).

The self-organization view (HKB model) stresses the importance of interactions between a person's sensory–motor system and the world in which actions are performed. The examination of humans who are learning new coordination patterns of relative phasing has contributed an important method for studying the evolution of skills against the background of existing skills. The method emphasizes changes in stabilities and instabilities, both temporary and long-term.

A recent motor learning theory, the OPTIMAL theory, is built on the premise that motor learning cannot be understood without considering the motivational and attentional influences on behavior. Important motivational variables in the theory are enhanced expectancies for performance and learner autonomy. Both are assumed to facilitate motor learning by making dopamine available for memory consolidation and development of neural pathways. An external focus directs attention to the task goal and suppresses a detrimental self-focus. All variables contribute goal–action coupling, thereby readying the motor system for effective and efficient task execution.

### Student Assignments

1. Prepare to answer the following questions during class discussion:
  - a. Using any sport skill, describe the skill characteristics of an athlete who is in the Fitts phases of learning: the cognitive phase, the associative phase, and the autonomous phase.
  - b. Using the same sport skill as in question 1a, describe the skill characteristics of an athlete who is in the Bernstein stages of learning: the freezing degrees of freedom stage, the releasing and reorganizing degrees of freedom stage, and the exploiting the mechanical–inertial properties stage.
  - c. Compare and contrast closed-loop theory (Adams, 1971) and schema theory (Schmidt, 1975) in terms of their memory requirements and predictions regarding transfer to novel variations of a learned

skill.

- d. What is goal–action coupling?
2. Find a research article that shows motivational influences on motor learning.
3. What are some predictions of the OPTIMAL theory of motor learning?

## Notes

<sup>1</sup> We have assumed normal distribution here, with the mode represented as the correct perceptual trace. With learning, the shape of the distribution of incremented perceptual traces moves from platykurtic (flat) to leptokurtic (peaked). Of course, other distributions are also possible. For example, in learning to play golf, many more people have trouble with slicing the ball than with hooking the ball. In this case, the shape of the distribution would be expected to change in both kurtosis and skewness, as a function of learning.

<sup>2</sup> Learning in Adams' theory was represented by changes in the normal distribution—a more pronounced mode and reduced variability. In schema theory, learning is represented by a regression-line analogy. A more *powerful* regression equation is developed with learning—one that has reduced residual variability and for which the regression coefficient ( $R^2$ ) approaches 1 (see discussion at end of chapter 2).

<sup>3</sup> In terms of the regression-line analogy, the predicted success of a novel variation of the regression line is reduced considerably when extended to parameters *beyond* those actually experienced in practice. Therefore, greater breadth in the variability of practice should extend the predictability of the schema to novel parameters.

<sup>4</sup> The term *gearshift analogy* is probably incorrect from a historical point of view. A similar idea was proposed by Jastrow before cars even had gearshifts: “At the outset each step of the performance is separately and distinctly the object of attention and effort; and as practice proceeds and expertness is gained . . . the separate portions thereof become fused into larger units, which in turn make a constantly diminishing demand upon consciousness” (Jastrow, 1906, p. 42).

<sup>5</sup> The HKB model described in this section represents one of several perspectives that consider how an individual's sensory–motor system interacts on various levels with the environment to influence the regulation of movement. An overview of various approaches is provided in Turvey and Fonseca (2009), Beer (2009), and Latash, Scholz, and Schönner (2007).

<sup>6</sup> In this study the left and right limbs were to produce different amplitudes at a 90° phase lag. In other studies, in which participants learn 90° phase lags with equal amplitudes, the left limb–right limb figure to be produced is a circle.

# Chapter 13

## Retention and Transfer

Some years ago in the process of revising this text, two of the authors (Dick Schmidt and Tim Lee) got together to discuss some ideas over a long bike ride on the beach in Venice, California. Although Tim had not ridden a bike in many years and, indeed, had never ridden this particular bike before, he managed to avoid causing any serious harm to the sunbathers and volleyball players gathered on the beach that warm spring day. Should we be surprised that the skill of bike riding is retained and transferred so easily? And what factors might influence how well we retain and transfer these and other types of motor skills? Such concerns about how well skills are retained over time and how well they transfer to different situations are of both theoretical and practical importance—theoretical because of the need to understand how the motor system is structured so that skills can be produced “on demand,” and practical because usually much time and effort have gone into the learning of the skills, and we need to know how such investments can be protected from loss. This chapter is about the empirical relationships and principles concerned with *retention* and *transfer*.

## Fundamental Distinctions and Definitions

You may have the impression that motor learning and motor memory are two different aspects of the same problem, one having to do with gains in skill, the other with maintenance of skill. This is because psychologists and others tend to use the metaphor of memory as a *place* where information is stored, such as a computer hard drive or a library. Statements like “I have a good memory for names and dates,” or “The person placed the phone number in long-term memory,” are representative of this use of the term. The implication is that some set of processes has led to the acquisition of the materials, and now some other set of processes is responsible for keeping them “in” memory.

### Memory

A common meaning of the term *motor memory* is “the persistence of the acquired capability for performance.” In this sense, habit and memory are conceptually similar. Remember, the usual test for learning of a task concerns how well the individual can perform the skill on a retention or transfer test. That is, a skill has been learned if and only if it can be retained “relatively permanently” (see chapter 9). If you can still perform a skill after not having practiced it for a year (or even for a day or just a few minutes), then you have a memory of the skill. In this sense, memory is the *capability* for performance, not a location where that capability is stored. Depending on one’s theoretical orientation about motor learning, memory could be a motor program, a reference of correctness, a schema, or an intrinsic coordination pattern (Amazeen, 2002). From this viewpoint, as you can see, learning and memory are just “different sides of the same behavioral coin,” as Adams (1976a, p. 223) put it (see also Adams, 1967).

Chapter 9 introduced the motor behavior–memory framework that connects the temporal evolution of motor memory processes and the phases of motor learning (Kantak & Winstein, 2012). Memory researchers describe the information processes as encoding, consolidation, and retrieval. Because learning and memory are just different sides of the same behavioral coin, we can map motor learning processes onto memory processes using this framework. Thus, acquisition or practice corresponds to the encoding processes of a motor memory, and the end-of-practice or immediate retention phase of motor learning corresponds to consolidation processes where the memory is somewhat more fragile, and finally, the delayed retention or transfer phase that represents retrieval processes are referred to as recall. We refer back to these memory processes throughout this chapter as they relate to retention and transfer.

### Forgetting

Another term used in this context is *forgetting*. The term is used to indicate the opposite of learning, in that learning refers to the acquisition of the capability for movement whereas forgetting refers to the loss of such capability. It is likely that the processes and principles having to do with gains and losses in the capability for moving will be different, but the terms refer to the different directions of the change in this capability. “Forgetting” is a term that has to do with theoretical constructs, just as “learning” does. Memory is a construct, and forgetting is the loss of memory; so forgetting is a concept at a theoretical, rather than a behavioral, level of thinking.

As shown in [table 13.1](#), the analogy to the study of learning is a close one. At the theoretical level, learning is a gain in the capability for skilled action, while forgetting is the loss of same. On the behavioral level, learning is evidenced by relatively permanent gains in performance, while forgetting is evidenced by relatively permanent losses in performance, or losses in retention. So, if you understand what measures of behavior suggest about learning, then you also understand the same about forgetting. Remember that we cannot measure forgetting directly; like learning, it must be inferred from performance. As such, an inability to retrieve a specific memory may only reflect a problem with the retrieval mechanism and not the memory itself. A good example of this

phenomenon is behavior after head trauma when a loss of memory is evidenced by forgetting. With time, however, the person is usually able to retrieve the information and thereby demonstrate that memory was intact all along but the retrieval processes were temporarily impaired (Coste et al., 2011).

	Theoretical level	Behavioral level
<b>Motor learning</b>	Acquiring the capability for moving, gains in memory	Relatively permanent gains in performance with practice
<b>Motor forgetting</b>	Losing the capability for moving, or forgetting, loss of memory	Relatively permanent losses in performance, or retention losses

## Retention and Transfer

Retention refers to the persistence or lack of persistence of the *performance*, and is considered at the behavioral level rather than at the theoretical level (table 13.1). It might or might not tell us whether memory has been lost. The test on which decisions about retention are based is called the *retention test*, performed at a period of time after practice trials have ended (following the *retention interval*). If performance on the retention test is as proficient as it was immediately after the end of the practice session (or acquisition phase), then we might be inclined to say that no memory loss (no forgetting) has occurred. If performance on the retention test is poor, then we may decide that a memory loss has occurred. However, because the test for memory (the retention test) is a test of *performance*, it is subject to all the variations that cause performances to change in temporary ways—just as in the study of learning. Thus, it could be that performance is poor on the retention test for some temporary reason (fatigue, anxiety) or a problem with the retrieval processes mentioned earlier, and so one could falsely conclude that a memory loss has occurred. (At this point it might be helpful to review the learning–performance distinction presented in chapter 9.)

For all practical purposes, a retention test and a *transfer test* are very similar. In both cases, the interest is in the persistence of the acquired capability for performance (habit). The two types of tests differ only in that the transfer test has individuals (all or some) switching to different tasks or conditions, whereas the retention test usually involves retesting people on the same task or conditions.

# Measuring Retention and Transfer

Tests of retention and transfer provide indicators about the persistence of an acquired habit during an absence from practice, or about the way in which previous practice influences performance on a new task. Unfortunately, straightforward conclusions from such tests are not always possible. Next, we present the most common and important of the various methods and measures of retention and transfer that have been devised by researchers, and we suggest which ones provide the most useful information.

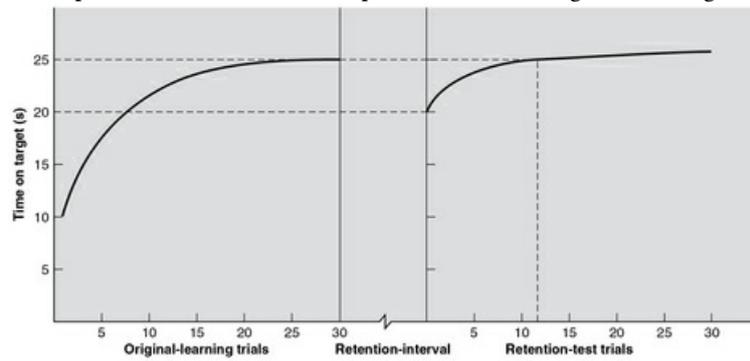
## Retention of Learning

In motor memory research, a number of different measures of retention have been used, and these different methods provide somewhat different interpretations about the underlying forgetting processes. The most common of these methods are *absolute retention* and various measures of *relative retention*.

### *Absolute Retention*

By far the most simple (and scientifically justifiable) measure of retention is absolute retention, defined simply as the level of performance on the initial trial(s) of the retention test. [Figure 13.1](#) shows the hypothetical scores of a group of individuals who practiced the pursuit rotor task (see [figure 2.5a](#)) for 30 trials and then, after a retention interval, performed a retention test involving 30 additional trials. The absolute-retention score is 20, because performance in trial 1 of retention is approximately 20 s of time on target (20 s TOT). Notice that the absolute-retention score is not based in any way on the level of performance attained in the practice trials.

Figure 13.1 Hypothetical performance curves on the pursuit rotor for original-learning and retention-test trials.



### Relative Retention

Various measures of relative retention are possible, such as those using a *difference score* and those using *percentage scores*. These measures express in various ways the absolute-retention score *relative to* scores obtained during the practice trials.

#### Difference Score

Probably the most common relative-retention score is a difference score that supposedly represents the “amount” of loss in skill over the retention interval. It is computed by taking the difference between the performance levels at the end of the practice session and the beginning of the retention test. In the example given in [figure 13.1](#), the difference score is 5 s, as the group performed with a TOT of 25 s before the retention interval and 20 s afterward. Such measures are aesthetically pleasing to many investigators because they seem (erroneously, however) to represent the forgetting processes more or less directly.

#### Percentage Score

A second kind of relative-retention score is a percentage score, which represents the “amount” lost in retention over the retention interval relative to the amount of improvement that occurred on the task in the practice session. That is, the percentage score is the difference score (as defined earlier) divided by the amount of change in performance during the practice session (another difference score), then multiplied by 100 for conversion into a percentage. In the example in [figure 13.1](#), the percentage score is the difference score (5 s) divided by the amount of performance change during the practice trials ( $25 - 10 = 15$  s) and multiplied by 100, or  $5 / 15 \times 100 = 33.3\%$ . The meaning usually given to the percentage score in this case is that one-third of the amount of original improvement during practice was lost over the retention interval. Be careful, though, because such estimates are sensitive to temporary factors that alter performance during practice (e.g., fatigue, random practice) and thus alter the size of the denominator. However, these scores are sometimes useful when one wishes to compare (usually informally) the retention on two different skills, perhaps with different scoring systems.

#### Savings Score

A third measure of retention, which was introduced long ago by Ebbinghaus (1913) and has regained popularity in recent years (e.g., Keisler & Willingham, 2007; Krakauer & Shadmehr, 2006; Leow, Loftus, & Hammond, 2012; Seidler & Noll, 2008), involves the “savings” in relearning. That is, after a retention interval, one measures the number of trials required for the participants to reach the level of proficiency achieved in original practice. In the example in [figure 13.1](#), the savings score would represent the number of trials “saved” in the retention test in the process of reaching the 25 s of TOT that had been achieved at the end of the practice session. Notice that the

number of trials to relearn is generally less than the total number of practice trials; in this case (as opposed to 30 trials in acquisition), 12 retention-test trials were required to reach 25 s TOT. Therefore, in the retention session, the participant regained the same level of proficiency as had been achieved in the practice session—but in this instance it required 18 fewer trials than it did in the practice session (savings = 30 – 12 = 18 trials). The idea of a savings score is that the more complete the retention, the faster should be the “rate” of relearning, even if the first trial or so show poor performance (due, for example, to warm-up decrement, discussed later).

### *Contrasting the Various Retention Measures*

While it may seem that these various methods merely provide subtle differences in the measurement of a single process (forgetting), this is not the case. According to an analysis of the problem some years ago (Schmidt, 1971a, 1972a), the relative-retention scores are flawed by a variety of factors. The basis of the problem is that all these scores come from *performance* measures, with changes in performance being used to infer something about the changes in the internal state (habit or memory) that underlies performance. Therefore, all the problems with performance curves that we mentioned with respect to the measurement of learning (ceiling and floor effects, for example, in chapter 9) also apply to the measurement of forgetting. In particular, difference scores are subject to a variety of influences that cloud interpretations about forgetting, casting doubt on their usefulness. Moreover, the percentage score is based on two difference scores, one divided by the other to gain the percentage, clouding the issue even further. The savings score suffers a similar problem since the assessment of “savings in relearning” itself employs a difference score in its computation.

The problem is not just a technical or academic one (Schmidt, 1971a). Some of the most fundamental variables in forgetting have empirical effects that seem to depend completely on the ways in which retention is measured. If forgetting in [figure 13.1](#) is measured by the absolute-retention method, then numerous studies show that absolute retention increases as the amount of practice increases, just as we might suspect. But if forgetting is measured by the relative-retention methods, then relative retention (computed from the *same* set of data) *decreases* as the amount of practice increases (see Schmidt, 1972a). Thus, the relationship between forgetting of skills and the amount of practice would be completely different depending on how retention is measured. Obviously, this has caused, and will continue to cause, many confusing situations for students who are attempting to understand the principles of motor forgetting. The absolute-retention score minimizes these problems, and it is the simplest and most straightforward one to use.

## Transfer of Learning

Transfer is usually defined as the gain (or loss) in the capability for performance in one task as a result of practice or experience on some other task. Thus, we might ask whether practicing a task like badminton would produce benefits or losses (or neither) for another task such as tennis. If it turns out that the performance of tennis is more effective after badminton experience than it would have been with no previous badminton experience, then we would say that the skills acquired in badminton have “transferred to” the skills involved in tennis. It is as if something that is learned in the badminton situation can be carried over to (or applied to) the task of playing tennis (Schmidt & Young, 1987).

### *Transfer Experiments*

Experiments on the transfer of learning can use a variety of experimental designs, but we will not consider them all here (see Ellis, 1965, for a complete description). In the simplest of all designs, assume that there are just two groups of participants (groups I and II). In [table 13.2](#), group I practices task A for some arbitrary number of practice trials, after which this group is transferred to practice on task B. Group II does *not* practice task A at all but merely begins practicing task B.



**Table 13.2 A Simple Design for an Experiment on Proactive Transfer of Learning**

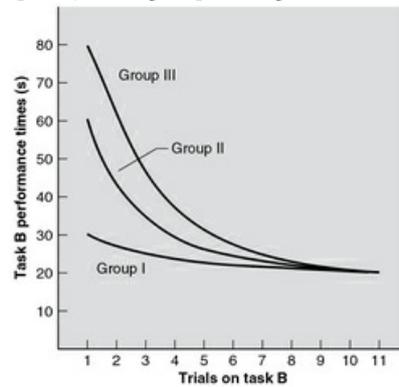
Group	Transfer task	Test
I	Task A	Task B
II	—	Task B
III	Task Z	Task B

You can think of tasks A and B as any two activities; they could be different tasks such as badminton and tennis, or they could be two slightly different variations of the *same* task, such as the split-belt treadmill ([figure 2.5d](#)) in which the independent belts are set at either 2:1 or 3:1 relative speeds. Thus, when the two groups begin practice of task B, the only systematic difference between them is whether or not they have had previous experience on task A.

### Positive and Negative Transfer

Consider the possible results of such an experiment as shown in [figure 13.2](#). Here, the task of interest is task B, so task A performance is not graphed. In [figure 13.2](#), group I, which had task A prior to task B, performs task B more effectively than does group II, which did not have the experience with task A. In this case, we conclude that experience on task A has provided increased capability for task B, equal to 30 units on trial 1 of task B. When the practice on task A enhances subsequent performance on task B, we say that *positive transfer* occurred from task A to task B.

Figure 13.2 Performances on task B for a group with no prior experience (II) or with prior practice on task A (group I) or task Z (group III). If group I outperforms group II, then positive transfer has occurred. If group III performs more poorly than group II, negative transfer has occurred.



Now consider what happens with another hypothetical group (group III). As seen in [table 13.2](#), group III practices task Z (rather than task A as group I did) prior to trials on task B. In [figure 13.2](#), the performance for group III is less skilled in relation to that of group II by 20 units on trial 1 of task B. For the reasons just mentioned, we conclude that experience on task Z has interfered with group III’s capability for performance on task B. In this case, we would say that *negative transfer* occurred from task Z to task B.

### Proactive and Retroactive Transfer

In the examples given so far, the transfer seemed to work “forward” in time from task A or Z to task B. This is termed *proactive transfer*. However, we can also consider *retroactive transfer*, that is, transfer that seems to work “backward” in time. Consider the more complex experimental design shown in [table 13.3](#). Here, two different treatment groups (groups IV and V) both perform task B. Then, group IV performs task Q while group V performs nothing. Later, both groups return to task B for a retention test. If the retention performance on task B is more effective for group IV than for group V, we say that positive retroactive transfer occurred from task Q to task B; practicing task Q seemed to “enhance” the capability already shown on task B. Alternately, if the performance of task B on the retention test is less effective for group IV than for group V, we say that negative retroactive transfer (or interference) occurred; here, practicing task Q seemed to degrade the capability for the previously practiced task B.

Group	Initial practice	Transfer task	Retention test
IV	Task B	Task Q	Task B
V	Task B	—	Task B

The retroactive- and proactive-transfer designs are similar in that they both consider the performance on the *initial* trials of task B in the retention test (or the test phase in [table 13.2](#)) to be the critical data indicating transfer. Some measures of these different performances are described in the next sections.

### *Measurement of Transfer*

The “amount” of transfer from one task to another can be assessed in a number of ways, all of which suffer from the basic problems raised many times earlier about the measurement of performance, learning, and forgetting; thus none of these methods will be very satisfactory in measuring transfer. Rather they are used to describe the relationships of the curves, such as those in [figure 13.2](#), and are occasionally helpful in discussion of the results of different transfer experiments.

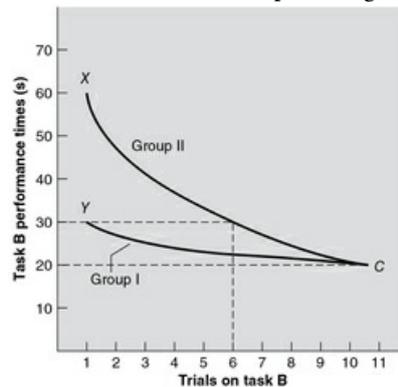
### Percentage Transfer

One method of estimating the amount of transfer is to consider the gain in performance as a result of experience on task A as a percentage of the “total amount learned” by group II in the experiment. The data from groups I and II are illustrated again in [figure 13.3](#). On trial 1 the difference between the two groups is 30 units (labeled as points *X* and *Y*). At the end of practice, group II’s performance level is 20 units (point *C*) and has therefore improved by 40 units (60 – 20). The amount of improvement in task B by group II can be represented as the total improvement shown in task B (or *X* – *C*). Thus, group I’s experience with task A has provided 30 out of the possible 40 units of improvement, or 75% transfer. In terms of a more general formula,

$$\text{Percent transfer} = (X - Y) / (X - C) \times 100 \quad (13.1)$$

in which *X* = 60, *Y* = 30, and *C* = 20 score units. The formula can also be used for negative transfer as shown in [figure 13.2](#). Here, the values *X* and *C* remain the same, but *Y* (the initial performance level on task B by group III) is larger than it was for group I (i.e., 80). Being careful to keep the signs of the numbers straight, and noting that the numerator of the equation is a negative number (i.e., *X* – *Y*, or 60 – 80, or –20), we calculate transfer as  $-20 / 40 \times 100 = -50\%$ .

Figure 13.3 The calculation of percentage transfer.



Roughly speaking, we can interpret the percentage transfer as the percentage of gain (or loss) on task B as a result of prior practice on task A. Positive transfer of 100% would imply that the performance on the first trial of task B for group I is at the final level of performance (i.e., point C in [figure 13.3](#)) demonstrated by group II. Transfer of 0% would mean that the two groups are the same in initial performance on task B (i.e., both at level X).

The reason this measure is inadequate, of course, is that the amount of improvement on task B (i.e.,  $X - C$ ) will depend on the amount of practice provided, on the scoring system used for task B, on the nature of the participants, and on countless other arbitrary factors that affect the shapes of performance curves. But using percentage transfer measures can serve a useful purpose in describing the relationships of the curves; just be careful not to take the finding of, say, 75% transfer too literally.

### Savings Score

Another, far less frequently used method for describing the amount of transfer is a savings score, as already discussed. Here, the savings score represents the amount of practice time “saved” (i.e., reduced) on task B by having first practiced task A. In [figure 13.3](#), group I (which had practiced task A previously) begins its performance of task B at a level of performance equivalent to that shown by group II after six trials. It is possible to say that group I “saved” six trials in the learning of task B by having first learned task A. But this is not the whole story; the “savings” on task B are almost certainly compensated for by a “loss,” because task A had to be practiced, and the practice time on task A is usually going to be longer than the amount of time “saved” on task B. That is, for learning task B, usually nothing is as efficient as practicing task B (for discussion on practice specificity see chapter 10).

Such “savings” begin to have importance when the financial cost of practice is considered. A common example is in learning to fly an airplane, such as the McDonnell Douglas MD-11. To practice in the actual MD-11 aircraft would be very costly, so computer-based simulators that closely resemble the airplane cockpit are frequently used for practice (see [figure 13.15](#) and the related discussion). Here, the time “spent” in the simulator (task A) is inexpensive relative to the time “saved” in learning to fly the MD-11 (task B), and it is safer as well. In such situations, the effectiveness of a simulator-based training program is often evaluated in terms of financial savings, such savings being the number of hours saved on task B (the MD-11) multiplied by the number of dollars per hour of practice on task B. In the case of the MD-11, dollar amounts of savings can be very large.

## Retention and Motor Memory

One of the most frequently studied theoretical issues in psychology—an issue that people often disagree about—concerns memory. Is memory a result of some processing of an event, or does memory refer to the processing itself? Are there different types of memory, such as memories for movements, for sensations, for smells, and the like, or is there just one memory, whose retention characteristics are a product of the nature and type of processing that is conducted? Questions such as these are hotly debated topics. For example, a scan of the chapters in Gluck, Mercado, and Myers, 2014 reveals an extremely wide diversity of topics, studied at many different levels of analysis. For the most part, these topics are beyond our present purposes. Rather, we present some of the evidence about the retention (this section) and retention loss (next section) of motor skills.

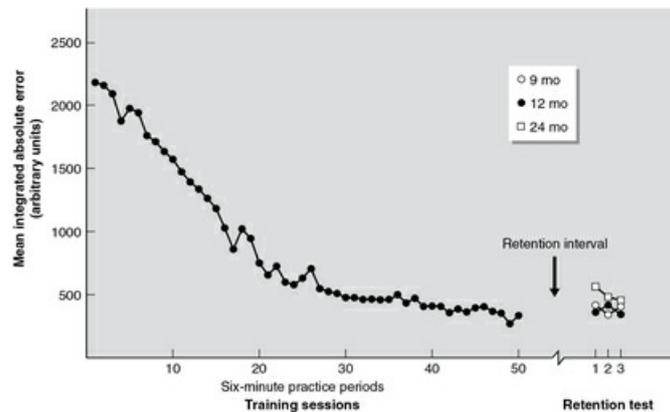
### Retention of Skill for Continuous Tasks

That many motor skills are nearly never forgotten is almost a cliché. Examples such as swimming and riding a bicycle, in which performance after many years of no intervening practice is nearly as proficient as it was originally, are frequently cited. Ideas about such examples, though, are seldom based on acceptable experimental methods; fortunately, many laboratory examples of these situations have been studied, and these results seem to say the same thing.

Although many studies could be cited to illustrate the point, we consider a representative study with long retention intervals by Fleishman and Parker (1962). They used a three-dimensional compensatory tracking task, with movements of the hands in forward–backward and left–right dimensions and movement of the feet in a left–right dimension. Participants practiced in sessions for 17 days, and then separate groups performed retests after either 9, 12, or 24 months.

The scores for practice and retention tests are shown in [figure 13.4](#), where scores for all three retention groups have been averaged together in the practice session. After the different retention intervals, the various groups were nearly equivalent, and none had shown any appreciable losses in proficiency even after two years of layoff. Some tendency was seen for the two-year group to have slightly less proficiency than the groups with shorter retention intervals, but the differences were very small and the losses were regained completely in three sessions. These small differences are not very meaningful when one compares the retention-test performance to the level of performance at the start of practice. Certainly, this continuous task was retained nearly perfectly for two years.

Figure 13.4 Mean performance on a three-dimensional tracking task in original learning and after three retention intervals.



Reprinted from E.A. Fleishman and J.F. Parker, 1962, "Factors in the retention and relearning of perceptual motor skill," *Journal of Experimental Psychology* 64: 218. Copyright © 1962 by the American Psychological Association.

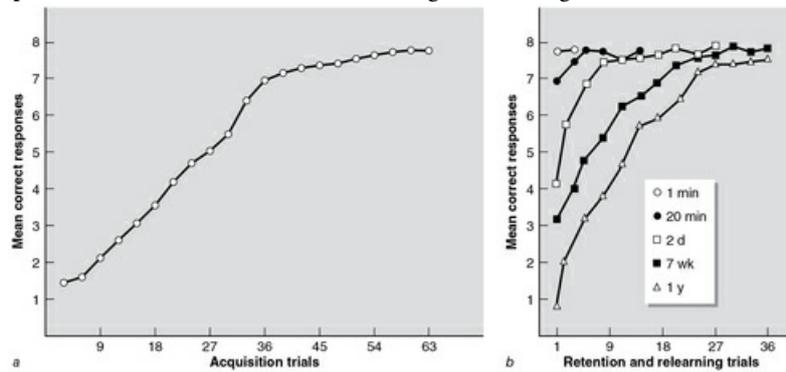
Other studies, using different continuous tasks, have shown very similar effects. Meyers (1967), using the Bachman ladder climb task, demonstrated nearly no loss in performance for retention intervals of up to 12 weeks. Ryan (1962), using the pursuit rotor and stabilometer tasks, found nearly no retention losses after retention intervals of 21 days; later, he found only small losses in performance on the stabilometer task with retention intervals of up to one year (Ryan, 1965). There are many other examples, and the generalization continues to hold. Continuous motor tasks are extremely well retained over very long retention intervals, just as the cliché about the bicycle would have us believe. In fact, once the continuous task is learned, it seems to be controlled automatically, without much conscious attention. The backward bicycle "experiment"<sup>1</sup> (a re-engineered bicycle that turns the front wheel in the opposite direction of the handlebars) showed how hard it was to override the basic control strategy and adapt to a new one.

## Retention of Skill for Discrete Tasks

While there is ample evidence of nearly complete retention of continuous skills, the picture appears to be quite different for discrete skills. Consider an example by Neumann and Ammons (1957). The participant sat in front of a large display with eight pairs of switches arranged in an inside and an outside circle of eight switches each. The participant was to turn the inner switch "on" and then discover which switch in the outer circle was paired with it; a buzzer sounded when the correct match was made. Participants learned the task to a criterion of two consecutive errorless trials, and then retention intervals of 1 min, 20 min, two days, seven weeks, and one year were imposed for different groups of people.

The main findings are presented in [figure 13.5](#). Some losses in performance appeared after only 20 min, and the losses became progressively greater as the length of the retention interval increased. In fact, after one year, the performance was actually less correct than the initial performance in practice had been, suggesting that the forgetting was essentially complete. However, notice that in all cases the improvements during the retention trials were more rapid than in the original-practice session (as indicated by comparing the slopes of the relearning and practice session curves), indicating that some memory for the skill was retained, which facilitated performance in these relearning trials.

Figure 13.5 Mean performance of a discrete task in (a) original learning and (b) after various retention intervals.



Reprinted, by permission, from E. Neumann and R.B. Ammons, 1957, "Acquisition and long term retention of a simple serial perception motor skill," *Journal of Experimental Psychology* 53: 160. Copyright © 1957 by the American Psychological Association.

## Continuous Versus Discrete Tasks

Why is there such a large difference in the retention characteristics of continuous and discrete skills, with continuous tasks having nearly perfect retention and discrete tasks having such poor retention? A number of hypotheses have been proposed to explain these differences, and they are discussed next.

### *Verbal–Cognitive Components*

One hypothesis is that verbal–cognitive components are somehow more quickly forgotten than motor components; because discrete tasks seem to have a heavier emphasis on verbal–cognitive elements (learning which switch in the inner circle is paired with which switch in the outer circle in the Neumann & Ammons study, for example), there is more loss for the discrete tasks over time. Ideas similar to this have generated considerable interest among neuropsychologists who study differences in the retention characteristics of various tasks (e.g., see "Retention of Motor Skills in Amnesia").

### Retention of Motor Skills in Amnesia

The examination of amnesia patients has provided some surprising information about the retention of motor skills compared to other types of information. Two patients are particularly noteworthy. One famous patient (H.M.) was studied by neuropsychologists for many years following an operation on the temporal lobes in his brain. The result of the surgery was a devastating memory deficit, leaving him unable to retain information in memory for more than very brief durations. H.M. was able to learn motor skills, however, such as mirror tracing and pursuit rotor tracking (Corkin, 2013). Remarkably, H.M. showed impressive retention of these motor skills after periods of no practice, despite the fact that he could not remember ever having practiced these tasks or the experimenters who had conducted the experiments (Milner, Corkin, & Teuber, 1968)!

Memory in a patient with Alzheimer's disease (M.T.) was documented during the play of two rounds of golf with neuropsychologist Daniel Schacter. This patient had been diagnosed with a progressively deteriorating memory disorder, and at the time of the golf "experiments" showed extremely poor performance on standard tests of verbal memory. What makes M.T.'s case interesting is that his golf skill had remained relatively unimpaired. According to Schacter (1983), he remained "able to execute a complex set of acquired perceptual-motor procedures in a relatively fluent manner . . . generally hit the ball straight and frequently hit it for respectable distances . . . frequently sank putts up to 5 or 6 feet long,

and twice holed putts from over 20 feet” (p. 239). Nevertheless, M.T.’s memory deficits caused frequent problems in playing golf. For example, if M.T. was the second person of the twosome to hit his tee shot and left the teeing area immediately, then he had a good probability of finding his ball. However, if he teed off first, then by the time that Schacter had played his tee shot, M.T. usually had no idea where the ball had gone and occasionally had forgotten that he had already played his tee shot!

The existence of motor retention for newly acquired learning in people with amnesia (H.M.) and for a previously acquired skill (M.T.) in the presence of severe retention deficits for other types of information is a type of memory *dissociation*. Similar dissociations for preserved retention of perceptual-motor skill, combined with memory loss for information about the details of the practice session, have since been documented for healthy persons (e.g., Hikosaka et al., 2002; Verdolini-Marston & Balota, 1994). These dissociations have been explained by some theorists as supporting the view that the retention of (or memory for) motor skills is fundamentally different from the retention of other types of information, such as verbal knowledge (e.g., Roediger, 1990; Schacter, 1987). Various dichotomies have been used to describe this distinction, such as implicit versus explicit memory and declarative versus procedural or nondeclarative memory, representing a continuing source of experimental and theoretical curiosity in contemporary research.

However, while it is true that most of the discrete tasks that have been studied in retention situations seem highly verbal-cognitive (e.g., Schendel & Hagman, 1982), there is no reason that discrete tasks must be so. Certainly, one can think of many discrete tasks that have relatively little reliance on verbal-cognitive abilities (e.g., throwing, striking, pole-vaulting). What would be the retention characteristics of a discrete task that was highly “motor” in nature? Lersten (1969) used an arm movement task (the rho task) in which a circular and a linear movement component had to be performed as quickly as possible. He found approximately 80% loss (of the original amount of improvement) in the circular phase, and a 30% loss for the linear component, with retention intervals of one year. Similarly, Martin (1970) used a task in which the participants moved the hand over two barriers and then returned to a starting switch as quickly as possible, finding approximately 50% retention loss over a four-month retention interval. The large amount of loss in retention for discrete skills that can be considered “mostly motor” is similar to the loss experienced by Neumann and Ammons’ participants (see [figure 13.5](#)), suggesting that there is more to these effects in retention than just the “motoriness” of the tasks.

### *Amount of Practice*

One of the major factors determining absolute retention is the amount of original practice, with retention increasing as the amount of original practice increases. In tracking, for example, there are many instances within a trial lasting 30 s in duration in which the pointer and track become separated, with each instance requiring a separate adjustment. Thus, a single “trial” may require many separate “discrete” actions. Contrast this situation to that for discrete tasks, for which a trial typically consists of a single adjustment or action. It stands to reason, therefore, that with the same number of acquisition trials, the continuous task receives far more practice than the discrete task. The extra amount of practice, according to this hypothesis, leads to increased retention, since it is well known that absolute retention is directly related to the amount of original practice.

### *What is a “Trial”?*

Another notion, related to the one just presented, is that the definition of *trial* is quite arbitrary; a trial can refer to both a 200 ms reaction-time (RT) performance and a 2 min duration performance on a tracking task. This poses a problem for defining the amount of original practice for the task, and it is also a problem in connection with the retention test. Remember, the level of absolute retention is measured in terms of the performance on the first few “trials” of retention-test performance. If a “trial” is a 2 min performance, there could be a great deal of relearning occurring *within* a trial for the continuous task, with no relearning within a trial for a rapid discrete performance. So the initial movements within the first trial for the continuous task could show considerable retention loss, but

the experimenter might not detect it because the error in the initial performance would be “averaged” with the later portions of the trial on which performance was more proficient. Because this could not occur for the discrete task, it is possible that the amount of forgetting is typically underestimated for the continuous task and not for the discrete task, making the two kinds of tasks appear to be different in their retention characteristics when they might otherwise not be. Fleishman and Parker (1962) found a great deal of improvement within a continuous-task trial, as might be suspected.

### *Retention of Generalized Motor Programs Versus Parameters*

Another possible difference in the forgetting of continuous and discrete tasks is that researchers might be examining different characteristics of the task. Evidence of this was found in a study by Swinnen (1988), who had individuals learn an elbow flexion–extension–flexion task with a goal movement time (MT) of 650 ms. Following 60 trials of practice (with KR), retention tests (without KR) were given after intervals from 10 min to five months. Swinnen analyzed separately the retention of absolute timing (related to the movement parameter) and relative timing (related to the generalized motor program, or GMP) and found that absolute timing decayed rapidly, supporting much of the research in this area for discrete tasks. In contrast, the GMP information suffered no loss in relative timing accuracy. These findings suggest that at least some information from learning discrete tasks is retained quite well. Moreover, these findings make sense from a schema theory view (Schmidt, 1975b). One has no need to retain parameter information over long periods of time, because that information is used only briefly to update the schema. In contrast, schema theory suggests that the retention characteristics of GMPs are quite strong so that the invariant features of the action can be recalled and parameterized as needed. Certainly, much more work could be done to explore the ideas introduced in Swinnen’s experiments.

## Retention Loss

In this section we present four different research methods used to investigate retention loss in motor performance, followed by a discussion of related theoretical and experimental issues about the processes through which retention loss occurs. Each method highlights some important features about performance loss that are revealed under different task conditions.

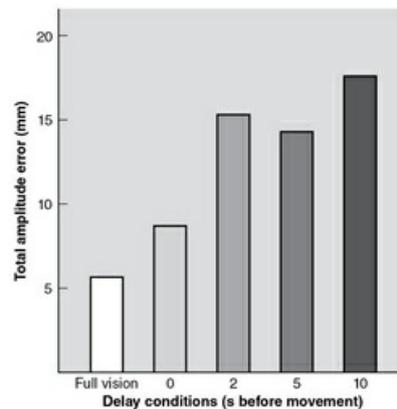
### Iconic Memory and Motor Performance

As we discussed in chapter 5, motor performance benefits considerably from the availability of visual information, especially for actions that require precise end-point accuracy, such as manual aiming (e.g., typing; moving a cursor). However, there is considerable evidence to suggest that *continuous* visual information is unnecessary in order to maintain accuracy (Elliott et al., 2017). The reason is that our memory for the immediate visual environment can “fill in” the gaps if the continuous supply of vision is cut off. For example, suppose you took aim at the bull’s-eye in dart throwing and the room lights suddenly went out just before you started moving the dart. How would performance be affected? Research using experiments that closely resemble this situation suggests that performance would depend on the length of time you were in the dark before throwing the dart.

Studies by Elliott and his colleagues suggest that motor performance deteriorates quickly because persistence of the visual information (the icon) fades rapidly from sensory memory (Sperling, 1960). For example, in a study by Elliott and Madalena (1987), participants moved a stylus to a target under various conditions of available room light. A control condition provided participants with continuous visual feedback of the target and stylus. In another condition, the room lights were extinguished as the participants initiated their movements; thus the entire movement (durations of 200-500 ms) was made in the absence of any direct visual information. The other three conditions also involved movements without visual information available; however, these movements were made after the room lights had been extinguished for 2, 5, or 10 s.

As [figure 13.6](#) shows, participants could perform the aiming movements well without visual information if the entire movement was *completed* within half a second after the room lights were turned off. Performance was markedly disrupted, however, after a wait in the dark of 2 s or more. Elliott and Madalena (1987) interpreted these findings to suggest that a very short-lived memory for visual information can support performance rather accurately (see chapter 3; reviews by Elliott, 1990, 1992; Elliott et al., 2017; Farrell & Thomson, 1998). However, the information is prone to forgetting due to a *decay* of the icon—a process whereby rapid information loss is attributable to the passage of time.

Figure 13.6 Total amplitude error in aiming under conditions of vision and without vision under various delay conditions.



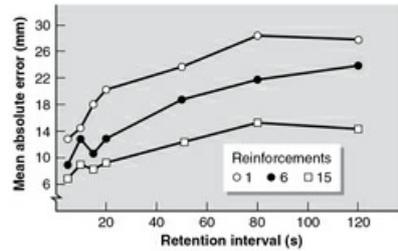
Data from Elliott and Madalena 1987.

The findings of Elliott and Madalena (1987) and others (e.g., Binsted, Rolheiser, & Chua, 2006) indicate that motor performance can be supported for a brief time by a short-term sensory store, which loses information quite rapidly. These findings suggest a process similar to that proposed in the oldest theory of forgetting, the *trace-decay theory*. It is a passive theory of memory loss caused by disuse—information is forgotten because it is not practiced and therefore “decays” with time. The memory of an item, event, or skill is thought to be represented as a trace in the central nervous system, with the strength of this trace weakening over time. When the information or skill in memory is needed at some future time, performance accuracy is related to the current strength of the trace. This idea accounts well for the common effects of disuse and, of course, for the fact that time, per se, seems to be a strong factor in forgetting.

Considerable research on trace-decay effects in slow, linear-positioning tasks has been conducted using what is called the *short-term motor memory paradigm* (see chapter 3). This involves the presentation of a movement, followed by recall of that movement after very brief time intervals, often only a few seconds in duration. These studies used methods that paralleled methods in experiments in memory for verbal materials, early investigations having been conducted by Brown (1958) and Peterson and Peterson (1959). In one of the first motor studies, Adams and Dijkstra (1966) had participants move to a stop that defined a target position, then return to a starting location for a retention interval, and finally, estimate the defined target position but with the stop removed. Participants were blindfolded and not given KR about their movement accuracy. In addition, participants were given various numbers of “reinforcements,” whereby movement to the target position was presented 1, 6, or 15 times before the retention interval.

The major findings are presented in [figure 13.7](#). The absolute errors on the recall trials are presented as a function of the number of “reinforcements” and the length of the retention interval. As the length of the retention interval increased, the error in recall also increased, with the increases being nearly maximized by the time the retention interval was 80 s in length and with no important increases thereafter. Similar to memory for verbal items, memory for these linear-positioning movements appears to have a forgetting process that is nearly completed in about 1 min. Also, the rate of forgetting appears to be slowed by “reinforcements,” or practice; the errors were systematically smaller with more repetitions of the target position.

Figure 13.7 Mean absolute error in positioning as a function of the retention-interval length and the number of “reinforcements.”



Reprinted, by permission, from J.A. Adams and S. Dijkstra, 1966, “Short-term memory and motor responses,” *Journal of Experimental Psychology* 71: 317. Copyright © 1966 by the American Psychological Association.

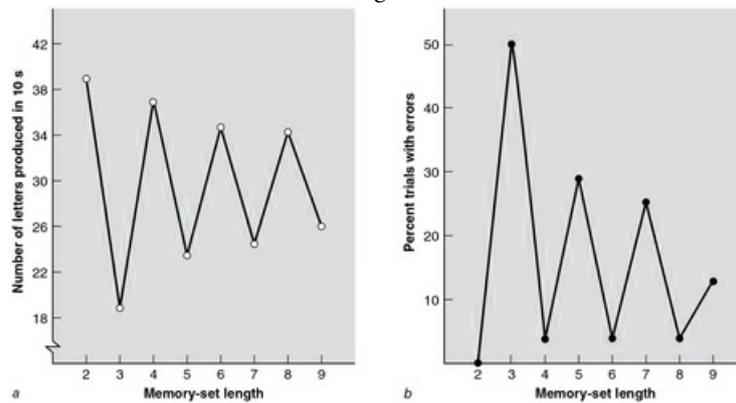
One interpretation of these results is that the movement to the stop created a short-term memory representation of the feedback qualities of the correct position. Further, it appeared that, although this representation was weakened over the course of the empty retention interval, it was strengthened by repetition. These factors combined to determine the “strength” of the representation against which the feedback was compared at the retention test—weakened by time but strengthened by repetitions. It is also possible that forgetting can occur by means other than trace decay. This idea is presented in the next example.

## Brief Postmovement Memory

Now consider a very different and clever memory-related paradigm, developed by Rosenbaum and his colleagues (Rosenbaum, Weber, Hazelett, & Hindorff, 1986; see also Rosenbaum, 2009). The individual’s task is easy to simulate: The basic requirement is to speak aloud as many letters as possible in 10 s, alternating between a loud voice and a soft voice with each spoken letter. For example, in one condition the participant would shout the letter *A*, then softly speak the letter *b*, then shout *C*, softly speak *d*, then start over again by shouting *A*, and so on (*AbCdAbCd . . .*). Notice that a loud vocalization was always required for the letters *A* and *C*, and a soft vocalization was always required for *b* and *d*. And this is true for any *even*-numbered memory set. Now compare this to an *odd*-numbered memory set, such as *AbCaBcAbCaBc*. Notice now that the stress on a specific letter *switches* to the opposite stress on each repeated cycle. This feature is consistent for all *odd*-numbered memory sets.

The speed and error data from Rosenbaum and colleagues’ (1986) experiment are presented in [figure 13.8](#). As you would expect, more letters in the even-numbered memory sets (2, 4, 6, 8) were produced in 10 s than in the odd-numbered sets (3, 5, 7, 9) ([figure 13.8a](#)). Also, trials on which errors occurred were more frequent for the odd-numbered than the even-numbered sets ([figure 13.8b](#)).

Figure 13.8 (a) Total number of letters spoken and (b) percentage of trials with errors as a function of memory set length.



Data from Rosenbaum et al. 1986.

What do these findings suggest about motor memory? One view is that this task required participants to vocalize letters (all having different learned GMPs) with different parameterizations—in this case the specific parameter of interest was whether the letter is spoken loudly or softly. Once the letter was produced, the parameter used for that instance was retained in memory. If the next vocalization of that same letter required the same parameter (i.e., as in an even-numbered memory set), the accurate representation that remained in memory *facilitated* performance. However, if the opposite parameter was required (i.e., as in an odd-numbered memory set), the memory of the previous parameter for that letter *interfered* with performance because the remembered parameter needed to be changed. Thus, a strong memory representation either facilitated or degraded performance, depending on the task demands.

But notice something else in the speed and error data in [figure 13.8](#). As the length of the memory set increased, the size of the performance difference between the even- and odd-numbered sets was reduced. The memory-set effect, which previously had either facilitated or degraded performance, was *reduced* when more letters intervened between the repetitions of any one letter. We expect that if the length of the memory sets had been extended even further (e.g., to 25 and 26 letters), the performance differences between the odd- and even-numbered letter strings might have been eliminated completely. This finding suggests a *weakening* of the influence of a previous performance on selecting a parameter for a subsequent performance, which is dependent on the memory-set size.

Two possible influences seem to be occurring in Rosenbaum and colleagues' (1986) study. As the length of the memory set increased, the *time* between any two vocalizations of the same letter increased, resulting in a decay of the representation for the previous parameter. The mere passage of time is not all that happened, though, because as the memory-set size increased, more intervening letters were spoken, which caused more *interference* with the memory for any specific previously spoken letter. Thus, another cause of forgetting may have had something to do with these events, rather than mere passage of time as trace-decay theory would have it.

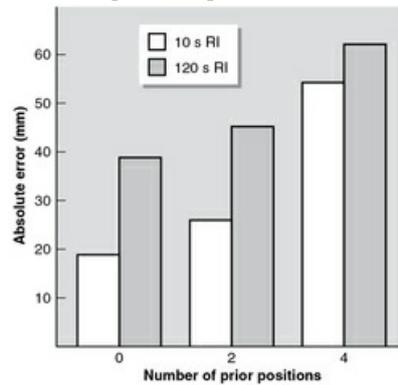
Interference theory suggests that memory is actively degraded by other events. Such interference, according to the theory, can be of two basic kinds: *proactive interference* and *retroactive interference* (Underwood, 1957). The most common research method involves an experimental paradigm in which the interfering event occurs between the time of the storage (encoding) of the to-be-remembered information and the time of the attempted recall (retrieval)—that is, during the retention interval. The term *retroactive* implies that the interference “works backward” on the memory; of course, it does not work backward at all, but it does nevertheless serve to disrupt the recall of something that occurred before the interference.<sup>2</sup> Interference can also occur in a less obvious way when something that happens before the criterion memory task causes interference with the recall of that criterion information. The term *proactive* implies that the information already “in memory” interferes with more recently acquired information. More recently acquired information may be in a much more fragile state (e.g. during consolidation), than information that has passed through the consolidation phase and into a more stable form.

Using the short-term motor memory paradigm described in chapter 3, experimenters have attempted to assess the

mechanisms causing forgetting in relation to interference theory. With respect to *proactive interference*, neither Adams and Dijkstra (1966) nor Posner and Konick (1966) found evidence that later positions to be remembered in a sequence were less accurate than earlier ones, which would be expected if the proactive interference from the earlier movements were disrupting the memory of the later positions. Such findings had been shown in verbal behavior. One reason these proactive effects may not have occurred in the motor studies is that the intertrial intervals were very long (2 min in Adams & Dijkstra's study; see [figure 3.20](#)), possibly providing an opportunity for forgetting of an earlier movement before a later movement could be presented.

Ascoli and Schmidt (1969) studied proactive effects by concentrating the prior movements into a short period of time. They presented either zero, two, or four positions just prior to the presentation of a criterion movement (the movement to be remembered). A retention interval of either 10 or 120 s followed the criterion movement, then recall of the criterion movement was attempted, and finally a recall of the preliminary movements (if any) was done. [Figure 13.9](#) presents absolute errors in recall for the two retention intervals and for the various numbers of prior movements. Errors increased as the length of the retention interval increased. But of more interest was the finding that the four-prior-position condition showed more error than either the zero- or two-prior-position condition. A major effect was seen for constant error, with increased prior positions making the movements systematically too short. The data can be interpreted to mean that proactive interference is a factor in the retention of these positioning movements, supporting the interference theory (see also Stelmach, 1969).

Figure 13.9 Mean absolute error in positioning as a function of the retention-interval length and the number of previous positions.



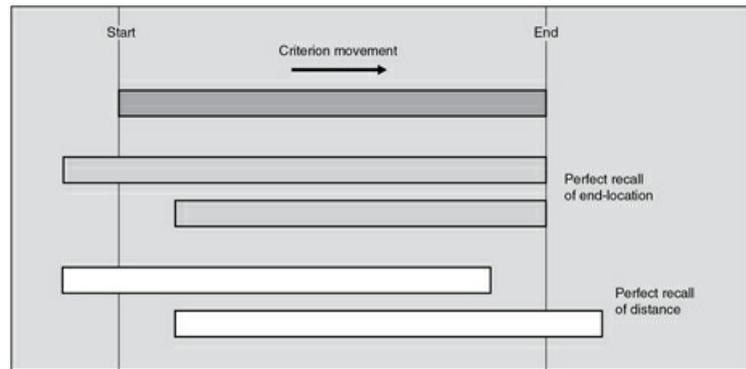
Data from Ascoli and Schmidt 1969.

With respect to *retroactive interference*, some earlier researchers failed to find effects of activities placed between the presentation and the recall of the test movements, casting serious doubt on the application of interference theory to memory for movements. But none of these studies reported constant errors, and the finding that proactive interference had its major effects on constant error raised the possibility that retroactive effects would be seen in the same way. In a reanalysis of earlier data, Pepper and Herman (1970) found that movements produced during the retention interval tended to have negative effects on movement accuracy when measured in terms of constant error. Subsequently, Patrick (1971) and Milone (1971) also provided evidence for retroactive interference.

### *Cue-Separation Techniques*

What does the performer remember and recall in these positioning tasks? One possibility is that the person remembers the sensory qualities of the target position and attempts to match these sensations through a closed-loop process during the recall (i.e., retention test) movement. That is, the person might be attempting to move to that position that is *recognized* as correct (see “Schema Theory” in chapter 12). Another possibility, however, is that the person remembers the distance moved, rather than the location of the target, and remembers a motor program that will move the limb a certain distance. These two possible cues (location vs. distance) were confounded in the earlier experiments on motor short-term memory. However, Keele and Ells (1972), Marteniuk (1973), and Laabs (1973) used a simple, but clever, method for unraveling these two potential cues ([figure 13.10](#) is an illustration).

Figure 13.10 Illustration of the motor short-term memory paradigm used to separate the effects of end-location and distance cues.



Adapted, by permission, from K. Imanaka, B. Abernethy, and J.J. Quek, 1998, The locus of distance-location interference in movement reproduction: Do we know any more 25 years on? In *Motor behavior and human skill*, edited by J.P. Piek (Champaign, IL: Human Kinetics), 33.

For example, Laabs (1973) had participants move to a stop for the presentation of the stimulus materials (as in the Adams & Dijkstra study). Then he formed two different conditions for recall. In both of these conditions, participants began at a *different* starting position for the recall movement. In one condition, they were asked to recall the same *location* on the curvilinear track as before, so the distance of the recall movement was different from that of the presentation movement, rendering memory for distance unreliable. In the other condition, the participant was asked to move the same *distance* as in the presentation movement, so the location of the presentation movement was unreliable to the performer for recall.

Laabs' major findings were that accuracy was far greater in the condition in which the location cue was recalled than in the one in which the distance cue was recalled. Subsequent research has suggested that people have a difficult time remembering cues about movement distance and that positioning movements are probably based on some memory of location. However, retroactive-interference effects for location and distance information may occur in complex ways in some instances (Imanaka & Abernethy, 1991, 1992; Imanaka, Abernethy, & Quek, 1998; Walsh, Russell, Imanaka, & James, 1979).

### *Preselection Effect*

In the usual paradigm for motor short-term memory studies, the individual is asked to move to a stop that is defined by the experimenter; thus the performer does not have any advance knowledge about where the movement end point is located until she contacts the stop. Marteniuk (1973) and Stelmach, Kelso, and Wallace (1975) introduced a new method when they asked people to choose their own movement end points. In effect, the instruction was to move to a position of the individual's choice (a stop was not provided); then the performer returned to the starting position and was asked to reproduce the position after a retention interval. This so-called *preselection* method led to much more accurate recall than the experimenter-defined method. Note that these findings have some similarity to recently studied effects in learning when participants are allowed to regulate their own practice schedule (see chapter 10) or augmented feedback presentations (see chapter 11). The key commonality may be related to the active involvement of the learner in remembering and learning processes.

When the participant is faced with these reproduction situations, it is likely that the nature of the methods will influence the way in which the person stores the information. For example, if the person does not know where the target will be (in the standard paradigm), this could force the individual to process sensory cues about the target location, perhaps leading to a strategy wherein the recall of the movement is produced through closed-loop processes. In the preselection method, however, the performer can generate a movement plan in advance, perhaps programming it, and thus can ignore the sensory consequences of the movement—simply rerunning the program at the retention (recall) test. This may also suggest that memory for programs or parameterizations may be more stable than memory about the feedback for correct locations.

## *Spacing of Repetitions*

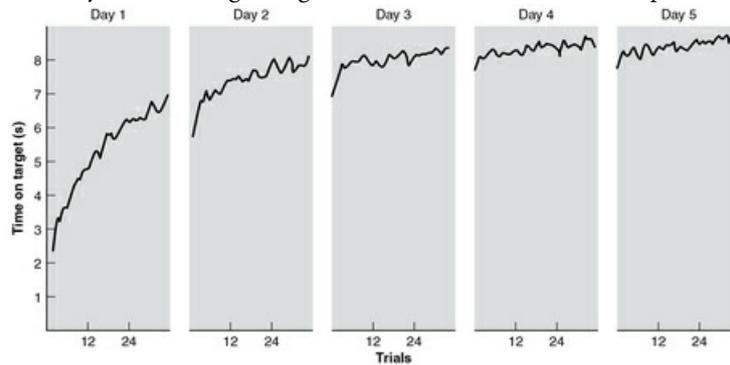
Earlier we presented the findings of the Adams and Dijkstra (1966) study, in which many reinforcements (or “repetitions”) of the movement reduced the loss of information during the retention interval. These findings have been replicated often (reviewed in Lee & Weeks, 1987), suggesting that a memory representation is stronger or more resistant to forgetting with “practice.” A curious finding, however, is that the repetition effect is enhanced if the repetitions themselves do not occur immediately but instead are spaced apart—especially so if some interference occurs between these repetitions (e.g., Lee & Weeks, 1987; Weeks, Reeve, Dornier, & Fober, 1991). One explanation for this *spacing effect* is that paradoxically, the forgetting that occurs following one repetition *enhances* the benefit of a subsequent repetition, on the retention (recall) test (see “When Forgetting Improves Remembering” in chapter 10). This finding is similar to the “Forgetting and Reconstruction Hypothesis” explanation of the contextual-interference effect discussed in chapter 10, suggesting that common underlying factors may be involved. Recent work that tested a unifying hypothesis of the spacing and contextual interference effects in visuomotor adaptation found that retention following adaptation is modulated by the degree of between-trial forgetting, which is due to time-based decay in a single adaptation task and interferences in multiple adaptation tasks (Kim, Oh, & Schweighofer, 2015).

## Warm-Up Decrement

To this point in the chapter, the focus has been on memory losses. But as mentioned earlier, not all decrements seen in a retention test are due to memory losses, such as loss of motivation, day-to-day fluctuations in performance, effects of drugs, and illness. Many of these have been discussed with respect to the measurement of performance (see chapter 2) and learning (chapter 10), and they are all involved in motor retention as well. But a special kind of decrement in motor performance has a small literature of its own, and it deserves special mention. This effect is called *warm-up decrement*.

The phenomenon can be easily introduced with an example. Adams (1952, 1961) studied a large group of performers on the pursuit rotor task, providing thirty-six 30 s trials per day for five days; the results are shown in [figure 13.11](#). The typical improvement with practice during a session of trials is seen, but also seen is a relatively large decrement in performance after each 24 h rest period. This decrement appears to be quite severe, and it is equivalent in size to the gains experienced in 5 to 10 trials. It is also rather short-lived, being eliminated in only a few practice trials. The phenomenon has been known for a long time and has been found in nearly every motor task that has been studied (see Adams, 1961, for a review). This decrement was thought to be related in some way to the need to “warm up” (probably not in the usual sense of warming up the muscles) for the task again after the rest, and the phenomenon came to be called *warm-up decrement*. It can be of potential importance when people are asked to perform after a rest period, as occurs with the worker operating a dangerous machine after a coffee break, the athlete going into the game from the bench, or a surgeon’s first operation of the day (Kahol, Satava, Ferrara, & Smith, 2009).

Figure 13.11 Mean performance on the pursuit rotor task for five days. (The decrements in performance from the end of one day until the beginning of the next are termed “warm-up decrement.”)



Reprinted from J.A. Adams, 1961, “The second facet of forgetting: A review of warm-up decrement,” *Psychological Bulletin* 58: 260.

Two major classes of explanation for warm-up decrement can be described. A *forgetting hypothesis* holds that the loss in skill is due to forgetting of the type mentioned in the previous sections. On the other hand, various versions of the *set hypothesis* argue that the loss in skill is due to a relatively temporary loss of bodily adjustments or states. These views and the evidence for them are contrasted in the following sections.

### *Warm-Up Decrement as Forgetting*

One major hypothesis, and probably the earliest and simplest explanation to be considered, is that warm-up decrement is simply another form of forgetting—that is, the loss of memory for the skill. In this view, the rest period allows certain forgetting processes to occur, with the initial phases of these processes being relatively rapid. These account for the rather large performance decrements seen with only a few minutes of rest. The improvements in performance with resumed practice are, in this view, due to relearning of the task whose memory was weakened over the rest period. This view does not seem to hold well for continuous skills, which as we have discussed, are not only retained well for long periods of time but also show substantial warm-up decrements. In general, there appears to be little support for a memory-loss explanation of warm-up decrement (Stratton, Liu, Hong, Mayer-Kress, & Newell, 2007).

### *Warm-Up Decrement as a Loss of Set*

In another view, the loss of skill is related to the loss of *set*—one or more temporary internal states that underlie and support the skill in question. Set could consist of postural adjustments, orientation of attention to the feedback channel that is relevant for the task (e.g., vision vs. kinesthesia), adjustments in emotional state, and many more. According to this view, warm-up decrement is caused by the loss (or disruption) of these adjustments (set) over the rest period. The hypothesis says that *memory* of the skill is not lost over the rest period; or perhaps very small memory losses do occur, but they are far too small to account for the large decrements seen. With practice resumed on the task after the rest, performance is improved because the internal set (or adjustments) that supports the skill is reinstated.

### Early Evidence on the Set Hypothesis

The set hypothesis seemed reasonable for many years, as it is easy to imagine how such a process might disrupt skills with rest, especially in the face of the nearly perfect retention of skills like those in the pursuit rotor task. Yet no evidence existed for these set-loss phenomena until Irion’s (1948) data with verbal skills suggested a way to study the problem. Irion’s idea was that it should be possible to reinstate a lost set through certain activities that are related to the action in question but that cannot be thought of as contributing specifically to the memory for it. Irion used verbal learning as the main task, with two groups; both practiced the verbal task, then had a rest,

then resumed practice again. One of the groups remained inactive during the rest period. The other group engaged in color naming during the end of the rest period—an activity presented on the same apparatus and having the same rhythms as the verbal-learning task but using none of the learned items from the main task. If the set hypothesis is correct, color naming should reinstate the lost set produced by the rest, and the initial performance on the verbal-learning task should be more accurate than for the group that simply rested. It was. Because color naming cannot be argued to increase memory strength for the verbal task, the implication is that color naming reinstated the lost set, in some way *preparing* the participants for the upcoming verbal task.

Numerous studies were done to evaluate the set hypothesis with motor skills but with few successes. In one such investigation, Ammons (1951) used the pursuit rotor; during the rest period, he had participants watch another active participant or follow the target area with the finger, for example, in an attempt to eliminate warm-up decrement. No procedures were found that would eliminate it (see Adams, 1955). These data seemed to say that either (a) the set hypothesis was wrong for motor behavior or (b) the appropriate nonmemory-set–reinstating activities had not been studied. In either case, the set hypothesis was not well supported. This evidence is reviewed more completely by Adams (1961, 1964) and by Nacson and Schmidt (1971).

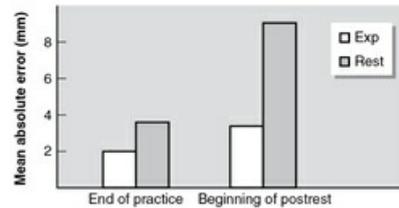
### Recent Evidence on the Set Hypothesis

Nacson and Schmidt (1971) tested the set hypothesis and provided considerable support for it. Their idea was that during practice, various supportive mechanisms are adjusted constantly so that performance is maximized; then, during rest, these functions are adjusted to levels most compatible with resting, leading to an ineffective pattern of adjustment when the task is resumed. Practicing a task requiring the same adjustments (set) as the main task just before returning to it should reinstate those adjustments, leading to a reduction in warm-up decrement, just as Irion (1948) had found with color naming.

The task used by Nacson and Schmidt (1971) involved a right-hand force production; the performer had to learn to squeeze a handle with a 21 kg force, with KR given after each trial and 10 s rest between trials. After trial 20, a 10 min rest was given, and then practice resumed for another 10 trials. The independent variable was the nature of the activities presented in the 10 min rest period. One group (Rest) was allowed to rest for 10 min. Another group (Exp) had 5 min of rest, followed by 5 min of another force-estimation task; this task, though, involved the left arm rather than the right arm, elbow flexors rather than the gripping action, and a different level of force (9 kg). So it could not be argued that this task would contribute to the memory of the right-hand grip task. After 18 trials of this task with the same intertrial interval and KR, participants were shifted immediately to the right-hand grip task for the retention test.

The absolute errors in the main (right-hand gripping) task are shown in [figure 13.12](#) for the two groups before and after the rest period. The group that simply rested (Rest) for 10 min showed the typical warm-up decrement after the rest; but the group with the left-hand activities (Exp) showed very little warm-up decrement, suggesting that the activities in the rest period reinstated the lost set. Similar findings have been shown for a linear-positioning task (with a positioning task as the warm-up task) by Nacson and Schmidt (1971; Schmidt & Nacson, 1971), and by Schmidt and Wrisberg (1971), using a movement-speed task (with another movement-speed task as the warm-up task). These data also argue against the hypothesis that warm-up decrement is simply forgetting; a forgetting hypothesis cannot explain why a different warm-up task (which seems to have no memory elements in common with the main task) should produce improvements in main-task performance.

Figure 13.12 Absolute error in a force-estimation task for original learning and after a 10 min rest. Group Rest rested during the interval, and group Exp performed a left-hand force-estimation task; error is measured as a polygraph pen displacement.



Other data (Schmidt & Nacson, 1971) showed that the reinstated set was rather transient in nature. If as few as 25 s of rest were inserted between the reinstatement of the set and the resumption of practice on the main task, the set was completely lost again. Also, activities can be designed that will *increase* warm-up decrement even more than resting does. For example, Schmidt and Nacson (1971) showed that a grip strength task (with maximum force) performed just before the resumption of practice on a linear-positioning task caused a very large increase in error on the first postrest trial, suggesting that the maximum-grip task required a set that was incompatible with the set for linear positioning. Other experiments indicate that *imagery* practice of the task just prior to the resumption of performance can reduce the warm-up decrement, although the nature of the reduction seems to be task specific (Ainscoe & Hardy, 1987; Anshel & Wrisberg, 1988, 1993; Wrisberg & Anshel, 1993).

In sum, these findings suggest that warm-up decrement is caused by some loss of internal adjustments (or set) over the rest period. These adjustments are critical to effective performance in the task, but they are not a part of the memory for it. Just as a race car needs to attain the proper temperature before maximal performance can be achieved, so too, it appears, must humans achieve the proper state of (temporary) adjustment for high-level skilled performance. It is not clear exactly what is being adjusted in these experiments, but probable candidates are the level of arousal, the rhythm and timing for the trial cycle, attention to the proper focus and sources of feedback, and so on.

These findings have considerable relevance for high-level performances, especially after performance is interrupted by rest or when major changes in tasks are required. For example, in golf, there are probably different sets for driving and putting, each of which must be re-established before each shot. Watch professional golfers before they execute a swing; or watch professional basketball players before they take a free throw. Most players carry out a “preshot routine”—a sequence of actions and thoughts that are specific to each athlete but done consistently by that athlete from shot to shot. It is tempting to suggest that the preshot routine is a method that reinstates the set and helps to overcome warm-up decrement (Boutcher & Crews, 1987), and some evidence exists to support the contention (Mack, 2001). However, much more research could be done to more fully investigate the idea.

## Consolidation

An old concept in motor learning research, which dates back well over a century (see McGaugh, 2000, for a historical review), has received renewed interest in recent years. Much of the current work is being conducted at the cellular level of analysis with animals and is beyond the scope of discussion here. However, a significant amount of research has also been conducted at the behavioral level, with intriguing results.

The basic idea is that practice produces a memory for motor skill that is unstable for a period of time but that stabilizes, or “consolidates,” during a critical period afterward. A frequently used method to examine consolidation uses a variant of the retroactive-interference paradigm discussed earlier. In this paradigm, one group learns task A, then immediately practices a second task (B). Another group undergoes the same learning procedures, except that a time interval is inserted prior to learning task B, which presumably allows for the consolidation of task A. Retention of task A is measured later for both groups.

This paradigm was used, for example, by Walker, Brakefield, Hobson, and Stickgold (2003) to examine the

retention characteristics of a finger-sequencing task. Participants who learned a different sequence (task B) immediately after practicing an initial sequence (task A) performed much less skillfully 24 h later in the retention trials of task A than participants who delayed practice of task B by 6 h after initial practice of task A. This suggested that the 6 h rest allowed some consolidation of task A, rendering it less vulnerable to interference from task B. Moreover, these consolidation effects appear to be larger if the consolidation interval includes a period of sleep (Stickgold & Walker, 2006).

These findings are not without some controversy, however, as failures to find consolidation effects appear to be related to task-specific differences and experimental design issues (e.g., Criscimagna-Hemminger & Shadmehr, 2008; Krakauer & Shadmehr, 2006). These consolidation effects are also difficult to reconcile with variability-of-practice effects discussed in chapter 10, in which retention and transfer following practice on a single task are less effective than with practice on multiple tasks (e.g., Shea & Kohl, 1991). Nevertheless, the renewed interest in these retention issues has escalated motor learning research in a number of experimental laboratories, representing a current “hot topic” in the literature. One example of this is a study focused on the brain and behavior showing that the neural substrates of motor memory consolidation depend on practice structure (Kantak, Sullivan, Fisher, Knowlton, & Winstein, 2010).

The focused review that provided support for the motor behavior–memory framework described at the beginning of this chapter (Kantak & Winstein, 2012), reported that 63% of the 41 motor learning studies (all examined the effects of conditions of practice on learning) that included both immediate and delayed retention or transfer tests found incompatible results for the two retention tests. Well-known practice structure effects, such as the “Contextual Interference” (see chapter 10) effect on learning were less prevalent at immediate retention than at delayed retention. From a theoretical standpoint, this distinction may indicate the distinct nature of memory processes that operate during practice (online) and after practice ends (offline) that are important for understanding motor learning. For example, a single bout of exercise was shown to improve motor memory when the intense exercise bout was performed immediately before or after practicing a visuomotor accuracy-tracking task. There was an advantage for the exercise bout if performed immediately after the tracking task but only for the 7-day retention test (Roig, Skriver, Lundbye-Jensen, Giens, & Nielsen, 2012). The offline memory phase immediately before and after practice most likely engages the more transient memory processes of consolidation, the mechanisms of which have become an important focus of current research.

# Transfer of Learning

A number of decisions about the design of practice sessions are based heavily on an understanding of *transfer of learning*—the gain (or loss) in proficiency in one skill as a result of practice on some other skill. Often, the task actually practiced in a session is not the activity of primary interest, the real concern being for some other task believed to be related to this activity. One example is the use of drills, in basketball. The instructor usually does not really care whether the student can perform these drills well; rather, the instructor assumes that, by practicing them, the student will learn something that will transfer to some other task that is of primary interest (e.g., performance in a basketball game). For drills to be successful, one must be certain that what is learned in practice on the drill transfers to performance of the desired *criterion task*.

Another example is the common method whereby the task is broken down into its components for practice. The assumption is that practice on the parts will transfer to the whole task. Still another example is the use of simulators of various kinds, such as a pitching machine to simulate a “real” pitcher in baseball, a dummy for training resuscitation skills, or a simulator to duplicate an aircraft cockpit. Does practice on these simulators result in improved performance on the criterion task—that is, do learning skills using the simulator *transfer to the task of most interest*? The choices about whether or not to use these methods, and about how they should be structured, if used, depend heavily on an understanding of transfer of learning. We consider some of the principles of motor transfer next.

## Basic Principles of Transfer

Many studies using different techniques and tasks have produced a vast array of different and sometimes contradictory findings on transfer (see Cormier & Hagman, 1987, for a review). Two major points emerge from the work on motor skills. First, the amount of transfer seems to be quite small and positive unless the tasks are practically identical. Second, the amount of transfer depends on the “similarity” between the two tasks (Schmidt & Young, 1987). Much of this work started in the lab of Franklin M. Henry, who investigated a then-popular idea called *general motor abilities*, which states that if transfer of skills within an individual is always strong and positive, then a person who is highly skilled in one task should also be highly skilled in related tasks.

### *Correlations of Skills*

A large number of separate investigations in the published literature deal with the correlations of well-practiced skills, but we discuss only three of these studies in order to give the general idea (for a review, see Marteniuk, 1974). One example from Henry’s laboratory is a study by Bachman (1961). A group of 320 people practiced two motor tasks that supposedly involved the ability to balance. One of these, the Bachman ladder task, required participants to climb a free-standing ladder. Bachman’s second task was the stabilometer (see [figure 2.5b](#)). This apparatus was an unstable balancing board on which the participant stood; it pivoted so that the right foot moved down as the left foot moved up. The performer’s task was to keep the unstable board still, with feet level. Bachman (1961) found that for various subgroups of participants (defined by age and gender), the correlations between success on the ladder and success on the stabilometer ranged from +0.25 to -0.15, with most correlations being very close to zero. These results ran contrary to a general motor ability hypothesis, or even to the concept of a general balance ability.

Lotter (1960) had participants perform striking actions of the hand and kicking movements with the foot and measured reaction and movement times for each. The hand action involved a forward–downward movement to hit a suspended tennis ball as quickly as possible (for the left and right hands separately); the leg movement involved kicking a small plate with a movement similar to a place kick in American football (again, for the right and left legs). The arm–arm correlation was 0.58, and the leg–leg correlation was 0.64. These correlations were considerably higher than those found by Bachman (1961), but they involve the same task performed with limbs

on opposite sides of the body. The correlations between arm and leg, on the same side of the body (e.g., right arm vs. right leg) or on opposite sides (e.g., left arm vs. right leg), were considerably lower: 0.24, 0.36, 0.23, and 0.18. These findings do not support a general motor ability hypothesis either.

Finally, Parker and Fleishman (1960) had 203 participants perform a battery of 50 tests in conjunction with an armed services testing program. This produced a 50 x 50 correlation matrix, whereby every test is correlated with every other test and the resulting correlations are placed in a large table. The majority of tests correlated about 0.40 or lower with each other; only rarely was there a correlation of 0.50 or higher, which again fails to support the idea of general motor ability.

Many similar studies have been done. Generally, low correlations are found among different skills. This pattern does not support the notion of a general motor ability or even of general motor sub-abilities such as balance (Bachman, 1961) or quickness (Lotter, 1960). Marteniuk (1974) published a critical review of the research conducted during the 1950s and 1960s that remains important and relevant today.

### *Henry's Specificity Hypothesis*

In the late 1950s, Henry (1958/1968, 1961) proposed the idea, in direct contradiction to the general motor ability hypothesis, that motor abilities are specific to a particular task. Essentially there were three aspects to this hypothesis. First, Henry thought that the number of motor abilities was very large—perhaps in the thousands. Second, he believed that these abilities are independent, so that the strength of any one particular ability is unrelated to the strength of any other ability. Third, each task or skill that we perform depends on a large number of these abilities. When the task is changed, the particular collection of abilities that supports the performance must change to meet the new task demands.

Probably the most important prediction of the *specificity hypothesis* is that two tasks, even if they appear to be quite similar (such as throwing a baseball and throwing a javelin), will tend to correlate nearly 0 with each other. The groups of abilities that underlie these two tasks are, according to this view, two distinct collections with few or perhaps no abilities in common. Because these abilities are assumed to be independent, the correlation of skills should be 0, or at least very low. As discussed in the previous section, the evidence supports such a viewpoint.

In addition, the Henry hypothesis predicts that transfer of skills should be quite low (Schmidt & Young, 1987). Transfer is defined as the attainment or loss of proficiency in one task as a result of practice or experience at some other task. If the two tasks have no abilities in common, then no element practiced in one of them will contribute (transfer) to the other. Generally, the transfer literature supports Henry's hypothesis, showing essentially that motor transfer is generally low and positive.

### *Exceptions to Henry's Specificity Hypothesis*

Although Henry's hypothesis about specificity of individual differences has been widely accepted for many years, work by Keele, Ivry, and others indicates that timing may represent an exception to Henry's view. This new work suggests that a general "timekeeping" ability underlies performance of a number of tasks. The research focuses on how the temporal aspects of movements are organized in the central nervous system and examines correlations of various tasks requiring central control of timing. In one study (Keele & Hawkins, 1982), correlations between maximum rates of tapping by various body parts (finger, thumb, wrist, arm, and foot) ranged from 0.60 to 0.80, considerably higher than the correlations seen in the earlier studies. In another study, Keele, Ivry, and Pokorný (1987) asked participants to maintain a regular beat by tapping with the finger or arm at 400 ms intervals; the measure of performance was the regularity of tapping, measured by the SD of the produced time intervals. The correlation between the SDs produced with finger and arm tapping was 0.90, suggesting a high degree of commonality between the two tasks. Keele and colleagues also included a task in which participants were required to produce certain forces with the finger and arm. The correlation between performance in the force production task and in the timing task was about 0.20. The dissociation of performance abilities within the same participants—showing specificity for the force and timing tasks but generality across different timing tasks—is evidence

against a strict view of Henry's hypothesis.

Support for a common timing ability has been found in a number of studies. For example, Keele, Pokorny, Corcos, and Ivry (1985) found that the correlations between perception of timing and the production of timing were relatively high (with  $r$ 's of about 0.60), suggesting a link between perception and production of action. Williams, Woollacott, and Ivry (1992) found that children classified as motorically "clumsy" were more variable in both motor and perceptual timing than age-matched controls. Research involving groups of individuals who have neurological damage suggests that the cerebellum may play a specific role in timekeeping ability (Ivry & Corcos, 1993; Ivry & Keele, 1989; Ivry, Keele, & Diener, 1988). These findings have led Keele and Ivry (1987) to suggest a modular view of individual differences (see also Jones, 1993). In this view, the brain is organized to perform certain functions rather than certain tasks. Modules represent neural systems that support a particular function. A timing module represents a type of timekeeper that functions to support the performance of both perceptual and motor tasks under a wide range of sensory and effector mechanisms.

Some controversy exists in this literature; not all studies of motor timing have supported a general timekeeping ability. Only moderate correlations (0.36 to 0.48) were found when the timing of limb and jaw movements were compared (Franz, Zelaznik, & Smith, 1992). Studies in which timed movements were made by tapping, line drawing, and circle drawing showed mostly small correlations; and correlations were significant only when the same tasks were performed at similar rates (Robertson et al., 1999; Zelaznik, Spencer, Doffin, 2000).

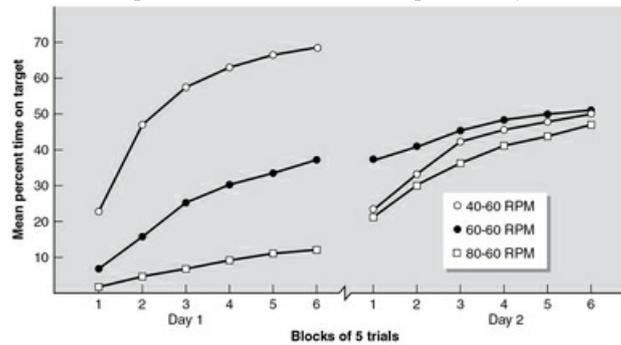
### *Motor Transfer Is Small*

When the transfer from one task to a completely different task—sometimes called *intertask transfer*—is studied, we typically find that the transfer is small or negligible. Such evidence comes from studies concerned with attempts to train some behavior or trait in one situation by providing presumably related experiences in different situations. For example, investigations by Lindeburg (1949) and Blankenship (1952) showed that "quickenings exercises" (various laboratory tasks that require rapid decision and action) provided no transfer to other tasks that required quickness. This is certainly not surprising in light of what is known about the specificity of motor abilities discussed earlier in this chapter, as the activities in the quickening exercises probably used different motor abilities than the task to which the exercises were supposed to have contributed (see "Myth of General Vision Training"). Evidence suggests that general traits such as quickness, balance, and coordination cannot be improved by the use of different activities supposedly involving that trait; and we would not expect that an *ability* would be improved by practice anyway.

What if the tasks are more similar? Here, the transfer of tasks tends to be higher than for the previous situation, but still the amount of transfer is typically small. For example, [figure 13.13](#) presents results from Lordahl and Archer (1958). Different groups of people practiced the pursuit rotor task on one day at 40, 60, or 80 rpm for 30 trials. All groups then switched to the 60 rpm version of the task for evaluation of the transfer effects on the next day. The group that had 60 rpm in both the training trials and the transfer trials was used as the standard against which the transfer in the other two groups was assessed (i.e., it served the role of group II in [figure 13.2](#)). Using the calculation for the percentage transfer introduced earlier in this chapter, the transfer from the 40 and 80 rpm versions of the task to the 60 rpm version was 12% and 31%, respectively, on the very first trial. And, as can be seen in [figure 13.13](#), both groups required considerable practice on day 2 to achieve the same level of performance as attained by the 60–60 group at the end of day 1 practice. Namikas and Archer (1960), using the same procedures, found somewhat higher transfer, ranging from 42% to 64%. Remember that in these experiments the transfer is between the pursuit rotor and *itself*, with only the speed of rotation changed to define the different "tasks." It is somewhat surprising that the transfer is so small, but numerous other experiments show essentially the same thing.



Figure 13.13 Mean time on target in pursuit tracking. Separate groups practiced on day 1 at speeds of 40, 60, or 80 rpm and transferred to 60 rpm on day 2.



Data from Lordahl and Archer 1958.

These generally small transfer effects seem to fit with a number of other phenomena that we have discussed already. First, the transfer findings coincide with the ideas about individual differences. An important concept discussed earlier in this chapter is that motor abilities are both numerous and specific, and that even similar tasks appear to correlate very weakly with each other (with the possible exception of timing skills). If so, then in transfer experiments when the task is changed in even a small way (e.g., changing the turntable speed of the pursuit rotor), it is likely that different and unrelated abilities are called into play. Thus, there might be low transfer of even very similar tasks because the abilities involved are almost completely different.

These findings also fit well with the GMP notion. In chapter 6, a major idea was that two tasks with different relative timing characteristics were assumed to be governed by different GMPs. If a shift in conditions requires participants to abandon one GMP in favor of another, then they will be performing two different GMPs in the two different variations of the “same” motor task. This is analogous to speeding up a treadmill so that jogging is substituted for walking, each activity having its own program (e.g., Shapiro, Zernicke, Gregor, & Diestel, 1981). It is difficult to say how wide the range of conditions produced by a given GMP might be, but we suspect that many GMPs exist and that they are shifted rather freely when the conditions change. Viewed in this way, it is not surprising that the tasks do not transfer to each other very strongly.

### *Transfer Depends on Similarity*

A second and related concept is that transfer depends on the similarity of the two tasks being considered. The idea of similarity is certainly not new, as Thorndike (1906) and Woodworth (1901) proposed that transfer depends on the number of “identical elements” that exist in common between two tasks. If one task had elements that were totally different from the elements in another task, then no transfer would be expected. Transfer would be 100% if the two tasks had all their elements in common. The problem with this theory was that it never specified what an “element” was and how it could be operationalized, so the theory cannot be put to empirical test. In the previous paragraphs, the implication is that the “elements” could be (a) abilities in common between the two tasks, (b) GMPs that are used for the two tasks, or (c) both. And other possibilities exist.

The theories of transfer have been improved considerably since the publication of this next idea. A major contribution was Osgood’s (1949) *transfer surface*, which provided a description of the amount of transfer of *verbal* learning as a joint function of the similarity of the stimulus elements and the response elements. Holding (1976) presented a related idea for motor skills. In all these cases, the notion of similarity is a dominant theme, as it always has been. But these recent theories are not completely satisfactory, as a large number of transfer phenomena do not appear to be explained by them. The problem seems to be related to our lack of understanding about what “similarity” is and what the “elements” are that are supposedly transferred across various tasks. Perhaps research with abilities and motor programs will contribute to this area, but to date this possibility has not been realized. The conclusion from a look at this literature is that motor transfer is still not well understood at all (Schmidt & Young, 1987).

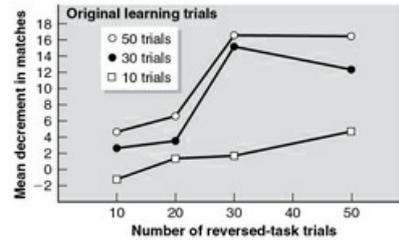
Recent work in the area of structural learning provides a new and perhaps more promising approach to understanding transfer of learning (Genewein, Hez, Razzaghpahanah, & Braun, 2015). Structural learning argues that transfer of learning can occur through the narrowing down of the parameter space. For a new task, if it shares some features in common with those already in a structure, the search for a new set of control parameters that provides a solution is more efficient. Some experimental work has suggested a probabilistic model of structural learning that accounts for this effect (Braun, Aertsen, Wolpert, & Mehring, 2009). Braun and colleagues (2009) outline three hallmarks of structural learning. First, learning is facilitated for new tasks within the same structure; second, a reduction occurs in the interference normally observed when switching between tasks that require opposite control strategies (like the backward bicycle example mentioned earlier in this chapter); and third, there is preferential exploration along a learning structure. Thus far, structural learning has been examined in the context of motor adaptation (Braun, Mehring, & Wolpert, 2010) but also for skills such as handwriting (Johnson, Culmer, Burke, Mon-Williams, & Wilkie, 2010) as well as in sensorimotor association paradigms (Braun, Waldert, Aertsen, Wolpert, & Mehring, 2010).

### *Negative Transfer*

We have mentioned that transfer is not always positive and that losses can occur in one skill as a result of experience on another. This is called *negative transfer*. Many people believe that negative transfer is relatively common and that the skill losses it produces can be quite large. Almost cliché is the story that tennis in the summer ruined the person's badminton game in the winter, presumably because the two tasks are quite similar yet somewhat incompatible (e.g., the arm action in the two strokes is different). But the research on transfer nearly always shows low but positive transfer; negative transfer is seldom the outcome. However, negative transfer can be produced if the proper conditions are presented, such as those provided by Lewis, McAllister, and Adams (1951). Lewis and colleagues used the Mashburn task, in which a two-dimensional arm control and a foot control are operated simultaneously to match the positions of lights on a display. After participants practiced for a varying number of trials (10, 30, or 50) with the usual configuration of the task, they were switched to a condition in which the control–display relationships were reversed. For example, in order to move the light on the display to the left, the lever had to be moved to the right rather than to the left as had been the case before. All three dimensions of the task (right–left, backward–forward, right foot–left foot) were reversed. This is analogous to driving a car in which the “normal” movements of the controls are suddenly backward (e.g., steering wheel turned clockwise to go left, brake pedal released to stop and also similar to the backward bicycle example described earlier). After 10, 30, or 50 trials on this reversed task, participants were switched back to the original configuration of the task to examine whether skill on it had been lost or gained. This is a retroactive-transfer design (see [table 13.3](#)).

The differences on the main task between the number of matches before and after reversed-task practice are plotted in [figure 13.14](#). A decrement score of zero means that the standard task was performed just as well after the reversed task as before, meaning that no negative (or positive) retroactive transfer occurred; larger decrement scores imply more negative transfer. Transfer was generally negative, and negative transfer increased as the number of reversed-task trials increased. This is what one might expect, as the amount of interference from this reversed task should be larger if it is learned more completely. (There was also an effect of the number of original-practice trials of the task with standard controls, but it is far from clear what this means; see Schmidt, 1971a, for a more complete discussion of this effect.) This is an example of clear and unmistakable negative retroactive transfer; similar findings have been produced in other studies using similar procedures (see Lewis, 1953; Schmidt, 1971a; Schmidt & Young, 1987).

Figure 13.14 Retroactive negative transfer (interference) as a function of amount of practice on the reversed task and the amount of original practice on the standard task.



Reprinted from D. Lewis, D.E. McAllister, and J.A. Adams, 1951, "Facilitation of interference in performance on the modified mashburn apparatus: I. The effects of varying the amount of original learning," *Journal of Experimental Psychology* 41: 53.

However, the negative transfer produced in these studies seemed mainly cognitive and may not have had much to do with *motor* negative transfer. The reversed conditions probably left the participants confused about what to do (which way to move) and may not have disrupted the motor control processes in the task at all. This argument is not strong, though, as it is difficult to know what the relevant motor and cognitive processes are in such tasks. Yet it seems logical to assume that a major portion of the problem for the participants on returning to the standard task was confusion about what the limbs controlling each of the three dimensions of the task were supposed to do.

## Myth of General Vision Training

A quick Internet search will reveal a growing industry that markets various "training programs" designed to improve vision. Some of these programs make the further claim that improvements in vision will transfer to improvements in performance, most notably sport performance. These claims are rather impressive, if not surprising, given that the amount of motor transfer between two tasks is normally small and restricted to training tasks that are highly similar to the transfer task (e.g., Lordahl & Archer, 1958; Schmidt & Young, 1987). However, a close look at the "evidence" provided in support of these programs quickly reveals it to be weak, biased, and perhaps even fraudulent.

Sport vision training programs generally make the following claims: (1) Superior athletes have superior visual skills; (2) visual skills can be improved with training; and (3) visual skills that are trained in sport vision programs will result in superior sport performance (Abernethy & Wood, 2001; Starkes, Helsen, & Jack, 2001; Williams & Grant, 1999). The first claim, that superior athletes have superior *visual* skills, has little to no support. Instead, the evidence suggests that superior athletes often have a *perceptual advantage*—that is, experts process specific sport-related perceptual information faster and more precisely than less skilled athletes (Starkes et al., 2001; Williams & Ward, 2003). Experts are similar to less skilled athletes in speed and precision in processing perceptual information (and visual information in general) that is not specific to the nature of their expertise (Starkes & Ericsson, 2003).

The second claim, that general visual skills can be trained, is misleading. There does appear to be evidence that some improvement can be gained from general visual skills training, but this benefit is limited to individuals with visual defects. In their review of the literature, Abernethy and Wood (2001) concluded that there was no evidence that visual skills were improved in *athletes*.

The last claim, that general visual skills training programs can improve sport performance, appears highly suspect or fraudulent. The "strongest" support is provided by case testimonials, usually by athletes who have undergone the training program. However, testimonials are not experimental evidence, and any *perceived* benefit could be due to expected improvements (i.e., a Hawthorne effect) or lack of control conditions (i.e., "compared to what?"). As we have suggested many times in this book, *transfer* is a highly selective and specific process. There is no evidence at all, for example, that intensive "training" to respond

to a stimulus light in the midst of a complicated array of lights will facilitate auto-racing performance. Tracking a swinging ball with ocular and finger pursuit movements will not improve forearm shots in tennis. And, trying to identify an alphanumeric character presented in a briefly-presented display will never help a batter to distinguish between a fastball and a curveball. The conclusion regarding this third claim—that general vision training can improve sport performance—appears to be an overwhelming “No!” based on theory and empirical evidence (Abernethy & Wood, 2001).

### *Negative Transfer of Timing*

Some studies suggest, however, that negative transfer of limb control can be quite large. For example, Shapiro (1977, 1978) had participants learn complex patterns of movements with a particular relative timing. Later, participants were instructed to speed up the movement, maintaining the same relative timing, which they had no trouble doing. But when they were told to *ignore* the temporal pattern they had learned earlier, they had a great deal of difficulty producing a new temporal structure. Instead, they sped up the original temporal structure, more or less as one would speed up a phonograph record. (These studies are discussed in more detail in chapter 6.) This can be seen as a kind of negative transfer, where the prior experience with the “old” temporal structure interfered with producing the “new” pattern at maximal speed. This might turn out to be an important finding for understanding transfer. Schmidt and Young (1987) suggest that tasks whose relative timing and sequencing are the same will tend to transfer to each other positively; two tasks whose sequencing is the same, but whose timing is different, will tend to transfer to each other negatively; most tasks with neither sequencing nor timing in common transfer to each other hardly at all.

Similar effects for learning new coordination-timing patterns were described in chapter 12. Strong negative-transfer effects are exerted by the existing, stable patterns (in-phase and anti-phase) when one attempts to learn a new pattern, such as a 90° relative-phase coordination (Zanone & Kelso, 1992; Lee, Swinnen, & Verschueren, 1995). This suggests that some negative transfer can result from the experiences that participants bring into the laboratory (i.e., before learning any specific task). Certainly much more can be discovered about negative transfer effects from this kind of research.

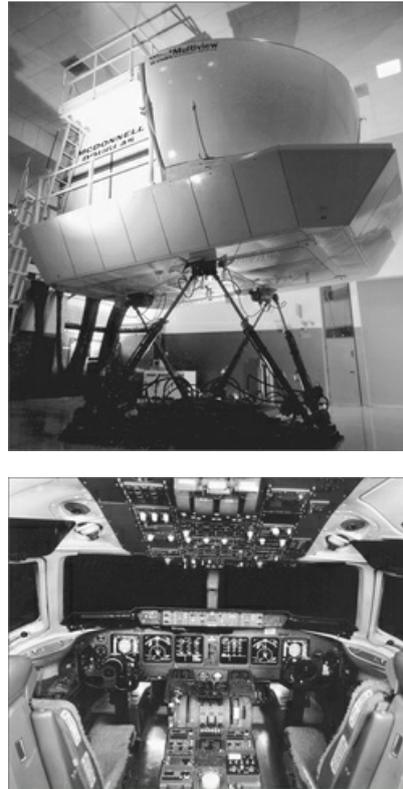
Another example involves second-language learners; here we consider the production of a particular language’s speech sounds (but not its grammar or vocabulary) as a motor skill. Common experience tells us that the difficulty in producing a particular speech sound in English, for example, is critically related to the speaker’s first language. The same acoustic goal is often produced differently by speakers whose native language is French versus German; these difficulties represent negative transfer from French (or German) to English. (One of us, R.A.S., was never able to perform the common “ui” sound in Dutch [e.g., “bruin”], despite much practice.) If negative transfer were *not* occurring, these pronunciation difficulties would not be common to a particular language group, and we would not expect to find, for example, French accents in English. Yet such accents are clearly differentiated from German accents, and are remarkably persistent across many years of speaking English. These phenomena seem to represent some of our strongest evidence for negative transfer.

Finally, it seems reasonable to think that two tasks, each containing a number of “elements,” may have some similar elements leading to positive transfer and have other, dissimilar elements contributing to negative transfer. In Shapiro’s (1977, 1978) studies, at the same time negative transfer of relative timing occurred, positive transfer of sequencing might also have been occurring. Other aspects of the task might not transfer at all—positively or negatively. This idea can be seen in many tasks in sports, for example handball and racquetball. There appear to be many common elements between these two games, such as the angles that the ball bounces off the walls of the court and the strategies of the game, all of which might lead to positive transfer (e.g., Smeeton, Ward, & Williams, 2004). Yet at the same time, other elements of the game would appear to lead to negative transfer, such as the exact positioning of the body just before the shot, or the limb actions in the shot itself. The point is that whether or not two tasks transfer positively or negatively might depend on a kind of “balance sheet” on which the elements that transfer positively are “weighed” against those that transfer negatively. This is not an adequate theory of transfer, but it may help to conceptualize some of the things that happen when two tasks interact.

## Simulation and Transfer

An important and commonly used method for training people in motor (and cognitive) tasks is *simulation*. The main feature of simulations is that they provide a practice task that is (supposedly) related to some *criterion task* (whose performance is the overall goal of the learning process) in some way. For example, pilots may practice procedural skills on ground-based devices that mimic the cockpit of the airplane, as seen in [figure 13.15](#). The reasoning is that the practice of these skills in the simulator will transfer to the actual skills in the airplane (the criterion task). Many aspects of simulators were reviewed in Sweezy and Andrews (2001).

Figure 13.15 The MD-11 flight simulator.



Copyright © Boeing.

### *Physical Simulators*

Many examples of simulators in learning situations could be mentioned. At one end of the scale are expensive and highly sophisticated devices that simulate large and complex systems (see [figure 13.15](#)). For example, the simulators for learning to fly are often elaborate, with very detailed and specific replications of the cockpit area, instrumentation, and so on. The pilot or learner is often given simulated displays showing airport runways; the instrumentation is complete and functioning; and the “feel” of the controls is as identical as possible to that in the real aircraft. In some simulators, even movements of the cockpit as a whole simulate the effect of control movements and the movements of the aircraft in a storm. In these situations, the information displayed on the gauges and dials is produced by a computer, and the learner’s responses are monitored as well; these are then used to move the simulator, its displays, or both. Comparable devices are used to simulate the behavior of a weapons system, and simulators for controlling the behavior of nuclear power plants have been developed. As you might imagine, these devices are very expensive to produce, operate, and update.

Some of the early medical simulators were less expensive and could be used to train procedural skills, such as resuscitation. Low-fidelity mannequins such as Resusci-Annie were the precursor to higher-fidelity simulators that remain in use today for resuscitation and many other types of medical diagnosis and treatment training (Cooper & Taqueti, 2009; Perkins, 2007). The use of minimally invasive surgical procedures (e.g., laparoscopic surgery) seems to require simulators for training; these kinds of simulators are by now quite common and generally supported in the medical community (Sturm et al., 2008).

At the other end of the scale, simulation devices can be made that are relatively simple and inexpensive. Many of us learned to drive a car by practicing on driver simulators that had not-so-realistic configurations of an automobile’s controls, so that we could learn the proper motions before we tried them in a real car. Some dental schools still use plaster-of-Paris models of the jaw—dentists-in-training practice dental skills with the “jaw” on a workbench or even in the position it would be in if it were the upper jaw of a patient. A simulator can require almost no apparatus; for example, you can practice golf putting on a living room rug with a glass lying on its side

on the floor.

Physical simulators provide a number of advantages, such as decreased cost or time of training (or both), increased safety, and the increased convenience of having the simulator available for use at any time in any weather. And yet simulators have a number of serious drawbacks. First, the “worth” of any simulation device has to be measured in terms of the amount of transfer that it provides to the criterion task. If the simulator does not provide transfer to the criterion task, the device is essentially useless in terms of the purpose for which it was originally intended. Thus, the evaluation of simulation devices usually places heavy emphasis on transfer of learning from the device to the criterion task (Alessi, 1988; Lintern, Sheppard, Parker, Yates, & Nolan, 1989; Schendel, Heller, Finley, & Hawley, 1985; Sturm et al., 2008).

One point that consistently emerged from our earlier discussion is that motor transfer is generally quite small unless the training and criterion tasks are so similar as to be practically identical. From these basic research findings, as well as from the literature and discussion on the specificity of individual differences mentioned earlier in this chapter and specificity of learning, it might be predicted that many simulators will not transfer well to the criterion tasks for which they were designed. Certainly a critical part of simulator evaluation is the conduct of a transfer experiment, perhaps with various versions of the simulator, to evaluate the amount of transfer that is actually produced. Transfer should increase from the simulator to the criterion task to the extent that the two are similar. Recognition of this fact has led the designers of simulation devices to make them very realistic—for example, the simulated airplane cockpit that moves as the actual aircraft would if it were in a storm. Much effort is devoted to making the controls feel as they do in the airplane, with proper resistances, feedback, and so on to maximize the similarity. This makes good sense. If differences between simulator and criterion task are too great, it is possible that separate motor control mechanisms might be learned in the two situations, producing no transfer to the criterion task.

Simulation devices are usually excellent for teaching *procedural skills*, the proper order of a sequence of activities, and the like. These aspects of the overall task are important, and considerable time can be “saved” by using simulators at early stages of practice, as sequence knowledge appears to be transferable between different effector systems (Fendrich, Healy, & Bourne, 1991; Keele, Jennings, Jones, Caulton, & Cohen, 1995). There is less certainty that the motor elements of the task are so easily simulated, however.

Simulations are often applied rather blindly without regard for the kinds of transfer that will be produced. Many examples are seen in athletics, in which certain kinds of behaviors are simulated in various drill procedures. The use of blocking dummies in American football may be helpful in the early stages of learning a play when the athletes have questions about where to go and whom to block, but there would seem to be little utility in using them beyond this point. Players would seem to require practice in blocking other players who do not wish to be blocked; this is, of course, very difficult to simulate. It is difficult to evaluate the effectiveness of these various procedures because we have no research about the transfer of these drills to game situations. Our guess is that the faith placed in many of these procedures is probably overdone. Certainly it would make sense to examine any such drills or simulations very carefully.

### *Virtual Simulators*

In contrast to the traditional type of physical simulators for use in training new skills are simulators that use computer-based technologies to train the perceptual–motor attributes of criterion tasks. *Virtual environments* often simulate the perceptual (visual, auditory, and haptic) demands of a task, together with a simulated effector system, and display these on a computer monitor. The actions of an individual can be mapped in terms of the actions of the simulated effector system, with the expected (computer generated) consequences displayed. One advantage of such devices is that they are much less costly to produce than many of the physical simulators already discussed. And, once developed, these computer programs should be modifiable so that newer versions need not be built again from scratch.

In recent years, one of the fields that has been developing virtual environments the fastest is the medical field.

Arnold and Farrell (2002) critically reviewed the early evidence and concluded that virtual reality was, at the time, unverified as a positive training aid for surgical motor skills. Another area of rapid growth and development for virtual environments is in motor rehabilitation, where engaging task practice is important for driving recovery of paretic limbs (Levin, Weiss, & Keshner, 2015). Similarly, the area of surgical robotics is a rapid growth area with advances in control and transparency between the robot and the human (H. Kim & Rosen, 2015; Rosen, Hannaford, & Satava, 2011). The potential for positive motor skills transfer, however, has been elevated by the use of robotic devices that provide simulated haptic and proprioceptive feedback. For example, robotic devices can provide the medical student with visual, auditory, and haptic feedback as a cut is made through bone or other tissue, thereby providing numerous sources of augmented information during training. Although researchers still await conclusive evidence about how to optimize virtual reality training (Fialkow & Goff, 2009; van der Meijden & Schijven, 2009), we suspect that the attempt to make training as task specific as possible, whether for robotic surgery or rehabilitation, can only be a positive advance for motor transfer. That said, we know from the literature on augmented feedback (see chapter 11) that complex and sophisticated feedback in simulators can be detrimental for learning if it is not used appropriately.

In contrast to expensive, high-fidelity training simulators, some researchers and practitioners are now using commercially available hardware and software to explore skill transfer. For example, the Nintendo Wii is a gaming system that combines many different types of part- and whole-body movements together with interactive visual and haptic feedback experiences. Physical therapists, for example, have employed the Wii to motivate active participation in movement-related activities, and have reported positive effects for an individual with cerebral palsy (Deutsch, Borbely, Filler, Huhn, & Guarrera-Bowlby, 2008). And in a rather surprising finding of transfer generality, extensive video gaming experience appears to be causally related to enhancements in visual attention (Dye, Green, & Bavelier, 2009; Green & Bavelier, 2003, 2006). Similarly, the rapid incorporation of new inexpensive technologies, such as the Microsoft Kinect for Xbox, into rehabilitation protocols shows considerable promise (Levac, Espy, Fox, Pradhan, & Deutsch, 2015). The capability for using inexpensive yet sophisticated gaming systems in these studies represents an exciting new development for future skills transfer research.

## Summary

Learning, memory, retention, and transfer are very closely related concepts. Motor memory is the persistence of the acquired capability for responding, and losses in memory are called forgetting. Forgetting is usually measured by performance losses on a retention test, administered after a retention interval. Different measures of retention can be computed, although the absolute-retention measure is the most useful.

A variant of the learning experiment is the transfer experiment, in which the effect of practicing one task on the performance of some other (criterion) task is evaluated. Transfer is often measured as a percentage, indicating the proportion of performance improvement in one task that was achieved by practice on the other task. Studies of transfer are important for evaluating training, simulation, and other instructional issues.

Continuous skills are retained nearly perfectly over long retention intervals. Discrete skills, on the other hand, can show marked performance losses during the same retention intervals. The reasons for this difference in retention are not clear, but they are probably not based on the tendency for continuous tasks to be more “motor” than discrete tasks. Perhaps the difference has its basis in the idea that continuous tasks, with more practice time in a typical experiment, are more resistant to forgetting because they are learned more completely.

The loss of information related to motor performance can occur in various possible ways. Information might decay from memory due to a passive process, or might be lost due to retroactive or proactive interference. Warm-up decrement is a retention loss caused by the imposition of a short rest in a series of practice trials. Research supports the set hypothesis to explain it, which holds that warm-up decrement is a loss, during rest, of a pattern of temporary nonmemory adjustments critical to performance. Consolidation of motor memories, a field of study that has recently reemerged, suggests that the interfering effects of learning a competing task are time dependent.

Two basic principles of transfer are (a) that motor transfer is usually small but positive and (b) that motor transfer depends on the similarity between tasks. Considerable difficulty exists in understanding the underlying basis of similarity, however. Negative transfer can be produced under certain conditions, but it is probably mostly cognitive in nature. Devices such as simulators and virtual environments provide promise for positive transfer, although their value seems to be highly specific to the similarity between the training and transfer tasks.

### Student Assignments

1. Prepare to answer the following questions during class discussion:
  - a. Using practical examples of discrete and continuous skills, illustrate the differences in expected retention characteristics.
  - b. Describe three workplace examples in which warm-up decrement might be expected to occur after a lunch break.
  - c. Suggest a computer simulation game that could be used to train physicians who are learning a microsurgery technique. Describe three key features of the simulation that should be particularly effective for learning.
2. Find a research article that was designed to examine the short-term retention characteristics of movement information.

### Notes

<sup>1</sup> Backward bicycle example. <http://ed.ted.com/featured/bf2mRAfC>

<sup>2</sup> Robert Bjork tells us that Stanford University’s first president, David Starr Jordan, who was an ichthyologist (i.e., he studied fish), once said that every time he learned the name of a new student he forgot the name of a fish—a claim of retroactive interference.



# Appendix

Logarithms to the Base 2

Number	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
0.		-3.32	-2.32	-1.74	-1.32	-1.00	-0.74	-0.51	-0.32	-0.15
1.	0.00	0.14	0.26	0.38	0.49	0.58	0.68	0.77	0.85	0.93
2.	1.00	1.07	1.14	1.20	1.26	1.32	1.38	1.43	1.49	1.54
3.	1.58	1.63	1.68	1.72	1.77	1.81	1.85	1.89	1.93	1.96
4.	2.00	2.04	2.07	2.10	2.14	2.17	2.20	2.23	2.26	2.29
5.	2.32	2.35	2.38	2.41	2.43	2.46	2.49	2.51	2.54	2.56
6.	2.58	2.61	2.63	2.66	2.68	2.70	2.72	2.74	2.77	2.79
7.	2.81	2.83	2.85	2.87	2.89	2.91	2.93	2.94	2.96	2.98
8.	3.00	3.02	3.04	3.05	3.07	3.09	3.10	3.12	3.14	3.15
9.	3.17	3.19	3.20	3.22	3.23	3.25	3.26	3.28	3.29	3.31
10.	3.32	3.34	3.35	3.36	3.38	3.39	3.41	3.42	3.43	3.45
11.	3.46	3.47	3.49	3.50	3.51	3.52	3.54	3.55	3.56	3.57
12.	3.58	3.60	3.61	3.62	3.63	3.64	3.66	3.67	3.68	3.69
13.	3.70	3.71	3.72	3.73	3.74	3.75	3.77	3.78	3.79	3.80
14.	3.81	3.82	3.83	3.84	3.85	3.86	3.87	3.88	3.89	3.90
15.	3.91	3.92	3.93	3.94	3.94	3.95	3.96	3.97	3.98	3.99
16.	4.00	4.01	4.02	4.03	4.04	4.04	4.05	4.06	4.07	4.08
17.	4.09	4.10	4.10	4.11	4.12	4.13	4.14	4.15	4.15	4.16
18.	4.17	4.18	4.19	4.19	4.20	4.21	4.22	4.22	4.23	4.24
19.	4.25	4.26	4.26	4.27	4.28	4.29	4.29	4.30	4.31	4.31
20.	4.32	4.33	4.34	4.34	4.35	4.36	4.36	4.37	4.38	4.39
21.	4.39	4.40	4.41	4.41	4.42	4.43	4.43	4.44	4.45	4.45
22.	4.46	4.47	4.47	4.48	4.49	4.49	4.50	4.50	4.51	4.52
23.	4.52	4.53	4.54	4.54	4.55	4.55	4.56	4.57	4.57	4.58
24.	4.58	4.59	4.60	4.60	4.61	4.61	4.62	4.63	4.63	4.64
25.	4.64	4.65	4.66	4.66	4.67	4.67	4.68	4.68	4.69	4.69
26.	4.70	4.71	4.71	4.72	4.72	4.73	4.73	4.74	4.74	4.75
27.	4.75	4.76	4.77	4.77	4.78	4.78	4.79	4.79	4.80	4.80
28.	4.81	4.81	4.82	4.82	4.83	4.83	4.84	4.84	4.85	4.85
29.	4.86	4.86	4.87	4.87	4.88	4.88	4.89	4.89	4.90	4.90
30.	4.91	4.91	4.92	4.92	4.93	4.93	4.94	4.94	4.94	4.95
31.	4.95	4.96	4.96	4.97	4.97	4.98	4.98	4.99	4.99	5.00
32.	5.00	5.00	5.01	5.01	5.02	5.02	5.03	5.03	5.04	5.04
33.	5.04	5.05	5.05	5.06	5.06	5.07	5.07	5.07	5.08	5.08
34.	5.09	5.09	5.10	5.10	5.10	5.11	5.11	5.12	5.12	5.13
35.	5.13	5.13	5.14	5.14	5.15	5.15	5.15	5.16	5.16	5.17
36.	5.17	5.17	5.18	5.18	5.19	5.19	5.19	5.20	5.20	5.21
37.	5.21	5.21	5.22	5.22	5.22	5.23	5.23	5.24	5.24	5.24
38.	5.25	5.25	5.26	5.26	5.26	5.27	5.27	5.27	5.28	5.28
39.	5.29	5.29	5.29	5.30	5.30	5.30	5.31	5.31	5.31	5.32
40.	5.32	5.33	5.33	5.33	5.34	5.34	5.34	5.35	5.35	5.35

Note: To find the Log<sub>2</sub> (23.5), for example, enter the row labeled 23, then move to the right under the column headed .5; the result is 4.55.

# Glossary

- absolute constant error ( $|CE|$ )—The absolute value of CE for a participant; a measure of amount of bias without respect to its direction.
- absolute error (AE)—The average absolute deviation of each of a set of scores from a target value; a measure of overall error.
- absolute frequency—The actual number of feedback presentations given in a series of practice trials.
- absolute retention—A measure of retention based on the level of performance on the retention test.
- action-specific perception account—The view of perception that people perceive the environment in terms of their ability to act in it.
- Adams' theory—A theory of motor learning proposed by Adams (1971), focusing heavily on the learning of slow positioning movements.
- amplitude—The distance between the two target centers in aiming tasks ("A" or "D" in Fitts' Law).
- anti-phase—A coordination timing pattern in which two movement components oscillate in opposition (180° relative phase).
- arousal—An internal state of alertness or excitement.
- attention—A limited capacity or set of capacities to process information.
- augmented feedback—Information from the measured performance outcome that is fed back to the learner by some artificial means; sometimes called extrinsic feedback.
- automatic processing—A mode of information processing that is fast, is done in parallel, is not attention demanding, and is often involuntary.
- autonomous stage—The third of three stages of learning proposed by Fitts, in which the attention demands of performing a task have been greatly reduced.
- autonomy support—Conditions that satisfy individuals' needs to exercise control over the environment (e.g., by allowing choices).
- average feedback—A type of augmented feedback that presents a statistical average of two or more trials, rather than results on any one of them.
- average knowledge of results—A type of summary-KR method that presents the results of two or more trials as a statistical average.
- bandwidth KR—Tolerance limits on errors that define when to provide qualitative or quantitative KR.
- blindsight—A medical condition in which the patient can respond to certain visual stimuli while being judged legally blind by other criteria.
- blocked practice—A schedule in which many trials on a single task are practiced consecutively; low contextual interference.
- capability—The internal representation of skill, acquired during practice, that allows performance on some task.
- central pattern generator (CPG)—A centrally located control mechanism that produces mainly genetically defined actions such as walking.
- change blindness—A failure to perceive changes in the environment as a consequence of directing attention to another object or event.
- choice reaction time—A variation in RT procedure in which the performer, when a particular stimulus is given, must choose one response (the "correct" response) from a number of possible predetermined responses; the temporal interval between the presentation of a given stimulus and the start of its associated response.
- choking—Scenario in which a performer changes a normal routine or fails to adapt to a changing situation, resulting in a failed performance.
- closed skill—A skill for which the environment is stable and predictable, allowing advance organization of movement.
- closed-loop system—A type of system control involving feedback, error detection, and error correction that is applicable to maintaining a system goal.
- cocktail-party effect—A phenomenon of attention in which humans can attend to a single conversation at a noisy gathering, neglecting most (but not all) other inputs.
- cognitive stage—The first of three stages of learning proposed by Fitts, in which the learners' performances are

heavily based on cognitive or verbal processes.

comparator—A component of closed-loop control that compares anticipated feedback with actual feedback, finally outputting an error signal.

concurrent feedback—Augmented (usually continuous) feedback that is presented simultaneously with an ongoing action.

constant error (CE)—The signed difference of a score on a given trial from a target value; a measure of bias for that trial.

constant practice—A practice sequence in which only a single variation of a given class of tasks is experienced.

constrained action hypothesis—According to this hypothesis, an internal focus on body movements constrains the motor system by interfering with automatic motor control processes, whereas an external focus on the movement effect promotes the utilization of automatic processes.

contextual interference—The interference in performance and learning that arises from performing one task in the context of other tasks; blocked practice has low contextual interference, and random practice has high contextual interference.

continuous skill—A task in which the action is performed without any recognizable beginning or end.

controlled processing—A mode of information processing that is relatively slow, serial, attention demanding, and voluntary.

coordination—The description of the relationship between several moving effectors while moving to achieve a goal.

correlation coefficient ( $r$ ) —A statistical method that evaluates the strength of a relationship between two variables; it does not imply causality.

cost–benefit analysis—A method by which the benefits from anticipating correctly can be weighed against the “cost” of anticipating incorrectly.

cutaneous receptor—A receptor located in the skin that provides inherent information about touch (haptic sensations).

deafferentation—A surgical procedure that involves cutting one or more of an animal’s dorsal roots, preventing nerve impulses from the periphery from traveling to the spinal cord.

degrees of freedom problem—The problem of explaining how a movement with many degrees of freedom is controlled or coordinated; see *degrees of freedom*.

degrees of freedom—The collection of separate movements of a system that need to be controlled; see *degrees-of-freedom problem*.

demonstration—Performance of a skill by an instructor (or a model) to facilitate observational learning.

differential method—A method of understanding behavior by focusing on individual differences and abilities.

discrete skill—A task that has a recognizable beginning and end; usually brief in duration.

distance effect—Refers to the distance of an external focus of attention from the body. A more distal focus tends to be more effective than a more proximal focus.

distributed practice—A practice schedule in which the duration of rest between practice trials is “relatively long”; the time in practice is often less than the time at rest.

dorsal stream—Visual information, used specifically for the control of movement within the visual environment, that is sent from the eye to the posterior parietal cortex; sometimes called ambient vision.

double stimulation paradigm—A method for studying information processing in which a given stimulus (leading to one response) is followed closely by a second stimulus (leading to another response).

dynamical-systems account—A philosophical and theoretical perspective about biological behavior which proposes that order emerges from principles of self-organization. Scientists who believe this deny the existence of representations for motor control.

effective target width ( $W_e$ )—The amount of spread, or variability, of movement end points about a target in an aiming task; represents the performer’s “effective” target size; the within-participant standard deviation of the movement distances for a set of trials.

elaboration hypothesis—The idea that frequent switching among tasks (e.g., in random practice) renders the tasks more distinct from each other and more meaningful, resulting in stronger memory representations; one explanation of the contextual-interference effect.

equilibrium-point models—Limb-control models in which a movement end point is produced through the

specification of an equilibrium point between the agonist and the antagonist muscle groups.

error-detection capability—The learned capability to detect one's own errors through analyzing inherent feedback.

especial skills—A specific representation for one skill (e.g., free throw in basketball) within a broader class of skills (e.g., set shots in basketball).

expected sensory consequences—A construct in schema theory; the anticipated feedback sensations that should be received if the movement is correct.

external focus of attention—Attention directed outside the body to an object or environmental goal.

exteroception—Sensory information arising primarily from outside the body.

extrinsic feedback—See *augmented feedback*.

faded feedback—The practice in delivering feedback whereby the frequency of feedback is decreased systematically across trials.

false-negative normative feedback—An experimental procedure in which learners are (mis)informed that their performance is less skilled than that of others.

false-positive normative feedback—An experimental procedure in which learners are (mis)informed that their performance on some task is more skilled than that of others.

far transfer—Transfer of learning from one task to another, very different task or setting.

feedforward—Anticipated sensory consequences of movement that should occur if the movement is correct.

Fitts' law—The principle that movement time in aiming tasks is linearly related to the  $\text{Log}_2(2A/W)$ , where  $A$  = amplitude and  $W$  = target width.

fixation (associative or motor) stage—The second of three stages of learning proposed by Fitts, in which learners establish motor patterns.

foreperiod—In a reaction time task, the interval of time between a warning signal and a stimulus to respond.

forgetting hypothesis—The hypothesis that frequent task switching in random practice causes forgetting of the planning done on the previous trials, therefore leading to more next-trial planning and resulting in stronger memory representations; a hypothesis to explain the contextual-interference effect.

forgetting—The loss of an acquired capability for responding; loss of memory.

functional connectivity—Time-linked, task-specific coherent activity over large and distinct regions of the brain. More distinct functional connections are associated with higher skill.

gearshift analogy—A model regarding the learning of motor programs using the analogy of learning to shift gears in a standard-transmission automobile.

generalizability—The process of applying what is learned in the practice of one task to one or more other unpracticed tasks.

generalized motor program (GMP)—A motor program whose output can vary along certain dimensions to produce novelty and generalizability in movement.

goal setting—A motivational procedure in which the learner is encouraged to set personal performance goals during practice.

goal-action coupling—Fluidity with which the intended goal is translated into action.

Golgi tendon organs—Small stretch receptors located in the tendons that provide precise information about muscle tension.

guidance hypothesis—A view emphasizing the guidance properties of augmented feedback, which promotes effective performance when it is present but has dependency-producing (guidance-like) effects on retention tests of learning.

guidance—A procedure used in practice in which the learner is physically or verbally directed through the performance in order to improve performance.

Hick's law—The mathematical descriptor showing a linear relationship between choice reaction time and the logarithm (to the base 2) of the number of stimulus–response alternatives.

hypervigilance—A heightened state of arousal that leads to ineffective decision making and poor performance; panic.

inattentional blindness—A failure to perceive objects in the visual environment when attention is directed to other objects or events.

index of difficulty (ID)—The theoretical “difficulty” of a movement in the Fitts' tapping task, or  $ID =$

$\log_2(2A/W)$ , where  $A$  is target amplitude and  $W$  is target width.

individual-differences variables—Characteristics that cannot be changed, they vary across the population.

Examples of independent difference variable are race, gender, religious affiliation and age.

information-processing approach—Approaches to the study of behavior that treat the human as a processor of information, focusing on storage, coding, retrieval, and transformation of information.

inherent feedback—Information provided as a natural consequence of making an action; sometimes called intrinsic feedback.

inhibition of return (IOR)—A delay in responding to a previously cued (orienting) stimulus, when the SOA is 300 ms or longer.

in-phase—A coordination timing pattern in which two movement components oscillate in synchrony ( $0^\circ$  relative phase).

instantaneous feedback—Augmented feedback delivered immediately after completion of movement (with no delay).

internal focus of attention—Attention directed to locations inside the body, or to motor or sensory information.

interstimulus interval (ISI)—See *stimulus-onset asynchrony*.

intrinsic feedback—See *inherent feedback*.

invariant—A feature of a class of movements that remains constant, or invariant, while surface features change (e.g., relative timing).

inverted-U principle—The principle that increased arousal improves performance only to a point, with degraded performance as arousal is increased further.

joint receptors—Sensory receptors located in the joint capsule that provide information about joint position.

knowledge of performance (KP)—Augmented information about the movement pattern the learner has just made; sometimes referred to as kinematic feedback.

knowledge of results (KR)—Augmented verbal (or at least verbalizable) information fed back to the learner about the success of an action with respect to the environmental goal.

KR-delay interval—The interval between the production of a movement and the presentation of KR.

learner-determined feedback—A schedule in which the provision of feedback is determined by the learner.

learning curves—A label sometimes applied to a performance curve (a plot of average performance against trials), in the mistaken belief that the changes in performance mirror changes in learning.

long-term memory (LTM)—A virtually limitless memory store for information, facts, concepts, and relationships; presumably storage for movement programs.

looked-but-failed-to-see accidents—Traffic accidents in which the driver looked at, but failed to notice (to see) the presence of a cyclist or pedestrian; believed to be related to inattention blindness.

M1 response—The monosynaptic stretch reflex, with a latency of 30 to 50 ms.

M2 response—The polysynaptic, or functional, stretch reflex, with a latency of 50 to 80 ms.

M3 response—The voluntary reaction-time response to a stimulus, with a latency of 120 to 180 ms.

massed practice—A practice schedule in which the amount of rest between practice trials is relatively short (often less than the time for a trial).

mental practice—A practice procedure in which the learner imagines successful action without overt physical practice.

modeling—A practice procedure in which another person demonstrates the skills to be learned.

motivation—Broad and inclusive term for factors influencing and encompassing the energization, direction, and intensity of behavior.

motor adaptation—An iterative process of adjusting one's movement to new environmental demands.

motor learning—A set of internal processes associated with practice or experience leading to relatively permanent gains in the capability for skilled performance.

motor performance—An observable outcome or behavior on one particular trial or instance of activity.

motor program—A prestructured set of movement commands that defines the essential details of skilled action, with minimal (or no) involvement of sensory feedback.

movement programming—The third stage of information processing in which the motor system is readied for the planned action.

movement time (MT)—The interval from the initiation of a movement until its termination.

muscle spindle—Structure located in parallel with muscle fibers that provides information about muscle length.

natural experiment—Empirical study in which individuals (or clusters of individuals) exposed to the experimental and control conditions are determined by nature or by other factors outside the control of the investigators, but the process governing the exposures arguably resembles random assignment.

near transfer—Transfer of learning from one task or setting to another that is very similar.

novelty problem—The concern that simple theories cannot account for the production of novel, unpracticed movements.

observational learning—The process by which the learner acquires the capability for action by observing model demonstrations.

open skill—A skill for which the environment is unpredictable or unstable, preventing advance organization of movement.

open-loop control—A type of system control in which instructions for the effector system are determined in advance and run off without feedback.

optical array—The collection of rays of light that are reflected from objects in the visual environment.

optical flow—The change in patterns of light rays from the environment as they “flow” over the retina during continuous movement of the eye through the environment, allowing perception of motion, position, and timing.

optimized-submovement model—A view of the speed– accuracy trade-off that optimizes the duration of an initial impulse and, if necessary, one or more corrective impulses.

order parameter—From the Haken, Kelso & Bunz (1985) model, a variable that describes the behavior of a number of variables that coalesce under the behavior of the order parameter.

overadditive—When the effects of two or more independent variables manipulated together are greater than the sum of the individual effects.

parameterized—The process whereby parameters are supplied to the generalized motor program to define its surface features.

parameters—Values applied to a generalized motor program that determine a movement’s surface features, such as speed, amplitude, or limb used.

perceptual narrowing—The tendency for the perceptual field to “shrink”; sometimes called tunnel vision, or “weapon focus” in police work.

perceptual trace—A construct in Adams’ closed-loop theory; a reference of correctness in memory that has been learned from feedback at the correct target position.

performance curve—Graphs of average performance for an individual or a group plotted against practice trials; sometimes incorrectly called a learning curve.

phase transition—An abrupt shift from one coordination pattern to another.

physical fidelity—The degree to which the surface features of a simulation and the criterion task are identical.

population stereotypes—Habitual stimulus–response relationships that dominate behavior due to specific cultural learning.

post-KR delay—The interval of time between the presentation of KR and the next movement.

precision of feedback—The level of precision with which augmented feedback describes the movement or outcome produced.

probe—A method that uses an RT task as a secondary task during the performance of a primary, criterion task to assess the attention demands of the criterion task.

progression–regression hypothesis—The idea that learning produces a progression to more complex control strategies and that stress or forgetting produces a regression to more simple levels.

proprioception—Sensory information arising from within the body, resulting in the sense of position and movement; sometimes called kinesthesia.

psychological fidelity—The degree to which the behaviors produced in a simulator are identical to the behaviors required by the criterion task.

psychological refractory period (PRP)—The delay in responding to the second of two closely spaced stimuli.

quiet-eye effect—The period of time when a performer fixates the eyes on a target just before movement onset.

random (or interleaved) practice—A schedule in which practice trials on several different tasks are mixed, or interleaved, across the practice period; high contextual interference.

reaction time (RT)—The interval from presentation of an unanticipated stimulus until the beginning of the response.

recall schema—A construct in schema theory; the relationship among past parameters, past initial conditions, and the movement outcomes produced by these combinations.

reflex-reversal phenomenon—The phenomenon by which a given stimulus can produce two different reflexive responses depending on the function of the limb in a movement.

relative frequency—The proportion of trials during practice on which feedback is given; absolute frequency divided by the number of trials.

relative phase—A measure of temporal coordination that expresses the position of one limb within its cycle relative to the other limb within its cycle.

relative retention—Measures of retention in which the performance on the retention test is evaluated in relation to the level of performance reached in original learning.

relative timing—The temporal structure or rhythm of action; the durations of various segments of an action divided by the total movement time.

repetition—A type of ineffective practice in which a movement is repeated again and again.

rescalability—A proposed property of discrete and repetitive aiming hand movements where changes in speed or movement time produce a proportional stretching or compressing of the temporal pattern, such that relative timing is maintained.

response-programming stage—A stage of information processing in which the previously chosen response is transformed into overt muscular action.

response selection—The second stage of information processing in which the system selects a response from a number of alternatives.

response time—The sum of reaction time plus movement time; sometimes called total time.

retention test—A performance test on a given task provided after a retention interval without practice; sometimes called a transfer test.

root-mean-square error (RMSE)—The square root of the average squared deviations of a set of values from a target value; typically used as a measure of overall tracking proficiency.

savings score—A statistic used in transfer experiments, representing the “savings” in practice time on one task resulting from experience on some other task.

schema theory—A theory of motor control and learning based on generalized motor programs and schemata.

schema—A learned rule relating the outcomes of members of a class of actions to the parameters that were used to produce those outcomes.

self-efficacy—Belief in his or her ability to successfully perform a given task in the future.

self-organization—A view that describes motor control as emerging from the interaction of the components of the movement system and the environment.

self-regulation—Technique used in motor learning studies in which the learners determine how to schedule practice or feedback or some other aspect of scheduling.

sensory neuropathy—A medical condition in patients who are unable to process and respond to most of their own sensory feedback.

serial skill—A task composed of several discrete actions strung together, often with the order of actions being critical for success.

set—A collection of psychological activities or adjustments that underlie performance but that can be “lost” after a rest.

short-term memory (STM)—A memory store with a capacity of about seven elements, capable of holding information briefly (perhaps up to 30 s); sometimes called “working memory.”

short-term sensory store (STSS)—A functionally limitless memory store for holding literal, sensory information from the various senses very briefly (for only about 1 s).

Simon effect—A type of stimulus–response compatibility effect in which irrelevant directional or location information interferes with the action.

simple RT—A reaction-time situation in which there is only one possible stimulus and one response.

simulator—A training device that mimics various features of some real-world task.

signal-detection theory (SDT)—A method of analyzing two-choice decisions, resulting in two types of correct

decision (hits and correct rejections) and two types of errors (misses and false alarms).

single-channel hypothesis—A theory of attention suggesting that the system can process only a single stimulus leading to a response at any given time.

skill—The capability to bring about an end result with maximum certainty, minimum energy, or minimum time; task proficiency that can be modified by practice.

spacing effect—The benefit to memory when two or more repetitions are spaced further apart in time.

spatial anticipation—The anticipation of which of several possible stimuli will occur; sometimes called event anticipation.

spatial occlusion methods—Involves masking certain relevant and irrelevant parts of a display, such as the various parts of the arm and racket of a badminton opponent.

spatial occlusion methods—Used to stop a display at critical points during an action.

specificity hypothesis—The hypothesis that individual differences are based on many independent abilities.

specificity of learning—A view that what you practice is what you learn.

speed–accuracy trade-off—The tendency for accuracy to decrease as the movement speed or velocity of a movement increases and vice versa.

stabilometer—Also called stability platform; a platform that sways from side to side with imperfectly balanced posture.

startle RT—A rapid (<100 ms latency) reaction to an unexpected, often very strong, stimulus; used to study the involuntary release of motor programs.

stimulus identification—The first stage of information processing in which a stimulus is recognized and identified.

stimulus-onset asynchrony (SOA)—The interval between the onsets of the two stimuli in a double-stimulation paradigm; sometimes called the interstimulus interval (ISI).

stimulus–response (S-R) compatibility—The degree of “naturalness” (or directness) between the stimulus and the response assigned to it.

storage problem—The concern that simple program theories would require an almost limitless storage capacity for nearly countless different movements.

structural connectivity—Structural brain changes resulting from the formation of new connections by dendritic spine growth and other neuroplasticity processes.

summary feedback—Information about the effectiveness of performance on a series of trials that is presented only after the series has been completed.

surface feature—An easily changeable aspect of a movement, such as movement time or amplitude, that does not affect the “deep structure” (the invariant features).

sustained attention—Maintenance of attention over long periods of work, such as monitoring a radar-based aircraft detection device; sometimes called vigilance.

tau ( $\tau$ )—A variable providing optical information about time-to-contact; the size of the retinal image divided by the rate of change of the image.

temporal anticipation—The anticipation of when a given stimulus will arrive or when a movement is to be made.

total variability (E)—The standard deviation of a set of scores about a target value; a measure of overall accuracy.

tracking—A class of tasks in which a moving track must be followed, typically by movements of a manual control.

transfer design—An experimental design for measuring learning effects, in which all treatment groups are transferred to a common level of the independent variable.

transfer of learning—The gain or the loss in proficiency on one task as a result of practice or experience on another task.

transfer test—A performance test in which the task or task conditions have changed; often provided after a retention interval without practice.

trials-delay—A procedure in which the presentation of feedback for a movement is delayed; during the delay the learner practices one or more other trials of the same task.

triggered reactions—Coordinated, learned reactions to perturbations that are manifest in large segments of the body; the triggered reaction has a latency shorter than RT yet longer than the long-loop reflex (50 to 80 ms).

unintended acceleration—Sudden, uncommanded, violent acceleration of a vehicle accompanied by the perception of a loss of braking effectiveness.

unit—A sequence of behavior with essentially invariant relative timing.

variable error (VE)—The standard deviation of a set of scores about the participant's own average (CE) score; a measure of movement (in)consistency.

variable practice—A schedule of practice in which many variations of a class of actions are practiced.

ventral stream—Information useful for the identification of an object that is sent to the inferotemporal cortex; sometimes called focal vision.

vestibular apparatus—Receptors in the inner ear that are sensitive to the orientation of the head with respect to gravity, to rotation of the head, and to balance.

warm-up decrement—Temporary worsening of performance that is brought on by the passage of time away from a task and that is eliminated quickly when the performer begins again.

whole practice—A procedure in which a skill is practiced in its entirety, without separation into its parts.

width—The size of a target in aiming tasks ("W" in Fitts' Law).

yoking—A type of control procedure in which a practice schedule is determined by (and matched to) a learner in a different experimental group or condition.

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## About the Authors



©Tim Lee

Timothy D. Lee, PhD, is a professor emeritus in the department of kinesiology at McMaster University in Hamilton, Ontario. He has published extensively in motor behavior and psychology journals since 1979, served as an editor for the *Journal of Motor Behavior* and *Research Quarterly for Exercise and Sport*, and has been an editorial board member for *Psychological Review*. Until his retirement in 2014, his research was supported primarily by grants from the Natural Sciences and Engineering Research Council of Canada.

Lee is a member and past president of the Canadian Society for Psychomotor Learning and Sport Psychology (SCAPPS) and a member of the North American Society for the Psychology of Sport and Physical Activity (NASPSPA). In 1980, Lee received the inaugural Young Scientist Award from SCAPPS, and 31 years later he was awarded its highest honor, being named a fellow of the society. He presented a prestigious senior lecture at NASPSPA's 2005 conference and received the organization's highest honor, the Distinguished Scholar Award, in 2017.

In his leisure time, Lee enjoys playing golf. He has maintained a lifelong fascination with blues music and would one day love to put years of motor learning study into practice by learning to play blues guitar.



©Carolee Winstein

Carolee J. Winstein, PhD, PT, is a professor of biokinesiology and physical therapy at the University of Southern

California, as well as in the department of neurology at the Keck School of Medicine. Winstein serves as an associate editor of the journal *Neurorehabilitation and Neural Repair* and is a fellow of the American Physical Therapy Association (APTA), the American Heart Association (AHA), and the National Academy of Kinesiology (NAK).

She has more than 30 years of multidisciplinary collaborative research experience focused on understanding rehabilitation outcomes and promoting optimal recovery of goal-directed movement behaviors that emerge from a dynamic brain-behavior system in brain-damaged conditions.

Over the past 25 years, her research program has been consistently funded through NIH, NIDILRR, and the Foundation for Physical Therapy. She has authored or coauthored more than 120 research papers, chapters, proceedings, and commentaries. Recently, the *Journal of the American Medical Association* published the results of her NIH-funded, multisite clinical trial of stroke rehabilitation. Winstein has mentored over a dozen doctoral students and postdoctoral scholars from diverse fields, including engineering, neuroscience, and rehabilitation.

In her free time, Winstein enjoys gourmet cooking and is pursuing her private pilot's license to fly a Cessna 172.



Photo courtesy of Astrid Eckert / Technical University Munich.

Gabriele Wulf, PhD, is a professor in the department of kinesiology and nutrition sciences at the University of Nevada at Las Vegas. Wulf studies factors that influence motor skill learning, including the performer's focus of attention and motivational variables (e.g., autonomy support and performance expectancies). Wulf has received various awards for her research, including UNLV's Barrick Distinguished Scholar Award. She served as president of the North American Society for the Psychology of Sport and Physical Activity (NASPSPA) in 2015. She has been elected a fellow of the National Academy of Kinesiology (NAK).

Her research has resulted in approximately 200 journal articles and book chapters, as well as two books. She served as the founding editor of *Frontiers in Movement Science and Sport Psychology* (2010-2012) and the *Journal of Motor Learning and Development* (2012-2015). In conjunction with Rebecca Lewthwaite, Wulf developed the OPTIMAL theory of motor learning.

In her leisure time, Wulf enjoys golf, tennis, skiing, and photography.

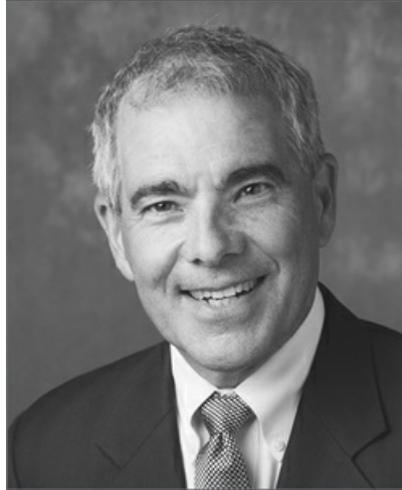
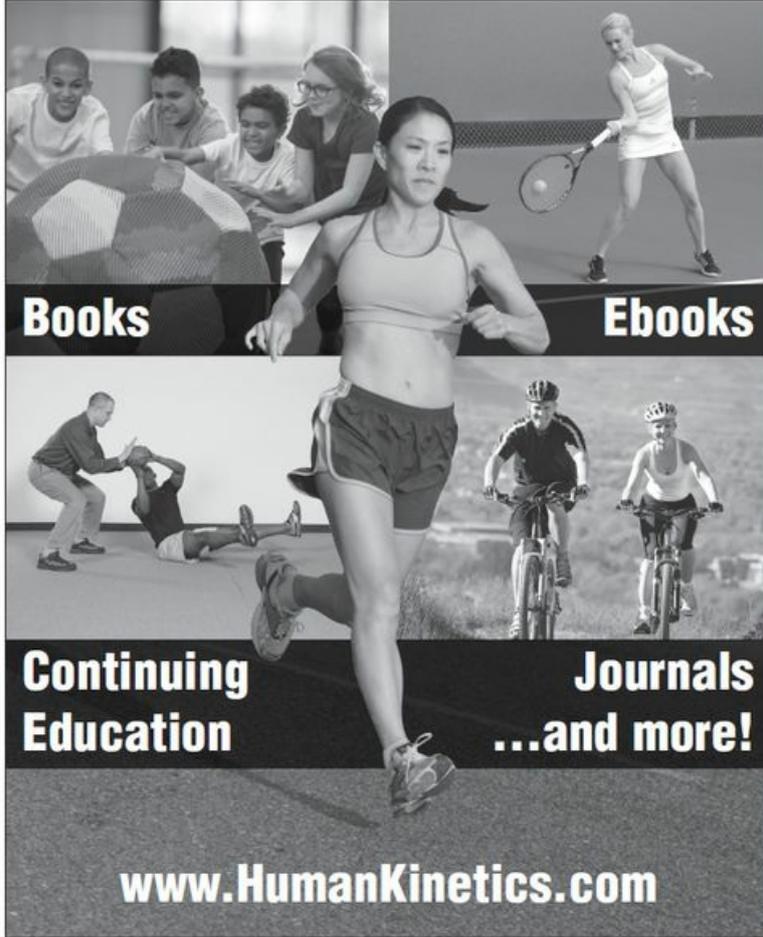


Photo courtesy of Purdue University.

Howard N. Zelaznik, PhD, is a professor of health and kinesiology at Purdue University. He is a fellow of the National Academy of Kinesiology, the Association for Psychological Science, the Psychonomic Society, and the American Association for the Advancement of Science, and he is an active member of the North American Society for the Psychology of Sport and Physical Activity. Zelaznik has served as executive editor for the *Journal of Motor Behavior*.

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A former college tennis player, Zelaznik is still an active (albeit unranked) tennis player. He is an active road cyclist and former marathon runner. As his students continually tell him, he does not have a good sense of humor, although he loves to laugh.



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