

CONCEPT 3.1

The control of coordinated voluntary movement involves open-loop and closed-loop control systems

Key Terms

coordination	perceptual	dynamic
degrees of freedom	trace	systems
open-loop system	memory trace	theory
closed-loop system	schema	coordinative structures
	generalized	
	motor	
	program	

Application

To successfully perform the wide variety of motor skills we experience in everyday life, various muscles and joints must be coordinated to function together. These muscle and joint combinations differ for many skills. Some skills require coordinating muscles and joints of the body and all the limbs, such as a serve in tennis or volleyball. Some skills involve the coordination of the arms, hands, and fingers, as in playing the guitar or typing on a keyboard. Other skills demand the coordination of fewer muscles and joints, as in manipulating a joystick or a simple lever, where only one arm and hand are involved.

In addition to coordination characteristics, there are other movement characteristics involved

in performing skills. Some skills are performed with relatively slow movements, such as positioning a bow before releasing an arrow, or picking up a cup to take a drink from it. Others require fast, ballistic movements, such as throwing a ball or jumping from a bench to the floor. Some motor skills are relatively simple, such as moving a gear-shift from first to second gear or buttoning a shirt, while others are very complex, as in a dance routine or playing the piano.

These different characteristics are important to consider as we look at the control processes involved in carrying out voluntary, coordinated movement to achieve a specific goal. The movements required for an action must be controlled by the nervous system in such a manner to allow the intended goal to be achieved. In the discussion of this concept, you will be introduced to one approach to describing the general components involved in the control process and how the components interact. The approach involves describing movement control by two general models of control systems called open-loop and closed-loop control systems. As you will see as you progress through the study of this chapter, the first concept discussed forms the basis for more specific control components and processes.

Discussion

The discussion of this concept is organized into three parts. First, the term *coordination* is discussed to establish its meaning and why it is an important consideration when studying the control of motor skills. Second, *open-loop* and *closed-loop* control systems are presented as two general models of control systems that are applicable to describing the control of motor skills. Finally, we

will look more closely at proprioceptive feedback as one type of feedback component essential to a closed-loop control system.

Coordination

Defining coordination. When some of the characteristics of skilled motor behavior of experts were described in Concept 2.2, coordination

For example, to walk along a certain pathway people must adapt the pattern of body and limb movements to the characteristics of the surface on which they are walking and to the characteristics of where they are walking. That is, we walk somewhat differently on a concrete sidewalk than we do on a sandy beach. And we walk somewhat differently when walking into a strong head wind than when there is no wind at all. Thus, coordination of skill must be thought of not only in terms of the body and limb movements involved in the skill itself, but also in terms of the environment in which the skill is carried out.

The degrees of freedom problem. Because coordination involves a pattern of body and limb movements, a logical question to ask is, How do we control the many muscles and joints involved in producing that pattern as we perform a skill? To answer this question we must take into account an important problem. This problem has come to be known as the "degrees of freedom problem." The degrees of freedom a system has refers to the number of independent elements or components of the system. The degrees of freedom problem arises when the system needs to be controlled to act in one specific way. Thus, the control problem is, how can an effective yet efficient control system be designed to allow this complex system to be constrained to act in a particular way?

Consider the following mechanical system example of a control problem. A helicopter is designed so that it can fly up or down, left or right, forward or backward, and so on, and at a variety of speeds. There are many different features in the helicopter that need to be controlled to enable it to do all these things. The control problem for the helicopter designer is to make the job of the pilot as simple as possible. If there were one switch or lever for each component involved in the helicopter flying a certain way, the pilot's job would be overwhelming. The designer, therefore, reduces the complexity of the control by allowing the pilot to control all possible helicopter actions with control sticks and pedals the pilot can control

was an important part of several of those characteristics. Skilled motor performance suggests that the performer organizes the muscles of the body in a way that enables him or her to accomplish the goal of the skill in an effective and efficient manner. It is this organizational aspect of the muscles that is at the heart of the definition of the term coordination. For this discussion then, we will define **coordination** as the patterning of body and limb motions relative to the patterning of environmental objects and events, which is a definition provided by Michael Turvey (1990) in an article in the *American Psychologist* about coordination.

You were introduced to the idea that coordination involves a pattern of body and limb motions in the various views of the stages of learning (Concept 2.2). Gentile (1972) emphasized the development of an appropriate pattern of movement as an important goal of the first stage. That is, in order to achieve the goal of a motor skill, a certain pattern of body and/or limb movements will allow for the achievement of that goal better than other patterns. For example, an experiment by Higgins and Spaeth (1972) looked at subjects learning to throw darts at either a stationary or moving target. A distinct pattern of movement emerged with the practice of these skills as described by the displacement characteristics of the three segments of the throwing arm (shoulder to elbow joints, elbow to wrist joints, and hand). Thus, the segments of the arm became organized in a way that established a pattern of motion for successfully performing the skill.

The second part of the definition of coordination may not be so obvious to you: The pattern of limb and body motion is relative to the pattern of environmental objects and events. This is a critical feature of our definition because it addresses the need to consider coordination of motor skill as it relates to the context in which the skill is performed. As discussed in Concept 1.1, motor skills are goal-directed actions. As a result, the movements that comprise these actions may vary according to the constraints imposed on them by the context in which the action is performed.

simultaneously with his or her hands and feet. Thus, several functions can be controlled by one stick or pedal rather than requiring a stick or pedal for each function.

The human body presents a degrees of freedom control problem similar to that of the helicopter. We know that there are 792 muscles in the human body that can act to make the 100 joints behave in different ways. And each joint has mechanical characteristics that define its degrees of freedom for movement. Turvey (1990) put into perspective the control of coordination problem by indicating that if the joints were all only hinge joints like the elbow, there would be 100 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 joints to carry out a specific act, the degrees of freedom would increase to 200. As you can see, the control problem involved in coordination of body and limbs to accomplish a goal-directed action is an enormous one that must be accounted for by any control system model developed to describe motor control processes.

The degrees of freedom problem continues to pose a challenge for motor control theorists. At present, there is considerable debate how this problem is solved by the human motor control system. In the sections that follow, you will be introduced to two general control systems models that provide one of several approaches to dealing with the control problem. The models in themselves do not offer specific solutions to the problem. Instead, they establish the basic framework within which control components can be described that can provide a basis for solving the degrees of freedom problem. These more specific control components involved in these control systems will be described and discussed in the next two concepts of this chapter.

Open-Loop and Closed-Loop Control Systems

To help you better understand how coordinated voluntary movement is controlled, two systems of control can be described that are incorporated into

most current theories of motor control. These two control systems, called **open-loop** and **closed-loop systems**, are based on mechanical engineering models of control. While these two control systems do not provide exact descriptions of control processes involved in controlling complex human movement, they do provide a useful guide for illustrating some of the basic components involved in the control process. Therefore, it will be helpful to view these two control models as elementary descriptions of how the central and peripheral nervous systems initiate action and control ongoing action so that the goal of that action can be achieved. These models will be referred to throughout the discussions in this chapter.

Diagrams illustrating simple open-loop and closed-loop control systems are presented in Figure 3.1-1. These are the typical diagrams you would see in any general presentation of these types of control systems. Notice that in each of these systems is 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 commands to the *effectors*, which are the muscles and joints involved in producing the desired movement. Both control systems also contain *movement commands* that come from the control center and go to the effectors.

These systems differ, however, in two essential ways. The first difference is evident in the diagrams. A closed-loop control system involves *feedback* while 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.

As you look at the closed-loop control system diagrammed in Figure 3.1-1, it is important to be aware that the way the feedback loop is depicted can be misleading. The feedback in the diagram indicates that the source is the muscles producing the movement, because these are the "effectors" that enable the body and limbs to move. But that is only partially correct because feedback may come from *any* of the sensory receptors involved

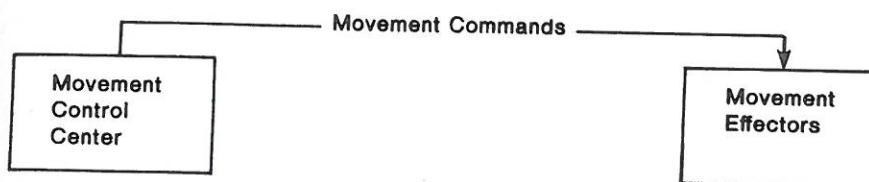
**Open-Loop
Control System****Closed-Loop
Control System**

FIGURE 3.1-1
Diagrams illustrating
the open-loop and
closed-loop control
systems for movement
control.

in the performance of the skill. Thus, visual, auditory, and tactile receptors, as well as proprioceptive receptors may be sources of feedback for the ongoing movement. We will discuss two feedback sources, proprioception and vision, in more detail later in this discussion and in the next concept.

The second important difference between open- and closed-loop control systems is the movement commands issued by the control center. In the open-loop system, the commands contain all the information necessary for the effectors to carry out the planned movement. While feedback is produced and available, it is not used to control the ongoing movement. This may be because feedback is not needed, or there is no time to use feedback to effectively control the movement after it is initiated. In either case, the feedback resulting from a movement may be used to help plan the next response after completing the present one. In the closed-loop system, the movement commands are quite different. First, there is an initial command to the effectors that is sufficient only to initiate the movement. The actual execution and

completion of the movement are dependent on feedback information reaching the control center. In this case, then, feedback is used to help control the ongoing movement as well as to help plan the next response using the same movement.

The question that is the focus of developing an appropriate solution to the control of coordination problems described earlier is, What characterizes the control center, its commands, and the feedback? To answer that question, several issues need to be resolved. For example, there is a need to determine what are the components in the control center and the responsibilities of each component. There is also a need to determine what information is needed by the control center to carry out its responsibilities, and to determine where that information comes from. And there is a need to characterize the movement commands forwarded to the effectors in terms of what information they need from the control center and what information they use from other sources, such as the environment. There is also a need to establish what feedback is needed to provide appropriate control and how that feedback is used and transmitted to

the effectors. We will not attempt to resolve the theoretical conflict that currently exists about the answers to these questions. However, in the discussions of the next two concepts in this chapter, an overview will be provided of some of the solutions proposed to address these specific control problem issues.

Mechanical examples of open- and closed-loop control. There are many machine-type examples of open-loop and closed-loop control all around us. For example, open-loop systems control traffic lights. Each light is programmed to go on at specific time intervals. Traffic conditions will not affect the intervals because the signals are impervious to that type of feedback. The alarm on your clock radio will turn on at the preset time regardless of whether or not you are asleep, want the radio to turn on, or are gone from the house. The only way you can stop this from occurring is by turning off the alarm. Similarly, you can program a video-cassette recorder to tape certain programs from your television even when you are not home. What is common in each of these examples is that commands are programmed in advance. These commands will be carried out as specified without regard to environmental conditions that may actually indicate that it is not necessary to carry out the prepared commands.

A good example of a mechanical closed-loop control system is a thermostat that controls the air-conditioning system in a house. The desired room temperature is set on the thermostat. The setting becomes a reference against which varying room temperatures can be compared. If the temperature is higher than the reference, a command is sent to the air-conditioning unit to turn on and begin cooling the room. If the temperature is lower than this reference, the unit stays off. Thus, continuous "information" is sent from the room, to the thermostat, to the air-conditioning unit, to the room, and back to the thermostat, thereby establishing a constant "loop" of information flow to control the room's temperature in accordance to the specified thermostat temperature. Other examples of mechanical closed-loop control systems

include such things as speed-control sensors included in many stereo turntables and cruise-control systems in automobiles. In each of those examples, feedback is necessary for the mechanism to carry out the desired action.

Relating Open- and Closed-Loop Systems to Movement Control

Because current theories of movement control include both control systems, it will be helpful to consider some examples of how these systems have been incorporated into models or theories of movement control. In this section, we will briefly consider some current theories of movement control that incorporate some type of open- and closed-loop control and that shape current views of how we learn and control motor skills. The first is the closed-loop theory presented by Jack Adams in 1971. The second is the schema theory published by Richard Schmidt in 1975. The third is the dynamic systems view of motor control, which takes issue with both the Adams and Schmidt theories.

Adams' closed-loop theory. The motivation behind Adams' development of a theory of motor learning was what he considered to be an unfortunate lack of a well-defined subject matter and a paradigm on which to base and pursue the study of motor learning. To overcome this problem, he presented his "closed-loop theory" of motor learning (Adams, 1971). Adams' frame of reference for his theory was simple, self-paced, limb-positioning movements. Although Adams felt that this theory could be generalized to include more complex movements, he argued that it was essential to begin the process of theory development for motor learning by focusing on simple skills. He also wanted to develop a theory around existing research literature, which primarily involved the use of simple, limb-positioning movements.

Every closed-loop control system must have a reference mechanism that can be used to assess the status of a movement being made. In Adams' theory, this reference mechanism is called the **perceptual trace**, which is the memory of past movements and is responsible for determining the status

of a movement in progress. It is used by the performer to know where to stop the limb as well as how to adjust another attempt at the same movement. These functions are accomplished by the perceptual trace by comparing feedback about what the movement is currently like with what it is supposed to be like. If there is a perfect match, the command is issued to stop the movement. If error is detected in this comparison, commands are sent to make some adjustments in the movement. How well this comparison and correction process can be accomplished depends on how accurate and well-developed the perceptual trace is at the time.

Essential to the development of the perceptual trace is that it gets stronger, or better developed, as practice of the movement occurs. Adams' view was that an essential part of this development is the availability of knowledge of results (KR), or information about the correctness of a response provided by some external source, such as an experimenter, teacher, or coach. (KR will be discussed in Chapter 7.) As a part of practice, the individual combines KR information with the feedback information received through his or her own sensory system. Eventually, the perceptual trace becomes strong enough for the individual to be able to detect and correct his or her own errors when making the movement. When this occurs, Adams indicates that the individual has moved to a "motor stage" of learning where the movement can be made "automatically."

The open-loop component of Adams' theory is the *memory trace*. While the perceptual trace is used to determine how far the limb should move, the *memory trace* is responsible for getting the limb moving in the first place. Adams proposed that the essential role of the memory trace is to "select and initiate a response, preceding the use of the perceptual trace" (p. 125). This trace is also developed as a result of practice. Different from the perceptual trace, the memory trace was described by Adams as a "modest motor program." That is, it is from this trace that all the necessary information to *initiate* the movement is sent, requiring no feedback.

Thus, according to Adams' theory, controlling a limb-positioning movement involves both open- and closed-loop control processes, despite the theory being called a closed-loop theory. Open-loop control is involved in initiating the movement while closed-loop control is needed for terminating the movement. The degrees of freedom problem is not directly addressed in Adams' theory but it is apparent that the memory and perceptual traces provide necessary control characteristics.

Schmidt's schema theory. Richard Schmidt (1975b) identified limitations in Adams' theory he proposed to overcome by presenting an alternative theory of motor learning and control. Two limitations were that the theory was limited to simple, slow, limb-positioning movements and could therefore not be generalized to other types of motor skills. The theory also did not provide a logical way to establish how people could make a correct response for a movement they had not previously performed in exactly that way, as is common in open motor skills.

To accommodate the limitations in Adams' theory, Schmidt presented his schema theory. A **schema** can be defined as a rule or set of rules that serves to provide the basis for a decision. A schema is developed by abstracting important pieces of information from related experiences and combining them into a type of rule. For example, the formation of your concept of "dog" is the result of seeing many different types of dogs. As a result of your experiences, you have developed a set of rules that will allow you to produce the response "dog" when you are asked to identify the animal that is being shown to you. You may never have seen that particular type of dog before, yet you still can identify it as a dog.

Schmidt proposed two control components that are characterized as abstract-rule based. The first is the **generalized motor program**, which is the general memory representation of the action to be controlled. This program is responsible for controlling a class of actions, such as a throwing or kicking action, or a walking or running action. The

second component is the *motor response schema*, which is responsible for providing the specific rules governing an action in a given situation. Thus, the motor response schema provides situation-specific characteristics to the action controlled by the generalized motor program.

The motor response schema is actually made up of two schemas, each with different responsibilities. First is the *recall schema*, which is responsible for adding specific response characteristics instructions to the motor program and initiating the execution of the intended action. The second schema, called the *recognition schema*, enables the performer to evaluate the correctness of the initiated action by comparing actual sensory feedback against the expected sensory feedback and make movement corrections.

Schmidt's theory did not address the question of how a generalized motor program is developed through learning. However, the theory proposes that for a given class of actions, such as the overhand throw, we abstract different pieces of information from every throwing experience we have that involves an overhand throwing pattern. We then construct schemas that will enable us to successfully use the overhand throw in a variety of situations and circumstances.

The recall and recognition schemas are constructed by abstracting four pieces of information from each movement experience. The first information concerns the *initial conditions* related to performing a skill, which includes things such as the position of the limbs and body, the environmental conditions in which the skill is performed, etc. Second, the performer stores information about the *response specifications*. These are the specific requirements of the action to be performed, such as the direction, speed, force, etc. These specifications must be applied to the motor program before the action can be carried out. Third, the *sensory consequences* of performing the skill are determined. These are acquired by the sensory feedback received from the various sensory systems during and after the movement is actually made. Finally, information is abstracted about the *response outcome*, which is information

related to the comparison of the actual outcome with the intended outcome. These four sources of information are stored to form the schemas responsible for controlling and evaluating movements.

One of the features of the schema theory that generated a great deal of research interest was the problem of accounting for success in performing a novel response within a movement class. That is, how can a person make a response that had not been made in exactly the same way before? Because the motor response schema is an abstract set of rules, Schmidt predicted that the performer can successfully perform a well learned skill in a novel situation. This is done by relating the response requirements of the novel situation to the general rules for performing that action available in the motor response schema. The probability of making a correct response in the novel response situation can be enhanced by increased amounts of practice and variety of practice experiences involving the skill. This practice prediction will be considered in more detail in Chapter 8.

According to Schmidt's schema theory, the degrees of freedom problem is solved by 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. Both open- and closed-loop control systems are involved in controlling coordinated movement. The generalized motor program and recall 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 the action is initiated, feedback can influence its course if there is sufficient time to process the feedback. Thus, for the control of a skill where there is time to use feedback, control is open-loop to initiate it and closed-loop to continue it to completion. However, for rapid, ballistic actions, such as swinging a bat at a ball or throwing a ball, there usually is not sufficient time to use feedback to make necessary movement corrections while the movement is being executed. The movement is completed too quickly

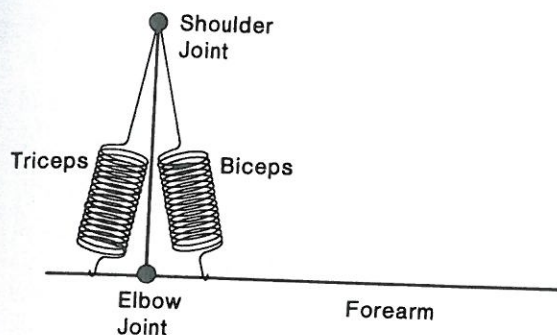


FIGURE 3.1-2 The mass-spring model illustrated by showing the biceps and triceps as springs attached to a mass at one end (forearm) and fixed at the other end (shoulder).

for the feedback-correction command loop to operate effectively. In such cases, Schmidt indicated that the entire movement is controlled by an open-loop system governed also by the motor program and recall schema. Feedback is used in the updating of the motor program and motor response schema.

Dynamic systems theory. An alternative to Adams' and Schmidt's theories of controlling coordinated movement is an approach commonly known as **dynamic systems theory**. Other terms used for this approach are "action theory" or "ecological theory." The key proponents of this view include Peter Kugler, Scott Kelso, Michael Turvey (e.g., Turvey, 1990). The dynamic systems theory approach to describing control of coordinated movement deemphasizes the role of the central command center and emphasizes the role of information in the environment and the dynamic properties of the body and limbs. The key characteristic of this approach to movement control is the interaction between the person and the environment. Perception and action are integrally linked so that control of action involves the setting in motion of specific actions according to the relationship between perceptual information and the motor system.

Rather than propose an executive command center and motor programs, the dynamic systems approach argues that skilled action is controlled by the nervous system constraining functionally-specific collectives of muscles and joints to act cooperatively so that an action can be carried out

according to the dictates of the situation. These functional collectives, called **coordinative structures** or action units, are developed through practice or experience, or may exist naturally. An example would be the muscles and joints (the degrees of freedom to be controlled) involved in the action of reaching and grasping an object. These muscles and joints are constrained to act together as a unit for the specific purpose of reaching and grasping an object. Thus, if a person has the intention to reach and grasp a cup, the coordinative structure involved in that action is organized to carry out that action in accordance to the dictates of the environmental constraints. Rather than the commands for this organization coming from a central executive, the coordinative structure is "self-organized" as a result of the person's intention to perform this action and of the characteristics of the environmental information related to the cup and its location.

An illustration of how this type of control can occur is seen in the mechanical example of a mass-spring system. If a mass is suspended by a spring it returns to an equilibrium point each time it is perturbed based on the mechanical properties of the spring, such as the stiffness, or length-tension ratio. The dynamic systems view argues that a person's arm is analogous to a mass-spring system. Because of this, it is possible to see how the arm could achieve a specific position in space, as is required in a reaching task, regardless of its starting point. As depicted in Figure 3.1-2, the forearm can be thought of as a lever that is attached to a pivot, the elbow. The agonist and antagonist

muscles involved in flexion and extension of the forearm, the biceps and triceps, are represented as springs, attached at one end to the forearm lever (a mass) and fixed at the other end to the shoulder. If a specific limb position must be achieved, the limb will stop at the desired location, regardless of its starting point, because the stiffness of the springs, preset by the movement commands, dictates the final equilibrium, or stopping point for the springs. In this way, the limb moves to its prescribed location in space without the need for sensory feedback to indicate where it should stop.

In this view of movement control, open-loop type control systems are operating. Commands are forwarded from the nervous system to the coordinative structures, prompting the action to occur. However, these commands do not necessarily come from a central executive command center but can come from various sources within and external to the person. These commands also do not necessarily involve specific movement information, as in the mass-spring example. Closed-loop control systems operate in this type of control but their operation is different from that described by the Adams and Schmidt theories. In the dynamic systems view, feedback loops exist within components of the coordinative structures so that adaptations to unique situations can occur. For example, if a person has a pencil in his or her mouth and tries to speak, the coordinative structure related to articulatory control of speech adapts to this situation by providing compensation for the inability of certain muscles to operate normally. This adaptation can occur from short feedback loops within the coordinative structure indicating the need for certain muscles in the collective to compensate for what other muscles cannot do at the time. The feedback does not need to return to a central command center to be operated on so that new movement commands can be forwarded to the musculature.

Feedback and Sensory-Perceptual Systems

A key feature in the distinction between open- and closed-loop control systems is the role played by feedback in the control of an ongoing movement. Because of this, it is important to develop a better understanding of feedback as it relates to movement control. Accordingly, the remainder of this discussion as well as much of the discussion of the next concept are devoted to the role of feedback in controlling coordinated movement.

Feedback is provided by sensory receptors located in various parts of the human body. The process of detecting sensory information is typically termed *sensation*. However, when that information is used or interpreted, the process known as *perception* is involved. However, in this text these two processes are considered closely linked and cannot be logically separated. Thus, when the terms *vision* and *proprioception* are used to refer to feedback, it is important to think of both sensation and perception because both the reception and interpretation of sensory information are involved. Because of this interaction between sensation and perception, we will refer to feedback sources such as vision and proprioception as *sensory-perceptual systems*.

For most motor skills, the most critical sensory receptors for providing feedback are those related to providing proprioceptive and visual information to the central nervous system. In the remainder of this discussion we will focus on proprioceptive feedback and its role in this control process. The focus will shift to the role of vision in the next concept in this chapter. However, before getting into those discussions there is an issue common to the study of both visual and proprioceptive feedback that is important for understanding these feedback systems. This issue, which concerns how well these systems discriminate sensory information, is discussed next.

The sensitivity of vision and proprioception.

An important characteristic of any sensory-perceptual system is what we will call the sensitivity of the system. That is, how easily that system can discriminate one level of intensity of sensory information from another. This characteristic must be taken into account when establishing how feedback is used in the control of voluntary movements.

An example of how this sensitivity question is related to movement control can be seen in the following question. How sensitive, or keen, is vision for judging if two lights are different in their intensity? In perceptual terms, the question becomes: Is one light brighter than the other? This question becomes an important movement control question when a specific action is demanded by different light intensities. The answer to this question must be considered two ways. One is an objective answer to the question because the intensity of the two lights can be objectively measured. However, the other way to answer the question is from the point of view of the person observing the light. While two lights may be measurably different in terms of their intensity, it is possible that a person may not judge them as different. In this case, the concern is how accurately we can make these types of comparison judgments when perceiving sensory information. The same questions relate to the use of proprioception as feedback in making perceptual judgments. For example, consider the question: How much heavier or lighter does a baseball bat need to be before you can tell that it is different from the one you just used?

In the study of perception, these questions are investigated by researchers involved in *psychophysics*, which is the study of the relationship between our objective world and our perception of it. Of particular interest for this discussion is how precisely our visual and proprioceptive system can discriminate differences. The measure that has been developed to indicate the sensitivity of a per-

ceptual system to make these discrimination judgments is called the *just noticeable difference* (*j.n.d.*). The *j.n.d.* is also referred to as the difference limen or difference threshold. The *j.n.d.* can be generally defined as the least amount of change in the intensity of a stimulus that can be correctly detected by the individual. For example, suppose you were given a tennis racket that was strung with 50 lbs. pressure. How much of an increase or decrease in that string weight would it take for you to detect that the new string weight was actually different from the 50 lb. one?

Research has shown that we have rather keen senses of vision and proprioception. For example, if a light has an intensity level of 1,000 photons, we can usually detect a change in intensity with only a 16 photon change in actual brightness (Woodworth & Schlosberg, 1954). For any luminance intensity level within that range, we would typically indicate that the two lights were the same. For proprioception, evidence indicates that people can discriminate between two arm positions if they are greater than 1.25 cm apart (Magill & Parks, 1983). Conversely, if the two positions are within 1.25 cm, it is unlikely that they will be detected as different.

Understanding the characteristics and limitations of proprioceptive feedback used for making perceptual judgments has implications for both movement control and motor skills instruction. For example, the fact that each sensory system has certain perceptual limitations suggests that any understanding of the roles of sensory feedback systems in the control of movement must take these limitations into account. In the Magill and Parks (1983) study, for example, it was demonstrated that we can more precisely discriminate differences between two limb positions in space than we can differences between two movement distances made by the same limb.

In terms of motor skill instruction, implications of understanding the perceptual limits of proprioception can most readily be seen in a situation

where the teacher or therapist must help a person correct a movement error. For example, as the students are working on a gymnastics or dance routine you notice an error in the arm placement of a student in a critical part of the routine. After repeated efforts to correct this problem, the student states that he or she can't seem to correct the problem because it feels like the arm is exactly where you indicated it should be. The problem here may well be an inability to discriminate between the arm position you have shown the student and the actual position of the student's arm during the routine. In this case, your awareness of this possible perceptual limitation can help you realize that correcting the problem will simply require more time than you had thought. Continued practice in making the correction will alleviate the problem.

Proprioceptive Feedback and Controlling Movement

Because the role of feedback is the primary distinguishing feature between open- and closed-loop control systems, it is important to establish the need for feedback in controlling movement. In the following sections, we will consider different experimental approaches that have been followed in attempting to determine the extent to which movement control depends on or does not require proprioceptive feedback. As will become apparent from studying these approaches, the evidence indicates that this is not an either/or issue. While there are situations in which open-loop control can lead to a movement carried out as required, these situations have distinct limitations.

Deafferentation studies. One approach to determining the extent to which proprioceptive feedback is important in controlling movement has been to compare a movement performed under normal conditions with the same movement performed when the proprioceptive feedback is not available. One way to make proprioceptive feedback unavailable is to surgically sever or remove the afferent pathways involved in the movement,

a process called *deafferentation*. Typically, this procedure is used in experiments using monkeys to perform movements.

An early example of using this deafferentation procedure was provided in several experiments by Taub and Berman (1963, 1968). In these experiments, the researchers observed monkeys performing well-developed motor skills, such as climbing, reaching, and grasping, before and after deafferentation of the afferent pathways from the limbs to the CNS. Results of these experiments were consistent in showing that the deafferented monkeys were still capable of performing the skills.

The studies of Taub and Berman considered skills that were well developed in the animals. What would happen if the same deafferentation procedure were used with newly learned skills? This approach was taken by Emilio Bizzi and his colleagues at Massachusetts Institute of Technology (e.g., Bizzi & Polit, 1979; Polit & Bizzi, 1978). In these experiments, monkeys were placed in an apparatus as shown in Figure 3.1-3 and trained to point an arm at one of a series of lights when it came on. The lights were arranged in a semicircle in front of the monkey, who could see the lights but not the arm making the pointing movement. Following training, that is, after the monkeys had learned to accurately point to each light when required, the monkeys were deafferented so that no proprioceptive feedback information from the pointing arm was available during the movement. The monkeys were again placed in the positioning apparatus. Results from these experiments showed that the monkeys were able to accurately position their limbs in the deafferented state. In fact, they were even able to make accurate movements from starting positions that were different from the starting positions used during training. As you may recall, this was one of the predictions made by the mass-spring model discussed earlier.

Deafferenting human subjects for experimental purposes is not possible for obvious reasons. However, Kelso, Holt, and Flatt (1980) reported an experiment that used humans who had no joint

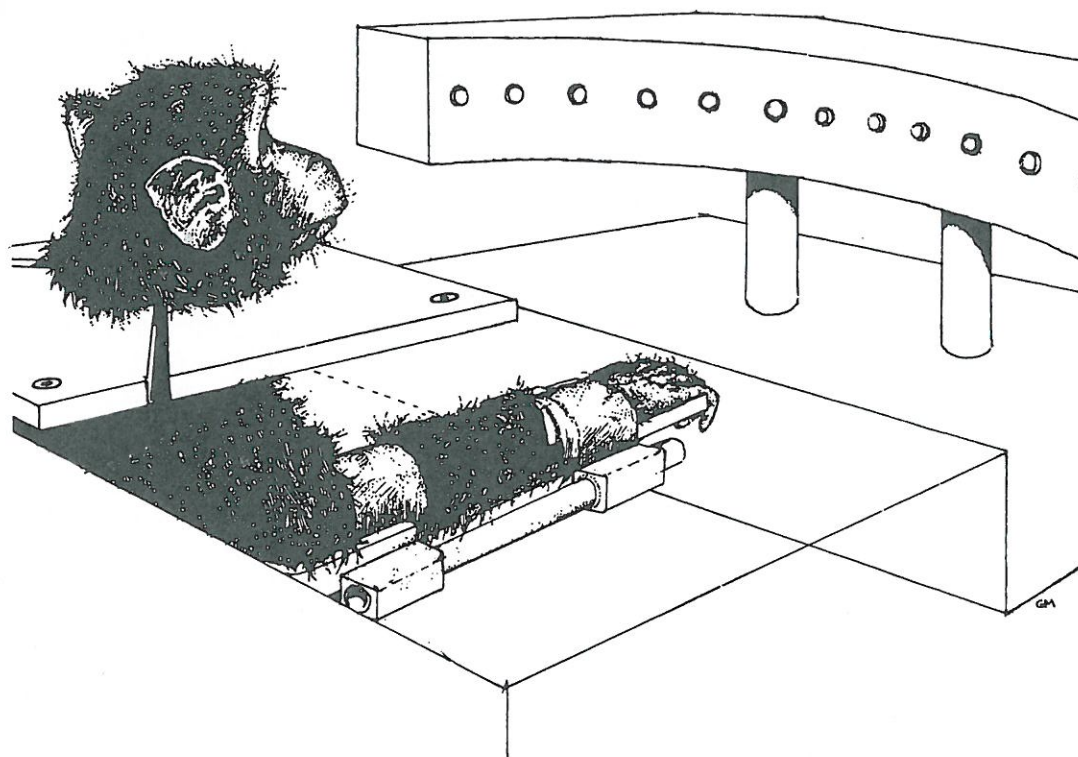


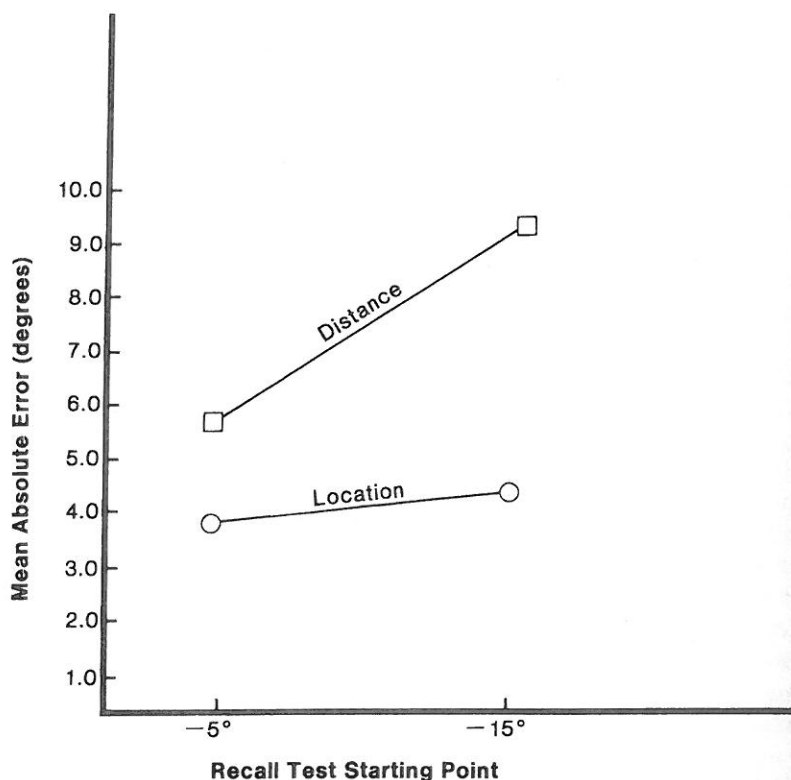
FIGURE 3.1-3 Monkey in the experimental apparatus used in the experiment by Polit and Bizzi. The monkey's arm is strapped to the splint that pivots at the elbow. Target lights are mounted at 5° intervals. During experimental sessions, the monkey could not see its arm and the room was darkened.

receptors available. The subjects in these experiments were rheumatoid arthritis patients who had recently had the metacarpophalangeal joints removed from their fingers. The joints were replaced with flexible silicone rubber implants to hold the bones together. As a result, joint receptors were not available as a source of proprioceptive information during movement. These patients performed positioning responses using a device that allowed only finger movement of a pointer over a protractor graduated in degrees. On each trial, the subjects moved to a specified finger position (the criterion location) or moved through a specified distance (the criterion distance), returned to a new starting point, and then attempted to reproduce the criterion location or

distance. Results, as shown in Figure 3.1-4, indicated the subjects had little difficulty in accurately reproducing the criterion location from a starting point that was either -5° or -15° from the original starting point. However, for reproduction of the movement distance, accuracy was severely influenced by how far the new starting point was from the original starting point.

Results of these studies suggest that limb movements, especially limb-positioning movements, *can* be carried out in the absence of proprioceptive feedback. The control of these movements must therefore be considered to follow an open-loop rather than a closed-loop system, because the lack of proprioceptive feedback did not disrupt the movements. However, this open-loop

FIGURE 3.1-4 Absolute error results from the experiment by Kelso, Holt, and Flatt where finger-joint-replacement patients were asked to reproduce location and distance movements. Recall movements were begun either 5° beyond (-5°) or 15° beyond (-15°) the starting point used for the presentation of the criterion movement.



control was seen as subject to specific limitations. Primary among these is the degree of accuracy possible without feedback in the control process. For example, in the Taub and Berman studies, the monkeys, while portraying climbing, grasping, and reaching responses, were clumsier than they had been before deafferentation. In fact, it was difficult for them to grasp food with their hands in this condition. In the Bizzi experiments, a relatively wide target area was used to indicate a correct pointing response for the monkeys. It is difficult, then, to compare the *precision* of the accuracy responses under the normal and deafferented conditions. In the Kelso, Holt, and Flatt experiments, while a comparison was not made of positioning

accuracy before and after joint-capsule replacement, distance movements were severely disrupted by changing starting positions. Thus, while open-loop control processes could control these movements, movement precision appeared to be enhanced by having proprioceptive feedback available.

Nerve-block studies. An interesting approach was developed by Judith Laszlo and her associates in Australia to try to replicate the animal deafferentation studies using humans but without having to surgically deafferent them. In this procedure, known as a nerve block, a blood pressure cuff is placed just above the subject's elbow and

then inflated until the subject can no longer feel anything with the fingers. Thus, afferent pathways are assumed to be blocked. However, it is important to note that while afferent pathways are inoperable, the efferent pathways remain unaffected. Following the nerve block, subjects were required to produce finger-tapping responses.

Results of several studies by Laszlo (e.g., 1966, 1967) indicated that motor skills could be performed in the absence of afferent sensory information from the muscles and joints of the fingers, hand, and forearm. However, some work by Kelso and others (e.g., Kelso, Stelmach, & Wanamaker, 1974; Kelso, Wallace, Stelmach, & Weitz, 1975) questioned the efficacy of Laszlo's procedures. A particular question has been the validity of the assumption concerning the unaffected condition of efferent pathways using these procedures. To overcome this problem, Kelso (1977) modified Laszlo's procedure by placing a child's blood pressure cuff on the subjects' wrists after the subjects felt no sensation in the fingers. The arm cuff was then removed and the positioning task was performed. Results of these experiments and others (Kelso & Holt, 1980) showed that subjects were able to position their fingers as accurately after the nerve block as they could prior to it. Again, evidence has been provided to show that certain kinds of voluntary movement can accurately be performed without proprioceptive feedback.

Switched-limb studies. Another way to examine the accuracy of limb movement and the involvement of proprioception is to have subjects reproduce a criterion location with the arm that was not used originally to experience or learn the movement. While the rationale behind this procedure was actually developed to test a question related to how we represent movement informa-

tion in memory (to be considered in Chapter 5), the switched-limb procedure can provide some insights into the role of proprioception in movement control.

An example of a study using this approach is by Wallace (1977). Subjects were blindfolded and required to move a lever to a specific location. The subjects were then required to reproduce the movement with either the same or opposite (switched) arm. If the same proprioceptive feedback available when the movement was first produced is not important, then the switched-arm movement should be as accurate as the same-arm movement reproduction. Wallace's results indicated that this was indeed the case as there was no difference between switched- and same-arm movement reproduction.

Recently, however, attempts to replicate Wallace's (1977) findings have not been successful. Reeve and Stelmach (1982), for example, found that reproduction of a series of six limb positions was more accurate when the subjects used the same rather than the opposite arm that was used for presentation of the movements. Magill and Goode (1982) found similar accuracy results when subjects were required to learn to position their arm to within 0.5 cm for three consecutive trials and then reproduce that position with either the practiced (same) or non-practiced (switched) arm (see Figure 3.1–5). However, when all subjects were then asked to move to specified positions and respond whether this position was or was not the learned position, they responded equally well with either limb, as shown in the bar graph on the right of Figure 3.1–5. These results suggest that reasonable or "ball park" accuracy of a learned limb position can be obtained without the same sensory feedback that was available during practice. However, limb-positioning accuracy can be increased when feedback is available.

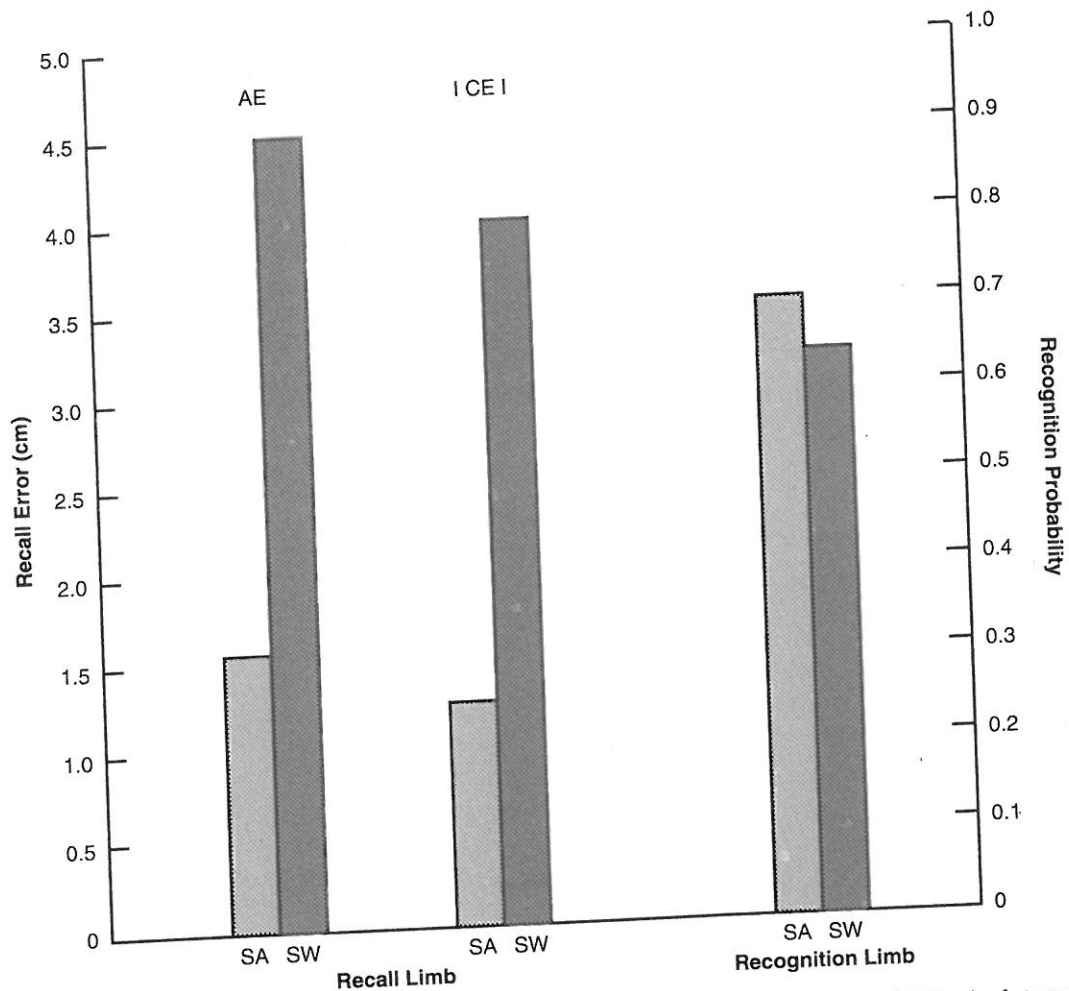


FIGURE 3.1-5 Results of the experiment by Magill and Goode showing absolute error (AE), absolute constant error (CE), and recognition probability for same (SA) and switched (SW) limb for the recall and recognition tests for a practiced limb-positioning movement.

Summary

Controlling movement should be thought of as a process in which coordinated body and limb movement is controlled. Coordination involves a pattern of body and limb movements that permit the person to achieve the goal of a skill in a specific situation. To achieve this goal, the degrees of freedom problem must be solved by the control system so that a specific pattern of movement occurs. Most present day theories of movement control incorporate two simple systems of control,

the open-loop and closed-loop systems. Both of these systems involve a command center, commands, and effectors. However, the closed-loop system operates on the basis of feedback from the different sensory-perceptual systems in the body.

When applied to the control of voluntary movement, these systems are involved in different ways in different theories of movement control. The Adams closed-loop theory views the memory trace as a type of motor program that initiates movement in an open-loop manner. However, the

movement is continued and terminated on the basis of closed-loop control processes involving the perceptual trace as the reference mechanism in the system. Schmidt's schema theory proposes that a generalized motor program provides the basis for controlling an action but requires situation-specific information to be added before the action can be carried out as required. Once the program is prepared, it initiates the action in an open-loop way but soon involves feedback to continue the action. Information specific to initiating and evaluating an ongoing movement is provided by recall and recognition schemas. The dynamic systems view de-emphasizes the role of the central command center and places emphasis on the role of the environment and the dynamics of the limbs and joints. The control of coordinated movement involves controlling coordinative structures that respond to the constraints of the environmental characteristics related to the required action. Commands to these structures can be from various sources within and external to the person. Feedback is involved in controlling movement but does not need to go to a central command center.

Proprioceptive feedback is one of several important sources of feedback involved in movement control. Several different experimental approaches exist for investigating the degree of pro-

prioceptive feedback needed to control movements. These include deafferentation, nerve blocks, and switching limbs. Results of these approaches have shown that certain movements can occur without proprioceptive feedback but the degree of precision in these movements appears to be negatively influenced when feedback is not available.

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