Fifth Edition

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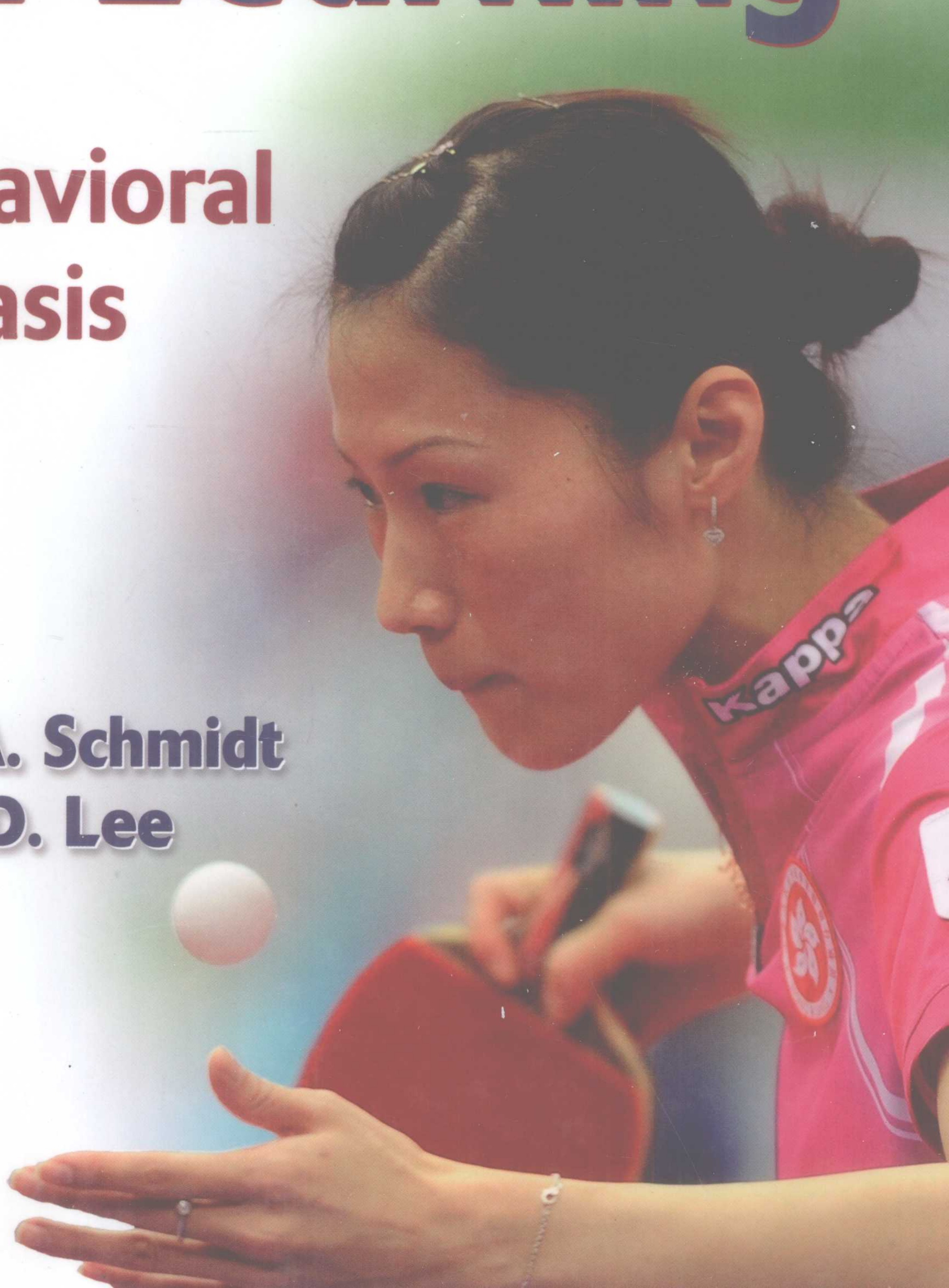
A Behavioral Emphasis

Richard A. Schmidt
Timothy D. Lee



MOTOR CONTROL AND LEARNING

A Behavioral Emphasis

FIFTH EDITION

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PREFACE

Most of us have marveled at one time or another about how the most highly skilled performers in industry, sport, music, or dance seem to make their actions appear so simple and easy—performed with incredible efficiency, smoothness, style, and grace. Like the first four editions of this text (Schmidt, 1982, 1988; Schmidt & Lee, 1999, 2005), the fifth edition of *Motor Control and Learning: A Behavioral Emphasis* was written for those who would like to understand how it is that these performers can achieve such artistry while we, as beginners in a similar task, are clumsy, inept, and unskilled. This book was written particularly 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. However, students in other fields, such as the neurosciences, physical therapy, occupational therapy, speech therapy, biomedical or industrial engineering, human factors or ergonomics, and sport, will also find many of the concepts contained here to be of interest, as movement behavior is a part of all of them. And for those who are, or who are becoming, practitioners in these fields, the principles of motor behavior outlined here should 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. That is, the primary focus is on movement behavior that can be observed directly, as well as 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. Yet, at the same time, we focus on the 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, and various biomechanical factors that act to determine the nature of our movement behaviors are all important if we are to understand 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 (or motor control), and biomechanics are rapidly moving together 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. We have directed considerable effort toward including the most recent knowledge from a number of rapidly developing subfields, and each chapter has been revised extensively in light of these newer concepts. In addition to including more than 280 new references to work published since the last edition (in 2005), we have also endeavored to pay homage to some of the important early research developments in the various areas. One of the features introduced in the previous two editions was sidebars highlighting specific research issues throughout the book. We have created more of these sidebars in this fifth edition with the idea that certain material requires a more detailed treatment to ensure understanding than is typical of passages in the text. Some of these sidebars highlight quotations from selected historical papers; other sidebars 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. And we have expanded other chapters and sections to present new, exciting areas of research that have emerged since the previous edition. Many new figures have also been included 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, therapy, and music are provided to illustrate motor control and learning concepts and provide suggestions for application. As before, the fifth edition reflects a logical progression so that later chapters build upon concepts presented in earlier chapters, with the final result being a consistent, defensible framework of ideas about motor skills. Having such a framework, or point of view, is important for those who wish to use the information presented here, both so that contributions to new applications may be made and so that the design of new skills research is facilitated.

The book is divided into three parts. Part I provides an introduction to research and fundamental concepts that are important to understanding motor behavior. The first chapter, a brief history of the field, is followed by a presentation of methods in movement research in chapter 2, focusing on various paradigms and statistical techniques used in the study of movement behavior. In chapter 3 the human is regarded as a processor of information, and we focus on the many ways that information is dealt with 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 views motor control from a closed-loop perspective, in which the sensory contributions to movement control are examined, 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. Some principles related to speed and accuracy are presented in chapter 7, together with a discussion of 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. The final chapter in this part contains a discussion of factors that determine skill differences between people and among groups of people, with emphasis on important themes about abilities and the prediction of skills.

Part III deals with the acquisition of skill, or motor learning. Chapter 10 concentrates on some special methodological problems for studying learning. The effects of practice, the structure of the practice session, and the many variables under the control of a teacher, coach, or therapist are discussed in chapter 11, while feedback contributions to learning are included in chapter 12. In both of these chapters, much new information is covered that demands important changes in our understanding of the processes involved in practice and the ways in which these influence learning. Chapter 13 presents various theoretical treatments of motor learning. And finally, chapter 14 deals with the factors associated with the retention and transfer of skills.

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Throughout the long process of this revision, a number of people provided very highly valued input. Judy Wright of Human Kinetics provided encouragement and many valuable suggestions for not only this revision, but on previous editions of the book as well. Her recent retirement closes an important chapter not only for the publisher, but also for the expression of ideas presented in this book. Judy, we wish you an energetic and successful next dance. Thanks also go to our editors, Melissa Zavala and Antoinette Pomata, for their excellent work on the project. We called upon a number of colleagues to read specific sections of the book. The many suggestions made by Ramesh Balasubramaniam, Ian Franks, Waclaw Petrynski, Gwen Gordon, and Laurie Wishart were invaluable in making these revisions. The final manuscript is much better as a result, and we are grateful for their time and effort.

CONTENTS

PART I

INTRODUCTION TO MOTOR BEHAVIOR

This first part introduces the field of motor control and learning. In chapter 1 the area is described, and the important distinctions separating motor control and learning from other, related fields of study are made. Then, a brief history of the field is given, showing how knowledge about movements from psychology and kinesiology, as well as from the neurosciences, has been combined. The second chapter deals with the various scientific methods used for studying motor skills. Here, we explain the tools of motor behavior research, focusing on the various ways in which motor behavior and skill can be measured. Chapter 3 presents the information-processing approach, which is fundamental to understanding how humans think and act. The last chapter in this section describes attention and its role in motor behavior.

CHAPTER 1

EVOLUTION OF A FIELD OF STUDY

Movement is a critical aspect of life. Without movement, we could not feed ourselves, we could not reproduce, and we would not survive. 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, operating a typewriter, or performing a triple twisting somersault from the diving board. 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 of skills: "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 add one important aspect to motor control that is sometimes not included—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, 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, a given 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 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 apparently genetically defined actions 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,[1] 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 (a) 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 (b) 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 subjects 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 unnoticed 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 is 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 (see chapter 9).

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 that we now call *motor development* (see Thomas, 1997, for a historical review).

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 that were later "rediscovered." 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, many of which seem at least reasonable today. Also, patients with accidental cerebellar damage were studied (e.g., by 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 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 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 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;

Nikolai Bernstein

At the same time that Ivan Pavlov dominated the field of Russian physiology during the 1920s and 1930s, Nikolai 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 has 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.

Perhaps the most telling evidence of Bernstein's influence on current motor control theorizing is the fact that the journal *Motor Control* has published over a dozen English translations of Bernstein's papers since 1998 and that a biennial conference celebrating his legacy continues to this day.

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