CHAPTER **5**

Motor Control Theories

Concept: Theories about how we control coordinated movement differ in terms of the roles of central and environmental features of a control system.

After completing this chapter, you will be able to

- Discuss the relevance of motor control theory for the practitioner
- Define the term *coordination* as it relates to the performance of motor skills
- Describe the *degrees of freedom problem* as it relates to the study of human motor control
- Compare and contrast an open-loop control system and a closed-loop control system
- Describe a primary difference between a motor program–based theory of motor control and a dynamical systems theory of motor control
- Define a generalized motor program and describe an invariant feature and a parameter proposed to characterize this program
- Define the following terms associated with a dynamical systems theory of motor control: order and control parameters, self-organization, coordinative structures, and perception-action coupling
- Discuss how a motor program–based theory and a dynamical systems theory each explain the basis for the relative time characteristics of human walking and running
- Describe how the OPTIMAL theory of motor learning complements the motor program-based schema theory and the dynamical systems theory by addressing issues these theories ignore

APPLICATION

To successfully perform the wide variety of motor skills we use in everyday life, we must coordinate various muscles and joints to function together. These muscle and joint combinations differ for many skills. Some skills, such as hitting a serve in tennis or getting out of a chair and into a wheelchair, require us to coordinate muscles and joints of the trunk and limbs. Other skills involve coordination of the arms, hands, and fingers; examples are reaching to pick up a pencil, playing the guitar, and typing on a keyboard. Other skills require us to coordinate our two arms or legs in such a way that each one does something different at the same time, such as when we hold a jar with one hand and screw open the top with the other or kick a ball with one leg while the other is firmly on the ground. For still other skills, where only one arm and hand are involved, we must coordinate only a few muscles and joints. We do this when we manipulate a computer joy stick or a car's gearshift.

Motor skill performance has other important general characteristics in addition to body and limb coordination. For example, we perform some skills with relatively slow movements; think of how we position a bow before releasing an arrow or pick up a cup to take a drink from it. Other skills, such as throwing a ball or jumping from a bench to the floor, require fast, ballistic movements. Some motor skills, such as writing a numeral or buttoning a shirt, have few component parts; other skills, such as performing a dance routine or playing the piano, have many parts and therefore are very complex.

Also, we can produce remarkably accurate and consistent movement patterns from one performance attempt to another. We are capable of performing well-learned skills with a remarkable degree of success in a variety of situations, even though we have never before been in similar situations. For example, a skilled tennis player will have to use a forehand stroke in many different situations in matches. The many different characteristics in any situation, such as the ball's flight pattern, speed, spin, bounce, and location on the court, as well as the opponent's position, the wind and sun conditions, and so on, provide little chance that any two situations can be exactly alike. Yet a skilled player can hit the ball successfully.

These examples of the variety of motor skills we can perform indicate the many different ways we must coordinate various parts of our body in order to achieve the action goals of these skills. An active nervous system underlies this amazing capability we have to perform such a variety of motor skills in so many different situations and contexts. The question we will address in this chapter is this: How does the nervous system function to enable us to carry out the movements required for the vast array of action goals we need to achieve on a daily basis?

Walking down a crowded flight of stairs is a good example of an action that requires a person to adapt his or her pattern of head, body, and limb movements to the characteristics of the stairs and the other people on the stairs.

Steve Mason/Getty Images

Application Problem to Solve Select a motor skill that you perform well as part of your daily experiences, or for recreational or sports purposes. As you study this chapter, address each of the following points: (1) Consider the coordination demands of this skill by describing the degrees of freedom the skill requires at the joint level. (2) How do you adapt the way you perform this skill to different characteristics you might encounter in the environmental context (recall what is included here from our discussion in chapter 1)? Describe some of those environmental context characteristics and indicate how you adapt to them in terms of the movement adjustments you make. Consider whether the adjustments involve some modifications to the movement coordination pattern you use to perform the skill or involve a change in the movement coordination pattern you use.

DISCUSSION

Before we discuss some prominent theories of how the nervous system controls coordinated movement, we will consider the importance of understanding the basic components of motor control theory. Then we will clarify a few terms, to provide a foundation for understanding those theories.

THEORY AND PROFESSIONAL PRACTICE

Students who are preparing for professions in which their primary responsibilities involve motor skill instruction often question the need to study motor control theory. This type of questioning often comes from those who believe their preparation needs to involve only "practical" information that will help them carry out their day-to-day responsibilities in the workplace. Unfortunately, this view is often the result of a lack of understanding of the relevance of theory to professional practice. In this section, we will discuss what a theory is and the relevance of motor control theory for practitioners. One of the goals of this section is to establish why the discussion of motor control theory is presented in this book before the discussion of specific topics related to motor control and learning.

What Is a Theory?

If we base our understanding of the term *theory* on how it is commonly used in everyday language, we come away with the view that a theory has little relevance to reality. But this view is shortsighted and misleading. In science, a theory helps us understand phenomena and explains the reasons why these phenomena exist or behave as they do. Stephen Hawking (1996), the late world-renowned physicist at Cambridge University in England, stated that a good theory should satisfy "two requirements. It must accurately describe a large class of observations . . . and it must make definite predictions about the results of future observations" (p. 15). In Hawking's domain of physics, theories are developed to help us understand various aspects of the physical universe in which we live. They do this by providing us with explanations of observable physical events, such as identifying the variables that make a rolling ball eventually stop rolling. By identifying these variables, we can then predict how far a ball will roll given specific characteristics of these variables.

In the behavioral sciences, which include the study of human motor control and learning, theories focus on explaining human behavior. When the human behavior of interest is the performance and learning of motor skills, we look to theories to provide us with explanations about why people perform skills as they do, which means identifying the variables that account for the performance characteristics we observe. For example, we know from our observations of people performing skills that a person can perform the same skill in a variety of different situations. A skilled basketball player can shoot a one-hand jump shot from a variety of locations on the floor and in a variety of game-related situations. Or, a skilled driver can successfully drive a car on either an open or crowded highway or street. A good theory of motor control will explain why this capability is possible. Similarly, if a rehabilitation therapist uses a specific intervention to treat an injury, a good theory of motor control will explain why this intervention is effective.

The Relevance of Motor Control Theory for the Practitioner

A benefit of a basic understanding of motor control theory is that it provides the practitioner with a base of support on which he or she can develop effective skill instruction and practice environments. Figure 5.1 illustrates the connection between theory and practice by indicating some of the many applications that will be enhanced when a practitioner has knowledge about the variables that influence motor skill performance. To use one of the examples given at the end of the preceding section, if we know *why* people can adapt to a variety of situations when they perform a motor skill, we can use this knowledge to develop practice conditions that we can confidently predict will facilitate this adaptation capability. Consider a different example.

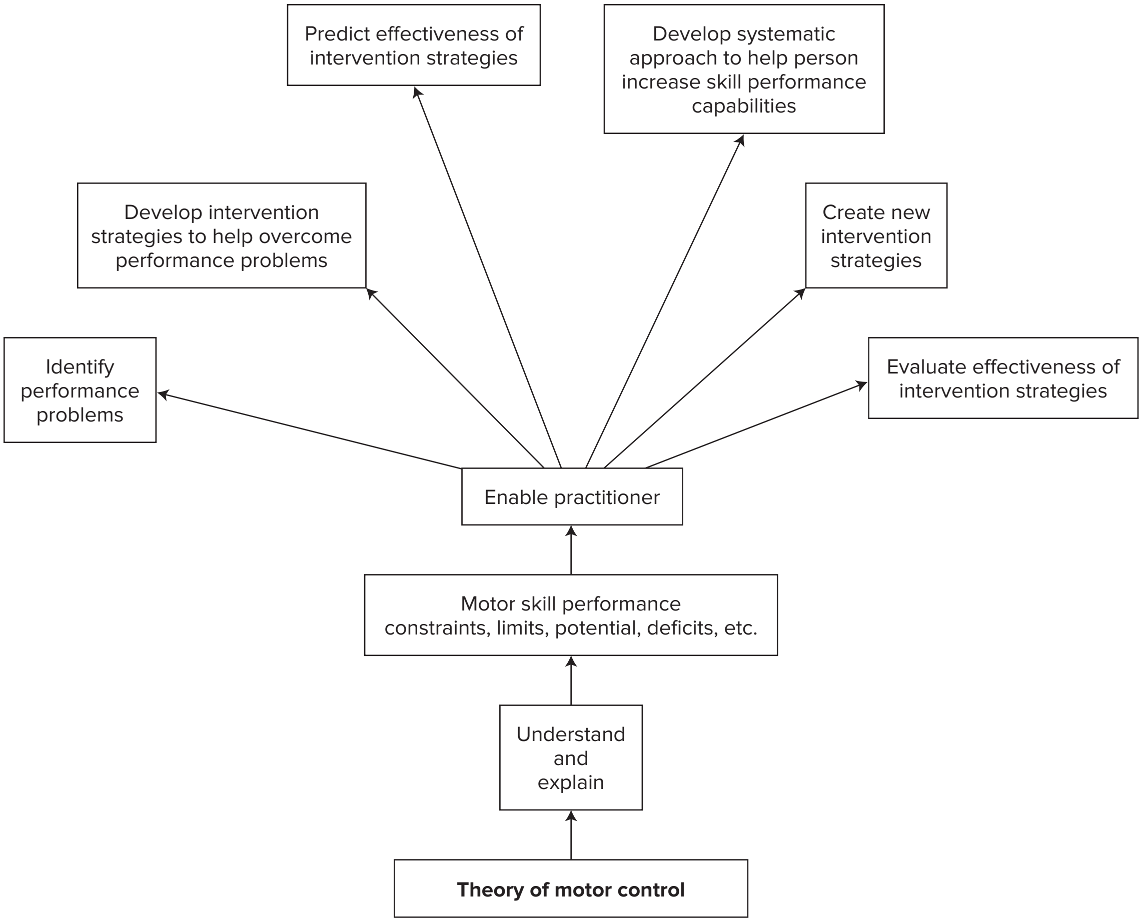

FIGURE 5.1 Motor control theory provides a foundation on which practitioners can base many tasks and responsibilities.

Suppose you need to help a person reacquire the capability to walk. Knowledge about the motor control mechanisms that underlie human locomotion and the environmental variables that affect it will allow you to develop more appropriate assessment and intervention strategies, because they will be based on variables that influence locomotion.

MOTOR CONTROL THEORY

In the earlier section titled "What Is a theory?" you read that a good theory should describe and provide explanations for a large class of observable events. In light of this requirement, what should a good theory of motor control describe and explain? Researchers generally acknowledge that it should describe and explain how the nervous system produces coordinated movement such that we are able to successfully perform a variety of motor skills in a variety of environmental contexts. In many respects, the attempt to understand how we produce coordinated movement is similar to wanting to know how a watch, which also involves the precise coordination of many components, keeps time.

The following sections discuss two essential issues important to a theory of motor control: the meaning of the term *coordination* as it applies to motor skill performance, and the "degrees of freedom problem." Although researchers have proposed additional issues that a theory of motor control should address,[1] these two will provide a sufficient foundation on which to base your introduction to the two prominent motor control theories discussed in this chapter.

It is important to note that the theories described here address motor control from a predominantly *behavioral level.* As you saw in chapter 1, this means that they focus on explaining observed behavior without attempting to specify neural-level features of the control process (for examples of neural models of motor control, see Bullock & Grossberg, 1991; Grossberg & Paine, 2000; Rokni & Sompolinsky, 2012; Wolpert & Ghahramani, 2000; Wu, Haugh, Sarnow, & Hitt, 2006). An important goal of behaviorally based motor control theories is to propose laws and principles that govern coordinated human motor behavior. A neural-level theory would be expected to describe neural mechanisms or neural mechanism interactions that explain how the nervous system is involved in these behavioral principles (see, for example, Willingham, 1998).

Coordination

An important characteristic of all motor control theories is that they include explanations of how we control coordination. Therefore, it is essential that we establish an understanding of the meaning of the term *coordination* as it applies to the performance of motor skills. The performance of a motor skill involves a person's organization of the activation of muscles in such a way that the goal of an action can be accomplished. It is this organizational feature that is at the heart of the definition of the term *coordination.* For the purposes of this textbook, we will use as a general definition one provided by Turvey (1990): **coordination** is the patterning of head, body, and limb movements relative to the patterning of environmental objects and events.

This definition contains two parts. Each is important to consider further. First, note that the definition

[1]For broader and more in-depth discussions of issues that are relevant for a theory of motor control, see books devoted to motor control issues, for example, Kelso (1995), Latash (2012), Rosenbaum (2011), and Shumway-Cook and Woollacott (2017).

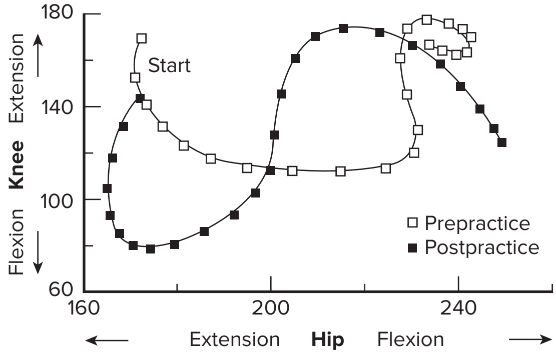

FIGURE 5.2 Angle-angle diagram from an experiment by Anderson and Sidaway showing coordination changes resulting from practice for the hip and knee relationship while performing a soccer kick. *Source:* From *Research Quarterly for Exercise and Sport*, Vol. 65, pp. 93–99, 1994 American Association for Health, Physical Education, Recreation, and Dance, 1900 Association Drive, Reston, VA 20191.

specifies that coordination involves *patterns of head, body, and/or limb movements.* Although a common colloquial use of the term *coordination* relates it to a characteristic of skilled performance, it should not be limited to this use. When used in reference to a movement pattern associated with the performance of a skill, coordination refers to the organizational relationship of movement characteristics of the head, body, and limb involved in the performance, *regardless of the skill level of the performer.* This means that when we consider the assessment of movement characteristics of the performance of a skill, it is necessary to consider coordination as referring to the relationship among the head, body, and/or limbs *at a specific point in time* during the skill performance.

As you saw in chapter 2, a common way to portray movement patterns is to represent graphically in an angle-angle diagram the relationship between the displacement patterns of limbs as they move while performing the skill. An example of this type of representation can be seen in figure 5.2, where

coordination the patterning of head, body, and/or limb motions relative to the patterning of environmental objects and events.

A CLOSER LOOK

Looking at the Degrees of Freedom Problem at the Level of Muscles and Joints

We know that there are 792 muscles in the human body that can act to make the one hundred joints behave in different ways. And each joint has mechanical characteristics that define its degrees of freedom for movement. On the basis of these features, Turvey (1990) put the coordination control problem into perspective this way. If all the joints were only hinge joints like the elbow, there would be one hundred mechanical degrees of freedom to be controlled at the joint level. But if two specific characteristics, such as position and velocity, needed to be defined for these types of joints to carry out a specific act, the degrees of freedom would increase to two hundred.

Consider the following examples. If you were seated at a table and decided to pick up a drinking glass in front of you on the table, the number of degrees of freedom involved just in terms of the number of joints (this does not take into account the number of ways each joint can move) would be the shoulder joint (1), elbow joint (1), wrist joint (1), and all the finger (3 joints × 4 fingers = 12 joints) and thumb (3) joints. The total number of joints that need to be controlled for this simple action is 18. Now suppose that the drinking glass in front of you is very large and requires two hands to pick it up. The nervous system must now control at least double the number of degrees of freedom compared to the one-hand situation. In both cases, you probably would not have any difficulty coordinating the joints of one or two limbs to achieve the action goal. But, if we consider these tasks from the level of neuromuscular control where the many degrees of freedom must be controlled to operate in very specific ways, the simple task of picking up a drinking glass becomes a very complex one. Yet, the nervous system handles this complex operation. Theories of motor control need to be able to explain how the nervous system does this.

the coordination of the knee and hip joint angles during a soccer kick is shown.

The second part of the definition states that the pattern of head, limb, and body motion is *relative to the pattern of environmental objects and events.* This is important because it establishes the need to consider movement coordination in relation to the context in which the skill is performed. The characteristics of the environmental context constrain the head, body, and limbs to act in certain ways so that the goal of the action can be achieved.

For example, to walk along a pathway, people must adapt their head, body, and limb movement patterns to the characteristics of the pathway. If, for example, a person is walking on a sidewalk and encounters a tree branch lying across it, he or she must use a new pattern of movements in order to step over the branch. The characteristics of the tree branch will dictate the characteristics of the movement pattern. If it is small, the person may simply need to adjust the length of a walking stride and take a large step; if it is a large branch, he or she may have to stop walking and climb over it.

The Degrees of Freedom Problem

Because coordination involves head, body, and limb movement patterns, an important question in the study of motor control is this: *How does the nervous system control the many muscles and joints involved in producing a complex movement pattern?* To answer this question, we must consider an important problem that was first posed by Nicolai Bernstein, a noted Russian physiologist whose work, produced from the 1930s to the 1950s, did not become known to the Western world until 1967. His work continues to influence research and theory related to motor control. Bernstein proposed that to perform a well-coordinated movement, the nervous system had to solve what he termed the "degrees of freedom problem."

The **degrees of freedom** of any system reflect the number of independent components of the system and the number of ways each component can vary. Each component is "free" to vary in specific ways, as in the case of the elbow joint, which can vary (i.e., move) in two ways: flexion and extension. The **degrees of freedom problem** arises when a complex

A CLOSER LOOK

Bernstein's Demonstration of the Degrees of Freedom Problem

Nicolai Bernstein's classic book *The Co-ordination and Regulation of Movement* (published in English in 1967) was a compilation of several of his publications. In the chapter titled "Some emergent problems in the regulation of motor acts" (originally published in Russian in 1957), Bernstein discussed the degrees of freedom problem that the motor control system must overcome in order to produce well-coordinated movement. In this discussion (p. 126f), he provided the following example to demonstrate the problem (which he said was "very useful for demonstrations in auditoriums").

> Fasten the handle end of a ski-stick in front of the buckle of a subject's belt. Attach a weight of 1–2 kg to the far end and on the right and left sides of the wheel [at the end of the stick] attach a length of rubber tubing long enough to allow the ends to be held in the subject's left and right hands. Instruct the subject . . . to stand before a vertical board on which a large circle, square or other simple figure has been drawn, and to try, manipulating the ski-stick only by pulling on the rubber tubing, to follow the contours of the figure with the point of the ski-stick. The stick here represents one segment of an extremity with two degrees of freedom; the tubing is analogous to two antagonistic muscles introducing a further two degrees of freedom into the system. This experiment . . . makes clear to all who attempt it just how difficult and complicated it is to control systems which require the co-ordination of four degrees of freedom, even when under the control of a human being in full possession of his full complement of receptors, but without motor practice with the task, who has been dealing with his bone-muscle motor apparatus from the first weeks of his life.

system needs to be organized to produce a specific result. The control problem is as follows: *How can an effective yet efficient control system be designed so that a complex system, having many degrees of freedom, is constrained to act in a particular way?*

Consider the following example of the degrees of freedom control problem in a complex mechanical system. A helicopter is designed so that it can fly up or down, to the left or the right, forward or backward, and so on, and at a variety of speeds. If the pilot had to control one switch or lever for each component needed to make the helicopter fly a certain way, the pilot's job would be overwhelming. Therefore, the helicopter designer reduces the complexity of the task by providing control sticks and pedals that the pilot can manipulate simultaneously with his or her hands and feet. Each stick or pedal controls several functions at once.

When the nervous system must control the human body so that it performs a complex motor skill, such as climbing a ladder, it faces a degrees of freedom control problem similar to that involving the helicopter. The determination of the actual number of degrees of freedom that must be controlled in coordinated human movement depends on which level of control we are considering. At one level, we might consider motor units as the elements that must be controlled. At another level, we could consider joints as the element of interest. Regardless of the control level considered, it becomes evident that for any motor skill, the control problem involved in enabling a person to perform that skill is an enormous one. However, as you will see in chapter 12, when a person practices a skill and progresses from a beginner to a skilled performer, the motor control system solves the degrees of freedom problem in ways that are evident from the changes we can observe in specific coordination characteristics.

degrees of freedom the number of independent components in a control system and the number of ways each component can vary.

degrees of freedom problem a control problem that occurs in the designing of a complex system that must produce a specific result; the design problem involves determining how to constrain the system's many degrees of freedom so that it can produce the specific result.

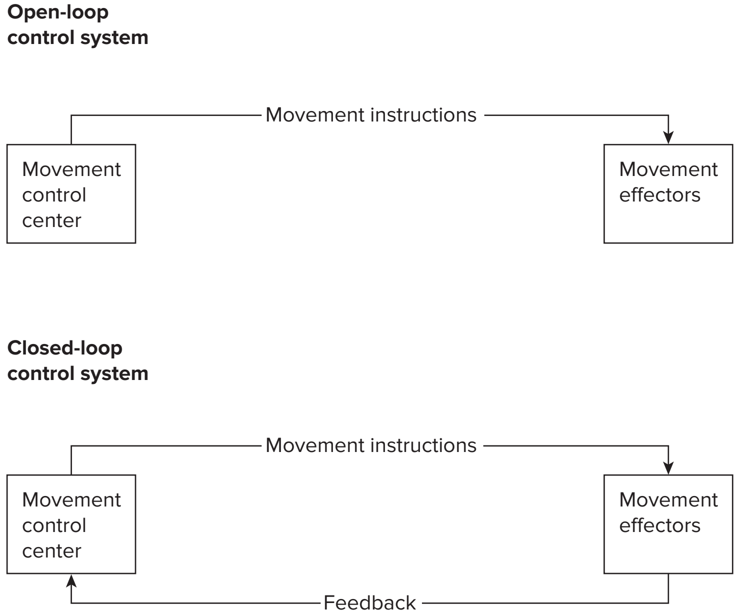

FIGURE 5.3 Diagrams illustrating the open-loop and closed-loop control systems for movement control.

OPEN-LOOP AND CLOSED-LOOP CONTROL SYSTEMS

Most theories of motor control incorporate two basic systems of control. These two systems, called **open-loop** and **closed-loop control systems**, are based on mechanical engineering models of control. Rather than provide exact descriptions of the control processes in complex human movement, these two models are general descriptions of different ways the central and peripheral nervous systems initiate and control action. These models serve as useful guides that illustrate some of the basic components involved in that process.

Figure 5.3 presents diagrams illustrating simple open-loop and closed-loop control systems. These are the typical diagrams you would see in any general presentation of these types of control systems. Notice that each of these systems has a *control center.* The control center is sometimes referred to as an *executive.* An important part of its role is to generate and issue movement instructions to the *effectors,* which, in the human, are the muscles of the limbs, body, and/or head involved in producing the desired movement.

Differences between the Systems

These systems differ in two ways. First, a closed-loop control system involves **feedback**, whereas an open-loop system does not. In human movement, the feedback is *afferent* information sent by the various sensory receptors to the control center. The purpose of this feedback is to update the control center about the correctness of the movement while it is in progress.

The second important difference between open- and closed-loop control systems relates to the *movement instructions* issued by the control center. In the open-loop system, because feedback is not used in the control of the ongoing movement, the instructions contain all the information necessary for the effectors to carry out the planned movement. Although feedback is produced and available, it is not used to control the ongoing

A CLOSER LOOK

Mechanical and Human Motor Skill Examples of Open-Loop and Closed-Loop Control Systems

Open-Loop Control

Mechanical example

- **Digital video recorder.** It can operate as an open-loop control system by being program med to record television programs on specified dates and at specified times. The DVR will turn on and off at the specified times. (Note that it will turn off at the specified time even if the program being recorded continues past that time.)

Human motor skill example

- **Throwing a dart at a dartboard.** When the person initiates the throw, the arm movement and dart release occur as specified by movement instructions developed before the initiation of the arm movement. Any feedback generated by vision or the muscles cannot be used to make a movement correction because the movement ended when the dart left the hand.

Closed-Loop Control

Mechanical example

- **Thermostat in a house.** It controls the air-conditioning and heating systems in a house. The desired room temperature is set on the thermostat. This setting becomes a reference against which actual room temperatures are compared. The room temperature serves as the feedback to the thermostat to indicate when to turn the air-conditioning or heating system on or off.

Human motor skill example

- **Driving a car.** When a person drives a car on a street or highway, he or she must keep the car within a specified lane. To do this the driver uses visual and proprioceptive feedback to control the steering wheel to make the needed adjustments to keep the car from going outside the lane boundaries.

movement. This may be so because feedback is not needed, or because there is not enough time to use feedback to effectively control the movement after it is initiated.

In the closed-loop system, the movement instructions are quite different. First, the control center issues an initial instruction to the effectors that is sufficient only to initiate the movement. The actual execution and completion of the movement depend on feedback information that reaches the control center. The feedback provides information about the status of the movement, which serves to enable the control center to do one of several things: allow the movement to continue as initially instructed, provide additional instructions to continue the movement in progress, or correct a movement error. It is important to note that one of the drawbacks of the classic diagram of the closed-loop system, as shown in figure 5.3, is that it depicts the movement effectors as the only source for feedback. However, in the actual performance of skills in which the closed-loop control system operates, there are several other sources of sensory feedback, such as the visual and auditory systems. These sources of feedback will be discussed in chapter 6.

open-loop control system a control system in which all the information needed to initiate and carry out an action as planned is contained in the initial instructions to the effectors.

closed-loop control system a system of control in which, during the course of an action, feedback is compared against a standard or reference to enable an action to be carried out as planned.

feedback information from the sensory system that indicates the status of a movement to the central nervous system; in a closed-loop control system, feedback is used to make corrections to an ongoing movement.

A CLOSER LOOK

The Evolution of the Motor Program Concept

- Early Greek philosophers such as *Plato* talked about a person's creation of an "image" of an act preceding the action itself.
- *William James* (1890) alluded to Plato when he stated that to perform an action, a person must first form a clear "image" of that action.
- *Karl Lashley* (1917) is regarded as the first person to use the actual term *motor program.* He initially viewed motor programs as "intention[s] to act," but later described them as "generalized schemata of action which determine the sequence of specific acts" (Lashley, 1951, p. 122). He proposed that these schemata were organized to provide central control of movement patterns.
- *Sir Frederick Bartlett* (1932) implied that a motor program exists when he used the term *schema* to describe internal representations and organizations of movements.
- *Miller, Galanter, and Pribram* (1960) proposed the notion of a "Plan," which was "essentially the same as a program for a computer" (p. 16), and was responsible for controlling the sequence of events of an action.
- *Franklin Henry* (Henry & Rogers, 1960) gave the motor program concept a needed conceptual and empirical boost. He hypothesized that 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" (p. 449). Henry's concept of the motor program was also that of a computer program. He proposed that when initiated, the program controls the exact movement details, with essentially no modifications possible during the execution of the movement.
- *Stephen Keele* (1968) offered a view similar to Henry's by defining the motor program as "a set of muscle commands that are structured before a movement sequence begins, and that allow . . . the entire sequence to be carried out uninfluenced by peripheral feedback" (p. 387).
- *Richard Schmidt* (1975) proposed that the motor program is not specific muscle commands, but is an abstract memory-based representation of a class of actions, with each class defined by invariant features. Because of these characteristics he called his version the "generalized" motor program.

TWO THEORIES OF MOTOR CONTROL

We can classify theories of how the nervous system controls coordinated movement in terms of the relative importance given to movement instructions specified by central components of the control system or by information arising from interactions among the performer, the task, and the environment. Theories that give prominence to movement instructions specified by the central nervous system in the control process have in common some form of memory representation, such as a motor program, that provides the basis for organizing, initiating, and carrying out intended actions. We will discuss a motor program–based theory as an example of this type of theory. In contrast, other theories give more influence to information specified by the environment and to the dynamic interaction of this information with information from the task and the body, limbs, and nervous system. We will discuss the dynamical systems theory as an example of this type of theory.

Motor Program–Based Theory

At the heart of central control–oriented theories is the **motor program**, a memory-based construct that controls coordinated movement. Various theoretical viewpoints attribute different degrees of control to the motor program. Undoubtedly, the view that best characterizes present-day thinking about the motor program comes from the work of Richard Schmidt (1988, 2003; Schmidt & Lee, 2019). In his "schema theory," Schmidt (1975) proposed that a serious problem with previous views was that they limited the motor program to controlling specific movements or sequences of movements. To overcome this limitation, Schmidt hypothesized the **generalized**

motor program (GMP) as a mechanism that could account for the adaptive and flexible qualities of human coordinated-movement behavior.

Schmidt's generalized motor program. Schmidt proposed that a GMP controls a *class of actions,* rather than specific movements or sequences. He defined a class of actions as a set of different actions having a common but unique set of features. For Schmidt, these features, which he called **invariant features**, are the "signature" of a GMP and form the basis of what is stored in memory. These movement-related features form the basis of what Schmidt (2003) referred to as *the fundamental pattern of the class of actions.* These features remain consistent from one performance of an action to another. In order for a person to produce a specific action to meet the demands of a performance situation, the person must retrieve the appropriate program from memory and then add movement-specific **parameters**. These are movement-related features of the performances of an action that can be varied from one performance to another.

An analogy that can help you understand the distinction between invariant features and parameters of a GMP is the distinction between rhythm and tempo in music and dance. A piece of music has a *rhythmic structure* that is specified by the time signature, or meter, which is indicated on the written music score, such as 3/4 or 4/4. The first number (which would be the top number on the music score) indicates the number of beats with equal proportions of time intervals per measure of music. This number establishes the music's rhythmic structure. The second, or bottom, number specifies which type of note receives one beat, which in the case of the two examples would be the quarter note—that is, the 1/4 note. For the 3/4 meter there are three beats with equal proportions of time intervals in every measure (i.e., the equivalent of three quarter notes in each measure); for the 4/4 there are four beats to every measure. In dance, a waltz, for example, has a 3/4 meter, which means it has three beats to every measure and gives it its familiar 1-2-3 sequence of steps. Note, however, that for the waltz, the three beats are not of equal length; the first is long, the second and third are shorter but equal in time. *Tempo* refers to the speed at which the music is performed. The same rhythmic structure can be played slowly or fast. You can try this by clapping your hands with one clap for each beat. Try a consistent series of three claps with equal proportions of time intervals between claps, which establishes the rhythmic structure of your clapping. Then clap the same way but faster. Notice that the rhythmic structure doesn't change even though you increase the speed of the clapping. In this analogy, rhythm in music is analogous to an invariant feature of the GMP; tempo is analogous to a parameter.

Invariant features and parameters. Although many possible characteristics could be invariant features of the GMP, one that Schmidt (2003) considered to be the most likely is the **relative time** (which is analogous to rhythm in music) of the components of the skill. Another is the order, or sequence, of the components. The term *relative* in *relative time* indicates that what is invariant are the percentages, or proportions, of the overall duration, or movement time of the components of a skill.

motor program a memory representation that stores information needed to perform an action.

generalized motor program (GMP) the memory representation of a class of actions that share common invariant characteristics; it provides the basis for controlling a specific action within the class of actions.

invariant features a unique set of characteristics that defines a GMP and does not vary from one performance of the action to another.

parameters features of the GMP that can be varied from one performance of a skill to another; the features of a skill that must be added to the invariant features of a GMP before a person can perform a skill to meet the specific movement demands of a situation.

relative time the proportion, or percentage, of the total amount of time required by each component of a skill during the performance of that skill.

A CLOSER LOOK

Defining the Motor Program: A Memory Representation versus a Plan of Action Prepared Just Prior to Moving

A problem that has arisen over the years has led to difficulties in understanding what the motor program is and how it functions. The problem is that the term *motor program* has been used to describe different functional constructs. In some discussions, the motor program refers to the memory representation of a movement or action. The generalized motor program (GMP) construct in Schmidt's schema theory is a good example. The theoretical arguments about the memory-representation type of motor program focus on which characteristics of a movement or action are stored in memory as a part of the motor program. We use the term this way in the present chapter.

The other use of the term *motor program* refers to what is constructed or prepared just prior to movement initiation, but following an intention to act. This use of the term, sometimes referred to as *motor programming,* is the focus of chapter 8, although we do make some reference to this preparation aspect of motor program–based control in the present chapter.

Figure 5.4 presents an illustration of how to interpret the concept of invariant relative time. Suppose you move the index finger of your hand as quickly as possible to press five keys on a keyboard in sequence. Now, suppose that the four components of this task (the time intervals between the keys: keys 1-2, 2-3, 3-4, 4-5) yield the following movement time (MT) proportions: component 1 takes up 30 percent of the total MT (component % = component MT/total MT); component 2, 20 percent; component 3, 40 percent; and component 4, 10 percent. If the performance of this skill under typical conditions has an overall duration of 10 sec [represented in part (a) of the figure], then regardless of how much you speed up or slow down this overall duration, the actual amount of movement time for each component changes proportionately. In figure 5.4, parts (b) and (c) represent this proportional component change for speeding up the skill [part (b)] and slowing it down [part (c)]. Thus, if you typically perform this skill in 10 sec, then the amount of time you spend performing each component is 3, 2, 4, and 1 sec, respectively. If you performed the skill twice as fast, in 5 sec, then each component would change proportionately to be 1.5, 1, 2, and 0.5 sec, respectively. If you slowed down your overall movement time to 15 sec, then each component would change to 4.5, 3, 6, and 1.5 sec, respectively.

Although motor program theory proposes that the invariant features of a GMP are rather fixed from one performance of a skill to another, it also holds that there are other features, called *parameters,* that can be varied. Examples include the *overall duration* and the *muscles* used to perform the skill. Skilled performers can easily change these from one performance situation to another, readily adapting them to the specific requirements of each situation.

The following two examples illustrate the relationship between invariant features and parameters. One relates to figure 5.4, which, as just discussed, portrays relative time as an invariant feature. This figure also illustrates the parameter of *overall duration.* The normal, faster, and slower speeds in the figure show that a person can change the overall amount of time taken to move without altering the relative time structure of the components of the movement. This type of situation occurs, for example, when a person walks faster or slower than his or her typical speed.

The second example concerns *muscles* as parameters. Research evidence shows that whether you sign your name with a pen held in your preferred hand, in the opposite hand, between your toes, or with your teeth, the two signatures have distinct invariant spatial as well as relative time features (see Wright, 1990 for an excellent review of this research). These results suggest that you can change the muscles involved in writing your signature without altering the invariant features represented in the generalized motor program. Interestingly,

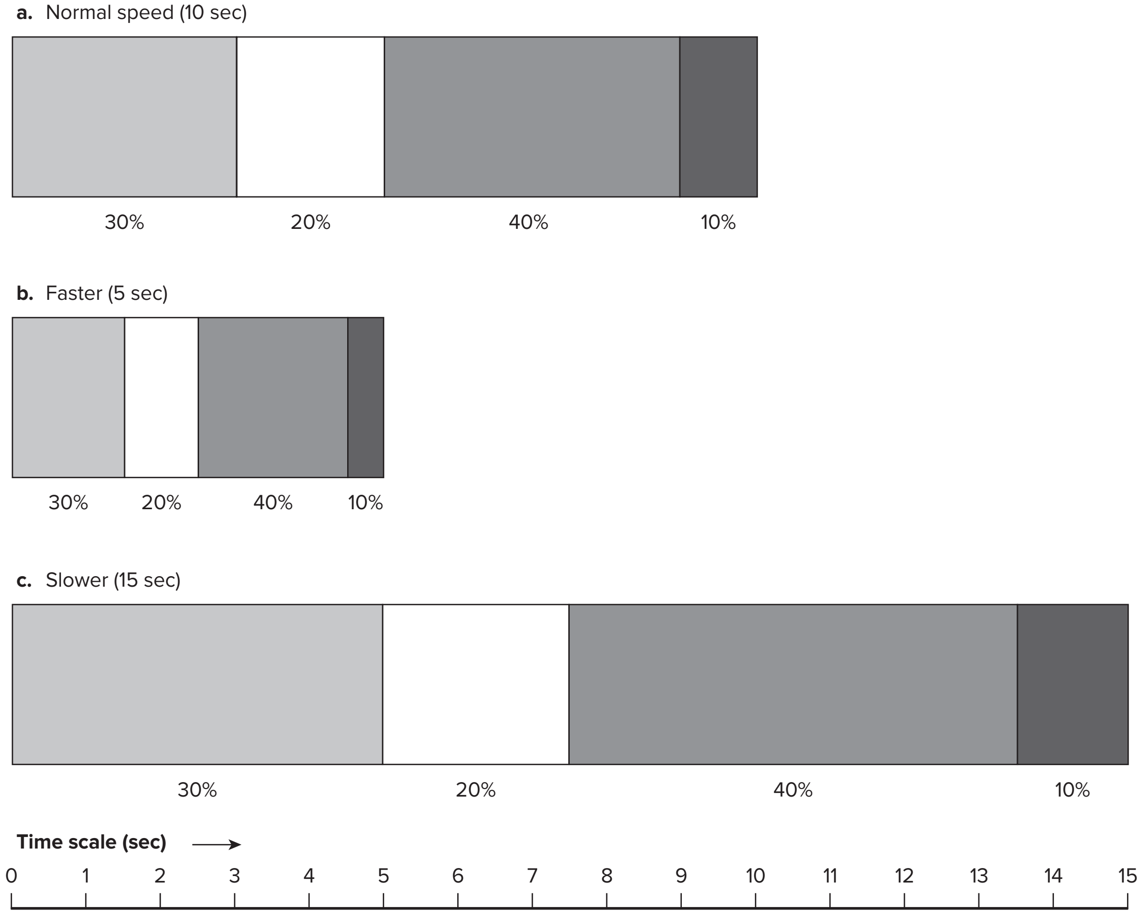

FIGURE 5.4 An illustration of invariant relative time for a hypothetical four-component motor skill when it is performed normally at a 10 sec duration (a), speeded up to a 5 sec duration (b), and slowed down to a 15 sec duration (c).

Rijntjes et al. (1999) provided neurological evidence for muscles as a movement parameter related to the signing of one's name by comparing brain regions activated by people signing their name with the finger of the preferred hand and with the big toe. Additional evidence and examples of muscles as parameters will be discussed in chapter 13, when we consider the topic of bilateral transfer.

Schmidt's schema theory. A formalized theory of how the GMP operates to control coordinated movement is Schmidt's schema theory (Schmidt, 1975, 1988, 2003). A **schema** is a rule or set of rules that serves to provide the basis for a decision. It is developed by abstracting important pieces of information from related experiences and combining them into a type of rule. For example, your concept of *dog* is the result of seeing many different types of dogs and developing a set of rules that will allow

schema a rule or set of rules that serves to provide the basis for a decision; in Schmidt's schema theory, an abstract representation of rules governing movement.

you to identify correctly as a "dog" an animal you have never seen before.

Schmidt used the schema concept to describe two control components involved in the learning and control of skills. Both are characterized as based on abstract rules. The first is the *GMP,* which, as just described, is the control mechanism responsible for controlling the movement coordination patterns of classes of actions, such as throwing, kicking, walking, and running. The second component is the *motor response schema,* which is responsible for providing the specific rules governing the performance of a skill in a given situation. Thus, the motor response schema provides parameters to the GMP.

The schema theory provides an explanation for how well a person can *adapt* to new situations or environmental contexts. People can successfully perform a skill requiring movements that have not been made in that same way before. For example, when you walk in a crowded mall or return a tennis serve, characteristics of the situation change in ways that you have not previously experienced. It is possible to perform the skill successfully in these situations because you can use the rules from the motor response schema to generate appropriate parameter characteristics; you add these to the GMP to perform the skill.

Schmidt's schema theory claims to *solve the degrees of freedom problem* in movement coordination through an executive control operation that organizes motor programs and schemas. An important emphasis in this approach is the abstract, or general, nature of what is stored in the control center. The GMP and motor response schema work together to provide the specific movement characteristics needed to initiate an action in a given situation. The action initiation is an open-loop control process. However, once movement is initiated, feedback can influence its course if there is sufficient time to process the feedback and alter the movement in progress.

Testing the invariant relative time feature. Researchers have attempted to provide empirical support for motor program–based control by investigating Schmidt's claim that a generalized motor program controls a class of actions defined by specific invariant features. Of the proposed invariant features, relative time has generated the most research interest. Support for the invariance of this feature has come from many experiments investigating several different skills, such as typing, gait, handwriting, prehension, and sequences of key presses, among others. (For reviews of this evidence, see Heuer, 1991; Schmidt, 1985, 1988, 2003; Shea & Wulf, 2005.)

Researchers typically have investigated relative time invariance by observing changes in relative time across a range of values of an associated parameter, such as overall duration or speed. The most commonly cited research example in this regard is a study by Shapiro, Zernicke, Gregor, and Diestel (1981) in which people walked and ran at different speeds on a treadmill. The researchers were interested in the percentages of the total step cycle time (i.e., relative time) that would characterize the four components, or phases, of the step cycle at each treadmill speed (i.e., the overall duration parameter). Their hypothesis was that if relative time is invariant for the generalized motor program involved in controlling walking and/or running gait patterns, then the percentages for a specific gait component should remain constant across the different speeds.

The results were consistent with the hypothesis of relative time invariance (see figure 5.5). As gait sped up or slowed down (at least up to 6 km/hr and beyond 8 km/hr), the percentage of time accounted for by each step cycle component remained essentially the same for different speeds. The differences between the relative time characteristics of walking and running are especially notable in the pie charts in the (b) section of figure 5.5. The pie charts show the relative time percentages for the average of the walking speeds and the running speeds for each of the four step cycle phases. Because the relative time percentages differed between walking and running, the authors concluded that two *different* motor programs control walking and running gaits. Within each gait pattern, the overall duration (i.e., speed) parameter could be increased or slowed down while the relative timing among the components of the step cycle was maintained.

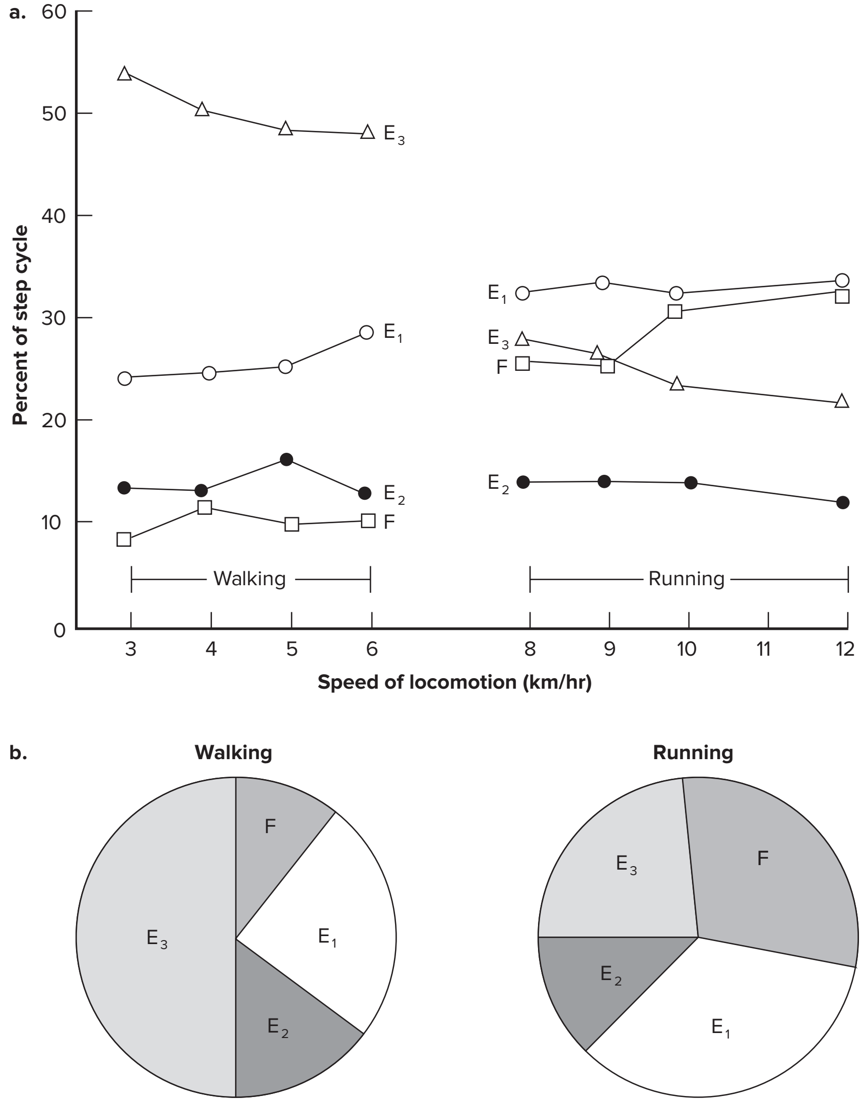

FIGURE 5.5 Results of the experiment by Shapiro et al. (a) The relative time percentage of total step cycle time for each of the four step cycle phases (Phillipson step cycle) at different speeds of walking and running. F = Flexion phase (from toeoff to beginning of knee extension); E_1 = Extension phase 1 (from beginning of knee extension to heelstrike); E_2 = Extension phase 2 (from heelstrike to maximum knee-angle flexion); E_3 = Extension phase 3 (from maximum knee-angle flexion to toeoff). (b) The average (of the four speeds) relative time percentages of total step cycle time for each of the four step cycle phases for walking and running. *Source:* From Shapiro, D. C. et al. (1981). Evidence for generalized motor programs using gait pattern analysis. *Journal of Motor Behavior, 13*, 33–47. 1981, Heldref Publication, Inc. Washington, DC.

A CLOSER LOOK

Two Views about the Source of Relative Time Invariance

Relative time invariance is a common component of both the generalized motor program and dynamical systems views of motor control. However, one of the important differences between these views is the source of the invariance.

- The *generalized motor program view* emphasizes that relative time, as an invariant feature of the GMP, is included in the movement commands sent to the musculature. Because of this, the resulting set of movements that comprise an action is obligated to perform according to this time constraint. Relative time invariance across variations of a parameter is an indicator of a class of movements that are controlled by the same GMP.
- The *dynamical systems view* prefers to use the term "temporal pattern" rather than relative time invariance. Although different with respect to some specific characteristics, temporal pattern is an analogous concept to relative time invariance. More important, the invariance seen in relative time for many actions is an *emergent* characteristic, which is *the result of* the person interacting with characteristics of the task and/or environment, or the mechanical dynamics involved in the body and limb movements. Relative time invariance across variations of a control parameter is an indicator of coordination pattern stability.

Dynamical Systems Theory

In sharp contrast to the motor program–based theory of motor control is an approach commonly referred to as **dynamical systems theory** (sometimes referred to as *dynamic pattern theory, coordination dynamics theory, ecological theory,* and *action theory*). The basis for this theoretical viewpoint is a multidisciplinary perspective involving physics, biology, chemistry, and mathematics. Proponents of this theory see human movement control as a complex system that behaves in ways similar to those of any complex biological or physical system. As a complex system, human motor control is seen from the perspective of *nonlinear dynamics;* this means that behavioral changes over time do not follow a continuous, linear progression, but make sudden abrupt changes. For example, in the physical world, when the temperature of water is increased gradually there is a specific temperature (100°C) at which the water boils; its behavior abruptly changes. This type of change represents a **nonlinear behavior**.

Those who study dynamical systems theory are particularly interested in how a system changes over time from one stable state to another because of the influence of a particular variable. In addition, they are interested in identifying physical and mathematical laws that govern such behavior. Although this approach has been used to model many complex systems in the physical world (see Gleick, 1987), only since the 1980s has it captured the attention of scientists interested in understanding and explaining human movement control.

Nonlinear changes in movement behavior. A series of experiments by Scott Kelso and his colleagues established for movement scientists that a systematic change in the level of one variable can cause a nonlinear behavioral change in human coordinated movement (e.g., Kelso, 1984; Kelso & Scholz, 1985). In these experiments participants began moving their right and left index fingers at a specified rate of speed in one stable coordination state, or pattern, described as an *antiphase* relationship (sometimes referred to as an *out-of-phase* relationship). This means that the muscle groups controlling the right and left fingers were operating simultaneously but in opposite ways: when the right finger was flexed, the left finger was extended, similar to the motion of windshield wipers in some vehicles. Quantitatively, the fingers were 180° out of phase with each other throughout the movement cycle. The participants systematically increased the speed of their finger movements by keeping their finger speed consistent with that of a metronome controlled by the experimenters. The result was that at a specific speed the finger movements spontaneously shifted to a second stable coordination state, or pattern, described as an *in-phase* relationship between the two fingers, where both were flexed or extended at the same time (i.e., 0 or 360° in phase with each other). It's important to note here that the actual speed at which the coordination pattern change will occur varies from person to person. The important point here is that every person will make the change at a certain speed.

You can experience this spontaneous, nonlinear coordination change yourself by making two fists with your hands and putting them on your desk or tabletop so that the little finger side of your fist rests on the desktop. Extend your two index fingers so that they face forward. Then begin to move them side-to-side (keep them parallel to the desktop) in the same way that was done in the Kelso experiment.

The shift to the in-phase coordination state occurred during the *transition* between the stable antiphase and in-phase states. The transition was a mixture of both antiphase and in-phase coordination patterns. But at slower speeds, only an antiphase pattern occurred, whereas at faster speeds, only an in-phase pattern occurred. Thus, a linear increase in movement speed led to a nonlinear change in the fundamental coordination pattern of movement between the two index fingers. That is, no notable coordination pattern changes occur as speed increases within a range from slow to fast and then the pattern change occurs rather abruptly at one specific speed.

When viewed from the perspective of coordination patterns, these experiments established that distinct coordination patterns can *spontaneously* develop as a function of a change in one specific variable; which in this case was movement speed. In the finger-movement task used in the Kelso experiments, the antiphase and in-phase finger-movement relationships represent stable coordination patterns. The importance of these experiments is that they provided an initial step in the investigation of coordination changes that can occur without resorting to a mechanism such as a motor program to specify movement characteristics for each coordination pattern.

These spontaneous coordination pattern changes are not limited to laboratory tasks. They also have been found for motor skills involved in sports and daily activities. For example, front-crawl strokes in swimming exhibit spontaneous arm coordination pattern changes at a specific swimming speed (Seifert, Chollet, & Bardy, 2004; Seifert et al., 2015). Another example is the change from a walking to a running coordination pattern that spontaneously occurs at a specific speed. The experiment by Shapiro et al. (1981), which was discussed earlier in this chapter, was an early demonstration of this spontaneous gait pattern change. Since that experiment, the walk-to-run and, conversely, the run-to-walk gait changes that occur as a function of speed have been demonstrated numerous times and have become the basis for an increasing amount of research (e.g., Abdolvahab & Carello, 2015; Diedrich & Warren, 1995, 1998; Farinatti & Monteiro, 2010; Wagenaar & van Emmerik, 1994). We will discuss this spontaneous gait change phenomenon in more detail in chapter 7.

dynamical systems theory an approach to describing and explaining the control of coordinated movement that emphasizes the role of information in the environment and the dynamic properties of the body and limbs; it is also known as the dynamic pattern theory.

nonlinear behavior a behavior that changes in abrupt, nonlinear ways in response to systematic linear increases in the value of a specific variable (e.g., the change from smooth to turbulent water flow in a tube at a specific increase in water velocity; the change from a walking to a running gait at a specific increase in gait velocity).

A CLOSER LOOK

Spontaneous Coordination Pattern Changes due to Speed in the Front-Crawl Strokes of Elite Swimmers

A change in the arm coordination pattern of the front-crawl stroke in swimming is a sports skill example of the type of spontaneous coordination pattern development originally reported by Kelso (1984) for the finger-movement task. In an experiment in France by Seifert, Chollet, and Bardy (2004), fourteen elite male sprint swimmers performed eight swim trials at a specified distance. The trials began at a speed that was similar to the pace for a 3,000 m distance. On succeeding trials swimmers were required to increase their speed by a specified amount, which was based on paces that would be used for 1,500, 800, 400, 200, 100, and 50 m; the eighth trial was at the swimmers' maximum speed. Arm coordination was quantified for each trial. The analysis of arm coordination revealed *two distinct coordination patterns:* a *catch-up pattern,* in which there was a lag time between the propulsive phases of each arm, and a *relative opposition pattern,* in which the propulsive phase of one arm ended when the propulsive phase of the other arm began. Analysis of the arm strokes showed that all the swimmers used a catch-up pattern during the first trial. But as they increased their swimming speeds on successive trials, there was a critical speed at which they all began to use a relative opposition pattern for their arm strokes.

Stability and Attractors

At the heart of the dynamical systems view is the concept of **stability**. In dynamic terms, stability refers to the behavioral steady state of a system. It is important to note that this use of this term is different from the concept of invariance. As used here, stability incorporates the notion of variability by noting that when a system is slightly perturbed, it will return spontaneously to a stable state.

By observing characteristics of a stable state, scientists can gain understanding of the variables that influence a system to behave as it does. For example, in the reciprocal rhythmic finger movements in the Kelso experiment just described, the researchers observed behavioral stability when the fingers were in antiphase and in-phase relationships with each other. These two stable states indicate two patterns of coordinated movement. Between these states, as finger speed increased, a *phase transition* occurred during which instability characterized the behavioral patterns. The instability continued until finger speed reached a point at which a new stable state spontaneously occurred.

The stable behavioral steady states of systems are known as **attractors** (or *attractor states*). In terms of human coordinated movement, attractors are *preferred behavioral states,* such as the in-phase and antiphase states for rhythmic finger movements in the Kelso experiment. *Attractors represent stable regions of operation around which behavior typically occurs when a system is allowed to operate in its preferred manner.*

Consider two examples of the presence of attractors for common motor skills. When people locomote at a speed of 3 mi/hr (i.e., 4.8 km/hr), the arms and legs are "attracted to" a coordination relationship that produces a walking gait. This gait pattern represents the preferred behavioral state for engaging in a locomotion action at this particular speed. But when people locomote at a speed of 10 mi/hr (16 km/hr), the walking gait is not the preferred locomotion state. At this speed, most people run, which, as you saw in figure 5.5, involves a coordination pattern that is different from a walking gait pattern.

The second example is postural coordination patterns. According to Bardy and his colleagues (e.g., Bardy, Ouiller, Lagarde, & Stoffregen, 2007) there are two stable patterns of postural coordination, as determined by the relationship between the movements of the hips (i.e., the joints that influence trunk movement) and ankles: an in-phase and antiphase pattern. These two patterns are analogous to the rhythmic finger-movement patterns described earlier, which means that the hips and ankles both exhibit flexion in the in-phase pattern, but one joint extends while the other flexes during the antiphase pattern. Each of these patterns characterize standing postural control coordination in situations in which a person is trying to maintain standing balance on an unstable surface, as would occur when you are standing in a moving bus. From a dynamical systems theory perspective, the transition from one coordination pattern to the other (in response to the movement of the bus) occurs automatically and spontaneously because the in-phase and antiphase modes of the postural coordination components (the hips and ankles) establish the "preferred" pattern.

Finally, attractor states are not only stable states of coordinated movement, but also optimally *energy-efficient* states. This means that when a person is moving at a preferred rate or using a preferred coordination pattern, that person uses less energy than he or she would if moving at a nonpreferred rate.

Order and Control Parameters

Proponents of the dynamical systems view place a priority on developing formal nonlinear equations of motion that specify the stability and loss of stability of movement coordination patterns during motor control, learning, and development. To develop these equations, scientists must identify the variables responsible for and associated with coordination. Primary among these variables are **order parameters** (sometimes the term *collective variables* is used). These are variables that define the overall behavior of a system. The order parameters enable a coordinated pattern of movement that can be reproduced and distinguished from other patterns.

Because *order parameters define a movement pattern,* it is essential to identify specific types. The most prominent of the order parameters identified by researchers is *relative phase* for rhythmic movements. Relative phase, which we briefly discussed in chapter 2, refers to a quantified value that represents the movement relationship between two movement segments. For the rhythmic finger-movement task in the Kelso (1984) experiment, the relative phase for the in-phase movement relationship was 360° (which is the same as 0°); the relative phase for the antiphase movement relationship was 180°. These two relative phases were determined by establishing that the maximum adduction of a finger had a phase value of 360° (i.e., 0°), and the maximum abduction had a phase value of 180°. On the basis of a common starting point, the relative phase was then calculated as the difference between the phase values of the two fingers at any point during the movement.

To apply the description from chapter 2 of the calculation of relative phase to this rhythmic finger-movement task, consider the following. For the in-phase movement, both fingers had a common starting point of maximum adduction (i.e., 360°). The fingers moved together to a maximum abduction position (180°) and then returned to the initial maximum adduction position. At any time during the fingers' movement, they had a relative phase of 360°, indicating that both fingers are at the same abduction position. The opposite holds for the antiphase pattern. At any point, the one finger is abducting the same amount as the other is adducting, which means the two fingers have a relative phase of 180°.

Another way to consider this phase relationship is from the perspective of the amount of simultaneous adduction and/or abduction movement. When moving in-phase with each other, both fingers

stability a behavioral steady state of a system that represents a preferred behavioral state and incorporates the notion of invariance by noting that a stable system will spontaneously return to a stable state after it is slightly perturbed.

attractors the stable behavioral steady states of systems. In terms of human coordinated movement, attractors characterize preferred behavioral states, such as the in-phase and antiphase states for rhythmic bimanual finger movements.

order parameters functionally specific variables that define the overall behavior of a system; they enable a coordinated pattern of movement to be reproduced and distinguished from other patterns (e.g., relative phase); known also as collective variables.

abduct or adduct the same amount at the same time; when moving antiphase, both fingers move the same amount simultaneously, but one is adducting while the other is abducting.

The **control parameter** represents the variable that when increased or decreased will influence the stability and character of the order parameter. For example, in the Kelso experiment, movement frequency (i.e., speed) was the control parameter. As the movement frequency was systematically increased by the metronome, the phase relationship between the two fingers underwent distinct changes. That is, the in-phase relationship was maintained (i.e., stable) through several frequencies, but then began to destabilize as frequency continued to increase. During an intermediate period neither an in-phase nor an antiphase relationship was detectable. However, as the frequency continued to increase, there was a critical frequency at which the new antiphase relationship emerged and became stable. The shift from one stable pattern to another stable pattern is known as a *phase transition.*

From an experimental point of view, the control parameter is important to identify because it becomes the basis for assessing the stability of a pattern of coordination and for shifting a pattern of coordination from one stable state to another. From an applied perspective, the control parameter may provide insights into a person's coordination characteristics that might not otherwise be observed.

An example of a situation in which a practitioner could vary the control parameter was reported in a study by van Emmerik and Wagenaar (1996). They demonstrated that Parkinson's disease patients had more difficulty than healthy age-matched control participants in adapting a specific coordination pattern while walking to gradually increasing speeds (i.e., the control parameter) on a treadmill. In this study, the relative phase (i.e., the order parameter) of interest was based on the relationship between the arm and leg swings while walking. The researchers concluded from their results that the assessment of the stability of the phase relationship for the arm and leg swings at various walking speeds provides a sensitive technique to diagnose and detect early stages of Parkinson's disease.

Self-organization. An important element of the dynamical systems perspective is the concept of **self-organization**. This means that when certain conditions characterize a situation, a specific stable pattern of behavior emerges. Many examples of self-organization exist within the physical world that illustrate applications of this concept to the human movement domain. For example, there is no hurricane program in the universe, but hurricanes commonly occur. However, they occur only when certain wind and water temperature conditions exist. When these variables achieve certain characteristics, a hurricane will self-organize in an identifiable pattern that distinguishes it from a tropical depression or any other weather system.

When applied to human movement coordination, the concept of self-organization means that when certain conditions characterize a situation, a specific pattern of limb movement emerges. Thus, rather than being specified by a motor program, the coordinated pattern of movement self-organizes within the framework of the characteristics of environmental conditions, the task demands, and limb dynamics. For example, in the bimanual finger-movement task performed in the Kelso experiments, the in-phase coordination pattern self-organized as a function of the movement speed (i.e., the control parameter). This same type of self-organization is seen for the walk-to-run, or run-to-walk, gait transitions that occur as gait speed increases or decreases and for the arm coordination change that occurs as swim speed increases (see, for example, Seifert, Chollet, & Bardy, 2004).

Coordinative Structures; Muscle Synergies

Another important aspect of the dynamical systems view relates to the unit of behavior that is controlled. Proponents of the view assert that skilled action results when a person's nervous system constrains *functionally specific collections of muscles and joints* to act cooperatively, so that the person can achieve an action goal according to the dictates of the situation. An individual may develop these performance synergies, called **coordinative structures**, through practice or experience, or they may exist naturally.

A CLOSER LOOK

Evidence for Relative Time in Brain Activity and Coordinated Movement

In an excellent discussion comparing and contrasting the motor programming and dynamical systems views of motor control, Kelso (1997) addressed various issues related to relative time, which is a key variable common to both views. One of the issues that motor control researchers have struggled with over the years is determining the relationship between brain activity and observable performance characteristics associated with movement. A possible breakthrough in this struggle appears possible through the use of functional brain imaging technology, which enables researchers to observe brain activity while a person engages in performing a motor skill.

Below are two key findings from research by Kelso and his colleagues in which they used this technology to investigate the issue of relative time. In these experiments, participants performed bimanual coordination skills to produce either in-phase or out-of-phase (antiphase) movement coordination patterns to a signal that specified movement speed, which was systematically increased.

- At low speeds, relative time remained stable (i.e., invariant) across a range of speeds for both in- and out-of-phase coordination patterns.
- Spontaneous transitions from out-of-phase to in-phase coordination patterns occurred (i.e., a new coordination pattern self-organized) at a critical movement speed.

The results indicated that in terms of the relative time characteristic of the patterns, the brain produced essentially the same pattern of activity as the movements produced during the performance of a motor skill. Kelso stated that an important implication of these results for the motor control theory controversy is that the dynamical systems view predicts these results, whereas the motor programming view does not because the motor programming view would regard the patterns as controlled by two independent GMPs, which would not predict a spontaneous transition from one to the other as movement speed increased.

One example of a coordinative structure is the muscles and joints (the degrees of freedom to be controlled) involved in the action of reaching and grasping an object. The groups of muscles and joints that must act together to enable a person to successfully reach and grasp an object are "converted" through practice into a task-specific ensemble.

An analogy here may help. The term "task-specific ensemble" can be thought of as analogous to singing groups, commonly called "ensembles," in which many individuals sing specific parts of a specific song; all the individual singers work together cooperatively (i.e., synergistically) to achieve a specific goal. Similarly, coordinative structures are ensembles of muscles and joints that work cooperatively to allow a person to achieve a specific action goal, such as grasping an object.

For the motor control system the existence of coordinative structures reduces the degrees of freedom that the system must control. Rather than having to control the many degrees of

control parameters coordinated movement control variables (e.g., tempo, or speed, and force) that freely change according to the characteristics of an action situation. Under certain conditions, they can shift a system's behavior from one coordination pattern to another coordination pattern. According to the dynamical systems view of motor control when a control parameter is systematically varied (e.g., speed is increased from slow to fast), an order parameter may remain stable or change its stable state characteristic at a certain level of change of the control parameter.

self-organization the emergence of a specific stable pattern of behavior due to certain conditions characterizing a situation rather than to a specific control mechanism organizing the behavior; for example, in the physical world hurricanes self-organize when certain wind and water temperature conditions exist.

coordinative structures functionally specific collections of muscles and joints that are constrained by the nervous system to act cooperatively to produce an action; sometimes referred to as muscle, or motor, synergies.

The coordination characteristics of hitting a tennis ball provide a good example of a coordinative structure that is acquired as a result of extensive practice.

JUPITERIMAGES/Creatas/Alamy

freedom represented by the many muscles and joints involved in performing an action, the motor control system can control one ensemble of muscles and joints. In this sense, the control system for a specific movement can be less complex than would be suggested by the number of degrees of freedom that need to be controlled. For the reach-and-grasp action the activation of the coordinative structure begins when a person has the intention to reach and grasp a cup and the environmental conditions specify that this action should occur. Then, in accordance with the characteristics of the limb and of the environmental constraints, the coordinative structure self-organizes to carry out the action.

An important behavioral benefit of coordinative structures is that they allow a person to achieve an action goal even when a muscle or joint that is a part of the structure is not able to function normally. For example, if you have a cast on your leg that keeps your knee from bending, you are able to walk up or down the stairs. This is possible because some of the muscles in the ensemble of muscles and joints (i.e., the coordinative structure) associated with walking up and down the stairs will activate in a way that compensates for the lack of involvement by muscles that can't normally function because of the cast. Consider this compensatory activity as similar to what occurs in sports teams when one of the players is not able to perform at his or her best, but the team performs well because players "step up" and perform at a higher level than they typically perform.

Coordinative structures can be intrinsic or developed through practice. *Intrinsic coordinative structures* are involved in actions such as walking, running, and bimanual coordination. When we perform these actions, the muscles and joints of the limbs involved have a natural tendency to demonstrate interlimb coordination patterns that have characterized our performance of them since early in life. For example, when performing a skill involving bimanual coordination, which requires the simultaneous use of both arms and hands, both infants (see, for example, Corbetta & Thelen, 1996) and adults (see Kelso, Southard, & Goodman, 1979, for instance) typically demonstrate a similar natural tendency to move the arms and hands in synchrony—that is, simultaneously both spatially and temporally. This means that when people first learn to perform a tennis serve, which requires each arm to simultaneously move in different ways, their initial tendency is to move their arms in the same way at the same time.

In contrast, *coordinative structures developed through practice* become new combinations of muscles and joints that act together to produce a coordination pattern that will allow the achievement of an action goal. The tennis serve just described is a good example of the development of a new coordinative structure as a result of extensive practice. Another example was described by Seifert, Chollet, and Allard (2004) for swimmers. As front-crawl swimmers achieved elite status, they began to demonstrate a stroke speed and length relationship with breathing frequency that allowed them to adapt to race situation demands more successfully than less skilled swimmers. Similar development of coordinative structures was found for skilled drummers as a result of practicing asymmetric bimanual coordination patterns (Fuji, Kudo, Ohtsuki, & Oda, 2010).

For the learning of certain skills, the intrinsic coordinative structures can lead to initial performance difficulties, as in the case of learning a tennis serve. However, after overcoming these initial difficulties, the person's performance of the skill will benefit from the newly developed coordinative structure, because it will allow him or her to achieve an action goal even though some slight perturbation occurs during the action. For example, if a tennis player is serving, and during the serve a gust of wind makes the ball deviate from its intended path, the player can quickly and easily adjust the movements involved in his or her serving action and achieve a successful serve. Similarly, if a person is jogging on a sidewalk and must step over a curb, the jogger can quickly and easily adjust movement characteristics of his or her gait pattern to avoid tripping while maintaining the jogging coordination pattern.

Perception and action coupling. Proponents of the dynamical systems view emphasize the interaction of the performer and the physical environment in which the skill is performed. From a motor control perspective, this interaction involves perception and movement variables that must be taken into account in any attempt to explain the mechanisms involved in the control of motor skills. The dynamical systems theory proposes that this interaction, which is referred to as **perception-action coupling**, is an essential element in accounting for skillful performance. The perception part of the interaction detects and uses critical invariant information in an environment (e.g., the amount of time until an object contacts the person, or vice versa); the action part involves the setting and regulating of movement control features that enable the person to achieve the action goal (e.g., kinematic and kinetic components of movements).[2]

An example of a perceptual variable involved in this type of coupling process is known by the Greek letter *tau* (τ), which is related to the time to contact between an object and a person's eye. (We will discuss *tau* further in chapters 6 and 8.) Researchers have demonstrated that *tau* guides actions such as steering a car, catching a ball, hitting a ball, jumping from a platform, and performing the long jump (Lee, 2009; Lee et al., 2009). As a person gains experience, the perceptual variable couples with the dynamics of movement so that a distinct coordination pattern can be reproduced and modified as needed.

Some additional examples of perception-action coupling include the coordination pattern people use to get on or over an obstacle, climb stairs, and go through a doorway. Researchers have found that obstacles in a person's pathway, stairs, and door openings specify size-related information that a person perceives in terms of an invariant relationship between an object's size and her or his own leg length (in the case of obstacles and stairs) or

[2]For an excellent discussion of perception-action coupling and its application to sport skill performance, see Buekers, Montagne, and Laurent (1999).

perception-action coupling the spatial and temporal coordination of vision and the hands or feet that enables people to perform eye-hand and eye-foot coordination skills; that is, the coordination of the visual perception of the object and the limb movement required to achieve the action goal.

A CLOSER LOOK

An Example of How Motor Program Theory and Dynamical Systems Theory Differ in Explaining the Motor Control of a Behavior: The Walk-to-Run Gait Change

People spontaneously change from a walk to a run gait pattern at a certain speed of locomotion. Although individuals vary in terms of the actual speed at which this change occurs, the shift appears to be common to all people. The motor program and dynamical systems theories differ in their explanations of why this coordination change occurs.

- **Motor Program Theory** The relative time structure of a coordination pattern distinguishes one generalized motor program from another. Because walking and running gaits are characterized by different relative time structures, they are controlled by different generalized motor programs. The walk-to-run gait pattern change occurs at a certain speed because the person chooses to change from the program that controls walking to the program that controls running.
- **Dynamical Systems Theory** Interlimb and body coordination patterns self-organize as a function of specific control parameter values and environmental conditions. For walking and running gait patterns, speed is a critical control parameter. The walk-to-run gait transition involves a competition between two attractors. At slow speeds, the primary attractor state is a walking coordination pattern. But as walking speed increases, there is a certain range of speeds at which this attractor state loses stability, which means that for this range of speeds, the walking pattern undergoes some change as a running coordination pattern self-organizes and eventually becomes the stable attractor state for gait at a certain speed.

Interpreting the Shapiro et al. (1981) Experiment Results (Figure 5.5)

Motor program theory. Gait is controlled by one generalized motor program when walking gait is observed (3–6 km/hr) and by a different generalized motor program when the running gait is observed (8–12 km/hr).

Dynamical systems theory. The walking and running gaits represent two attractor states that remain stable within the speed ranges of 3–6 km/hr and 10–12 km/hr. But for gait speeds of 7–9 km/hr, the order parameter becomes unstable during a transition period in which a new gait pattern (running) self-organizes and becomes stable for a certain range of speeds.

body size (in the case of door openings). Thus the person will step or climb over the obstacle on the basis of this perceived relationship, choose one of various stair-climbing options, and walk through a doorway sideways or face-forward depending on this perceived relationship between the environmental feature and his or her own body size–related feature. The reciprocal fit between the characteristics of a person and the characteristics of the environment that permit specific actions, such as stairs having the physical characteristics to permit stair climbing, are referred to as **affordances** in the perception-action coupling literature (Gibson, 1979). Learning to detect affordances is central to motor control and learning from this perspective.

A COMPLEMENTARY THEORY: THE OPTIMAL THEORY OF MOTOR LEARNING

For many years, Schmidt's schema theory and the dynamical system theory dominated the discussion about theories of motor learning and motor control. Then, in 2016, Gabrielle Wulf and Rebecca Lewthwaite published a new perspective on these theories by presenting some issues the prevailing theories ignored, namely "(a) conditions that *enhance expectancies* for future performance, (b) variables that influence learners' *autonomy*, and (c) an *external focus of attention* on the intended movement effect" (p. 1382). As such, their theory serves as a complementary theory of motor learning rather than as an alternative theory to the schema and dynamical systems theories. Wulf and Lewthwaite called their theory the "OPTIMAL" theory of motor learning. OPTIMAL is an acronym for "**O**ptimizing **P**erformance **T**hrough **I**ntrinsic **M**otivation and **A**ttention for **L**earning." Wulf and Lewthwaite stated that ". . . motor learning cannot be understood without considering the motivational (e.g., social-cognitive and affective) and attentional influences on behavior" (p. 1383). In the following sections we summarize the primary points of this theory to describe its relationship to motor learning and to both the schema and dynamical systems theories.

Enhanced Expectancies

Wulf and Lewthwaite described "enhanced expectancies" as a person's expectations or expectancies for future performance success in the learning and performance of motor skills. They indicated that the "concept of expectancies . . . refer[s] to a range of forward-directed anticipatory or predictive cognitions or beliefs about what is to occur" (p. 1383). They argued that including this concept in the schema and dynamical systems theories would fill a void in these theories by expressing the importance of this concept's role in the learning and control of motor skills. In the psychological domain, they indicated that expectancies have been discussed as related to the work of Bandura (1977) concerning the concepts of self-efficacy and outcome expectations. More specifically, these concepts relate to influencing motor skill performance through a person's confidence in being capable of accomplishing a specific performance outcome, which is typically influenced by the person's own past performance success, or lack thereof. Further, Wulf and Lewthwaite described research related to phenomena in the performance of motor skills such as "choking under pressure" and "flow states" to link their concept of enhanced expectancies to the learning and performance of motor skills. In addition, in both the schema and dynamical systems theories, augmented feedback plays important roles in skill learning and performance. Similarly, in the OPTIMAL theory augmented feedback is proposed to provide performance-based information that influences expectations of performance achievements. You will learn more about the concept of augmented feedback later in this book (chapter 15).

Autonomy

The concept of "autonomy" in human learning and performance refers to a person being able to exercise control over a situation. Wulf and Lewthwaite incorporated this concept into their theory of motor learning by referring to research that has consistently demonstrated that when people have a choice about certain aspects of their practice and/or performance environment, they are more motivated to perform and typically give more effort to their performance in the situation. Some examples include control over certain characteristics of practice conditions, such as when to receive augmented feedback, or whether they can use an assistive device to help perform a balance task. Wulf and Lewthwaite described some possible explanations for the learning benefits of being able to control practice conditions. For example, researchers have demonstrated that this control led to learners being more actively engaged in the learning process, promoted deeper processing of information relevant to achieving task goals, and increased interest in performing the task being practiced. Each of these learning benefits is consistent with both the schema and dynamical systems theories views of motor learning and motor control, although these theories do not explicitly incorporate the "autonomy" perspective in their theories.

External Focus of Attention

The third primary component of the OPTIMAL theory is the benefit of the learner or performer engaging in an external focus of attention. Although this

affordance the reciprocal fit between the characteristics of a person and the characteristics of the environment that permit a specific action to occur, such as stairs having the physical characteristics to permit stair climbing.

topic will be discussed in more detail in chapter 9 of this book, we will briefly summarize it here to show its relationship to the OPTIMAL theory. An external focus of attention refers to a person actively monitoring environmental or task-related cues rather than body-related cues while performing a motor skill. For example, if a person performs a standing balance task that requires minimizing movements of a moving platform, focusing on the platform would lead to better balance performance than focusing on keeping the feet from moving. Wulf and Lewthwaite discuss this and other examples, which are included in chapter 9 of this book. One of the primary benefits of an external focus of attention is that it promotes non-conscious, or automatic, control of a skill.

THE PRESENT STATE OF THE CONTROL THEORY ISSUE

The motor program–based theory and the dynamical systems theory are the predominant behavioral theories currently addressing how the nervous system produces coordinated movement. Debate and research continue as scientists attempt to answer this important theory question. A benefit of the debate between proponents of these theories is that critical issues have become clarified and future directions more evident. We now know, for example, that a theory of control cannot focus exclusively on the movement information that is specified by the central nervous system. Theorists also must take task and environmental characteristics into account. As we discussed in chapter 1, Newell (1986) stated, the optimal pattern of coordination is determined by the interaction among constraints specified by the person, the environment, and the task.

Opinions vary in terms of the resolution of the motor control theory debate. For example, some researchers foresee a compromise between the two theories, which would lead to the development of a hybrid theory that incorporates the strengths of each theory (e.g., see Abernethy & Sparrow, 1992; Walter, 1998). Some research evidence that suggests the potential for some compromise was reported by Amazeen (2002). In a series of experiments, she demonstrated that the application of specific aspects of a dynamical systems theory to the generalized motor program theory could account for performance characteristics associated with the acquisition of rhythmic bimanual coordination skills that the generalized motor program theory alone could not. However, she left open the possibility that her results could be interpreted as support for only the dynamical systems theory.

Others argue that a hybrid theory is unlikely. For example, Abernethy and Sparrow (1992) speculated that a compromise theory would not emerge because the two theories represent two vastly different approaches to explaining the control of coordinated movement. They reasoned that because of this difference, the history of science would predict that one will eventually become the predominant theory. Kelso (1997) expressed a similar view, but was more specific in his projections. He argued that because many aspects of the motor program view can be subsumed within the dynamical systems theory, especially those related to invariant features and control parameters, and because the dynamical systems theory can explain and predict more of the behavioral features of coordinated movement, the dynamical systems theory will eventually become the predominant theory. However, at this point in time, that predominance has yet to be established.

LAB LINKS

Lab 5 in the Online Learning Center Lab Manual provides you the opportunity to experience the spontaneous, nonlinear change in gait coordination that occurs with increases in gait speed.

SUMMARY

- Motor control theory, like any theory, provides an explanation for why observable phenomena or behavior exist or behave as they do. It also provides the practitioner with a base of support on which to develop effective motor skill instruction and practice environments.

- The term *coordination* refers to the patterning of head, body, and/or limb movements in relation to the patterning of environmental objects and events. When the term *coordination* is used in reference to the movement patterns associated with the performance of a skill, it refers to the relationship among head, body, and/or limbs at a specific point in time during the skill performance.

- For a person to learn to produce a well-coordinated movement that achieves an intended action goal, the motor control system must solve the degrees of freedom problem, which concerns constraining the many degrees of freedom that characterize muscles, joints, and the like. A theory of motor control should provide an explanation of how the motor control system solves this problem.

- Theories of motor control typically incorporate features of open-loop and closed-loop control systems. Both involve a control center, information and effectors. The closed-loop system also includes feedback as part of the system. In an open-loop system, the control center sends the effectors all the movement instructions they need to perform a skill from beginning to end. In contrast, the control center in a closed-loop system sends movement instructions to the effectors that enable them to initiate the performance of a skill; feedback from the effectors and other sources provides the control center with the information needed to give the effectors the instructions to continue and end the movement.

- Motor control theories can be distinguished in terms of the relative importance given to the information specified by central components of the control system or by the environment. Theories that give prominence to information from the control center have in common some form of stored memory representation, such as a motor program, that provides the movement instructions to the effectors. In contrast, theories that give prominence to information specified by the environment emphasize the dynamic interaction of this information with the body, limbs, and nervous system.

- Schmidt's schema theory is the most popular representative of motor program–based theories. It proposes that a generalized motor program (GMP) serves as the central, memory-based mechanism for the control of motor skill performance. The GMP is an abstract representation of a class of movements that is stored in memory and retrieved when a skill involving that class of movements is to be performed. Stored in the GMP are invariant features of the movement class, such as the order of movement events and the relative time of the movement components. When a specific action is to be performed, specific parameter values must be added to the GMP; these include the overall duration of the movement and the muscles that will be used.

- The dynamical systems theory takes issue with the importance motor program theories give to memory-based representations for the control of motor skills. The dynamical systems theory proposes that factors such as environmental invariants and limb dynamics can account for much of the control ascribed to the motor program. The theory views coordinated movement as following rules associated with nonlinear dynamics. The theory incorporates dynamic features such as attractor states, which are preferred, stable patterns that define specific coordination patterns; order parameters, such as relative phase, that functionally define attractor states; and control parameters, such as speed or frequency, that influence the stability and instability of attractor states. Coordinated movement self-organizes as coordinative structures according to the characteristics of the interactions among the person, the environment, and the skill to be performed.

- At present, there are strong proponents of both the motor program and the dynamical systems theories of motor control. Opinions vary in terms of how the current theory debate will be resolved.

POINTS FOR THE PRACTITIONER

- Theories are more than abstract ideas. Good theories provide a foundation on which you should build effective instruction and practice condition environments; good theories also provide a base for creating instruction and practice condition alternatives when those that were planned are not successful.
- A new perspective on the two main theories is called the OPTIMAL theory of motor learning, which is an acronym for **O**ptimizing **P**erformance **T**hrough **I**ntrinsic **M**otivation and **A**ttention for **L**earning. This theory, which serves as a complementary theory of motor learning rather than as an alternative theory to the schema and dynamical systems theories, presents some issues the prevailing theories ignored, namely (a) conditions that *enhance expectancies* for future performance, (b) variables that influence learners' *autonomy*, and (c) an *external focus of attention* on the intended movement effect. People will develop their own strategies to control the number of degrees of freedom involved in the coordination of the limbs, trunk, and/or head when they first try to perform a skill. You should be aware of these strategies and determine whether they need to be changed with practice in order for the learner to improve performance beyond an initial level.
- The relative time invariance of a GMP and the changeable characteristic of the overall duration parameter indicate that when teaching a skill in which a specific rhythm must be performed at a fast speed, the rhythm feature of the skill should be taught first at a slow speed. When the rhythmic pattern has been learned, then the speed of performing the skill can be increased.
- You can assess movement problems and capabilities for functional skills by testing performance characteristics across skill and environment characteristics that can be systematically modified, such as speed or distance, and observing movement changes that accompany these modifications.
- Coordination characteristics observed in people with movement disorders may be optimal because of the constraints imposed on the motor control system by the pathological condition and the environmental conditions in which a skill is performed. As a result, attempts to make adjustments to the coordination characteristics may not be fruitful or desirable.

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STUDY QUESTIONS

1. (a) Describe two characteristics of a good theory in science. (b) How can a good theory in a behavioral science like motor control and learning be useful to a practitioner?
2. Define the term *coordination* and describe how a limb movement displacement graph can portray a coordinated movement pattern.
3. What is the *degrees of freedom problem* as it relates to the study of human motor control and learning?
4. Describe the similarities and the differences between a closed-loop control system and an open-loop control system. For each system, describe a motor skill that could be characterized as having that type of control system.
5. Define a generalized motor program and describe one invariant feature and two parameters proposed to characterize this program.
6. Describe an example of nonlinear changes in human coordinated movement.
7. Define and give an example of the following key terms used in the dynamical systems theory of motor control: (a) stability; (b) attractors; (c) order parameters; (d) control parameters; (e) coordinative structures; and (f) self-organization.
8. Discuss how relative time characteristics of human walking and running gaits are explained by (a) motor program–based theory and (b) dynamical systems theory.
9. Discuss how the OPTIMAL theory views how (a) enhanced expectancies about future performance success, and (b) external focus of attention can influence the learning of motor skills.

Specific Application Problem:

(a) You are working in your chosen profession. Describe a *motor skill* that people with whom you work would need to improve their performance capabilities.

(b) Describe how you would apply concepts from a motor program–based theory and the dynamical systems theory to help you identify the performance problems a person currently has and would need to improve.