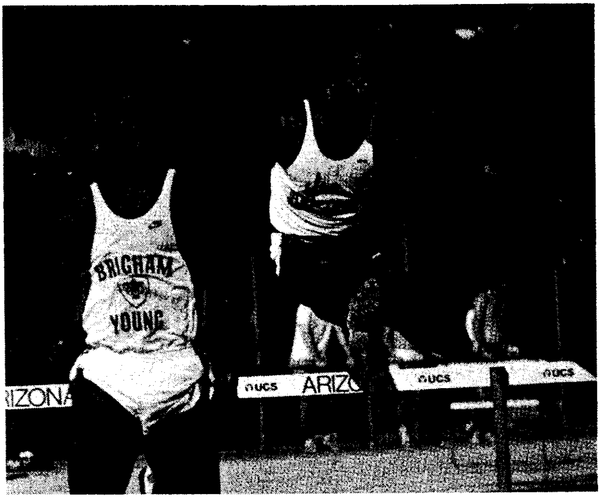
4 Movement Production and Motor Programs



PREVIEW

Watching the high-hurdler go over the barriers in a meet, I am dazzled by the number of separate actions that appear nearly simultaneously. At each hurdle the athlete stretches forward with the lead (right) leg to clear the hurdle, brings the right arm forward, almost touching the toes, moves the left arm backward with the elbow flexed, brings the left leg to the side with the knee sharply flexed to clear the hurdle, and then brings the right leg down sharply to the ground to initiate the next step.

The hurdler executes many identifiable actions in an instant, with correct sequencing and a coordination among them that give the impression of a single, fluid action. How does the skilled athlete produce so many movements so quickly? What controls them, and how are they combined to form a whole movement? We have the impression that these quick movements are organized in advance and are run off without much feedback.

This chapter investigates the idea of open-loop control, introducing the critical concept of the motor program as the structure responsible for this kind of movement control. Then the various reflex pathways discussed in the previous chapter are examined as to their interaction with motor programs, giving a more complete picture of the interplay of central and peripheral contributions to movements. The chapter also focuses on the concept of generalized motor programs, which can account for the common observation that movements can be varied slightly along certain dimensions (e.g., making a fast or a slow pitch).

STUDENT GOALS

1. To become familiar with the concepts of open-loop control for movement
2. To learn the rationale for and characteristics of motor programs
3. To understand how to generalize programs to allow novelty and flexibility
4. To apply the principles of programming to practical performance situations

In many actions, particularly quick ones produced in stable and predictable environments (e.g., diving, hurdling, dart throwing), most people would assume that a performer somehow plans the movement in advance and then triggers it, allowing it to run its course without much modification or awareness of the individual elements. Also, the performer does not seem to have much conscious control over the movement once it is triggered; the movement just seems to "take care of itself." Perhaps this is obvious. Certainly, you cannot have direct, conscious control of the thousands of individual muscle contractions and joint movements, the degrees of freedom, that must be initiated and coordinated as the skilled action is unfolding. There is simply too much going on for the limited-capacity attentional mechanisms to appreciate.

If these individual contractions are not controlled very directly by processes of which you are aware, how then are they controlled and regulated? In many ways, this question is one of the most fundamental to the field of motor behavior because it runs to the heart of how biological systems of all kinds control actions. This chapter focuses on the ways the central nervous system is functionally organized before and during action and how this organization contributes to the control of the unfolding movement. As such, this chapter is a close companion to chapter 3, which considered the ways sensory information contributes to movement production, although without discussing very much about what the sensory information was modifying. This chapter adds the idea of centrally organized commands that sensory information may modify somewhat. First, though, comes the important concept of a **motor program**, which is the prestructured set of movement commands that defines and shapes the movement.

During this discussion of movement production, some of the important questions are these:

- How is it known that some movements are organized in advance?
- Can movements really be controlled without awareness?
- How are many degrees of freedom organized into workable units?
- How can the capabilities for these actions be learned?

MOTOR PROGRAM THEORY

The concept of the motor program, which is central to this whole chapter, is based on a kind of control mechanism that is in some ways the opposite of the closed-loop system described throughout chapter 3. This type of functional organization is open-loop control.

Open-Loop Control

Figure 4.1 is a diagram of a typical **open-loop control** system. It consists of essentially two parts: an executive level and an effector level.

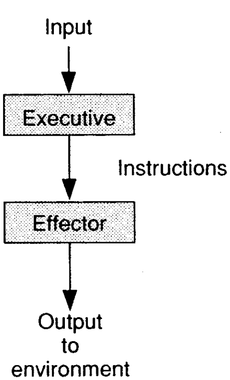


Figure 4.1 Elements of an open-loop control system.

Notice that this open-loop structure has two of the features used in closed-loop control (compare Figure 3.1), but missing are feedback and comparator mechanisms for determining system errors. The system begins with input being given to the executive (or decision-making) level, whose task is to define what action needs to be taken. It passes instructions to the effector level, which is responsible for carrying out these instructions. Once the actions are completed, the system's job is over until the executive is activated again. Of course, without feedback the open-loop system is not sensitive to whether the actions generated in the environment were effective in meeting the goal, and modifications to the action cannot be made while the action is in progress.

This kind of control system is widely used in many different real-world applications, for example, in most traffic signals, where it is effective in sequencing and timing the red, yellow, and green lights that control the traffic flow. If an accident should happen at that intersection, the open-loop system continues to sequence the lights as if nothing were wrong, even though this standard pattern would be ineffective in handling this new, unexpected traffic flow problem. Thus, the open-loop system is effective as long as things go as expected, but it is inflexible in the face of unpredicted changes.

Another example of an open-loop system, which is the basis of the idea of the motor program, is the computer program. In most computers the instructions that form the program tell the machine what operations to do at each step along the way and in what order to do them, and in some cases it specifies the timing of the operations. Although many computer programs are indeed sensitive to feedback, the classical open-loop computer program is not, and the machine follows the instructions to generate various computations without any regard for whether these computations are correct or have met the programmer's goals.

Generally, the characteristics of a purely open-loop control system can be summarized as follows:

- Specific advance instructions give the operations to be done, their sequencing, and their timing.
- Once the program has been initiated, the system sequences through the instructions without modification.
- There is no capability to detect or to correct errors because feedback is not involved anywhere.
- Open-loop systems are most effective in stable, predictable environments where need for modification of commands is low.

Motor Program as an Open-Loop Control System

In a sense, much movement behavior—especially those actions that are quick and forceful, such as kicking and throwing—seem controlled in an open-loop fashion and without much conscious control. The performer in these tasks does not have time to process information about movement errors and must plan the movement properly in the first place. This is quite different from the style of control discussed in the previous chapter, where the movements were slower and strongly based on feedback processes of various kinds.

Open-loop control seems especially important when the environmental situation is predictable and stable, with no changes in

There is little time for corrections here, and the movement needs to be planned and organized correctly from the start.

the environment requiring changes in the planned movement after it has started. Under stable circumstances, human movements appear to be carried out without much possibility of, or need for, modification. This general idea was popularized 100 years ago by the psychologist William James (1890) and has remained as one of the most important ways to understand movement control ever since. The basic open-loop system seen in Figure 4.1, augmented by some of the processes discussed in earlier chapters, gives the general idea of motor program control for movement behavior (see Figure 4.2).

Consider a task such as hitting a pitched baseball. The executive level, which consists of the decision-making stages of the system defined in chapter 2, evaluates the environment in the stimulus-identification stage, processing such information as the speed and direction of the ball. The decision about whether to swing is made in the response-selection stage. The movement is programmed and initiated in the response-programming stage, where details about the swing's speed, trajectory, and timing are determined.

Control is then passed to the effector level for movement execution. The selected motor program is now carrying out the swing movement by delivering commands to the spinal cord, which eventually direct the contraction of the muscles involved in the swing. This movement then influences the environment when the bat contacts the ball.

This view has the motor program as the agent determining which muscles are to contract, in what order, and with what timing. Although the decision-making stages determine what program to initiate and have some role in the eventual form of the movement (e.g., its speed and trajectory), movement execution is not actually controlled by the conscious decision-making stages: Therefore, the movement is carried out by a system that is not under direct conscious control.

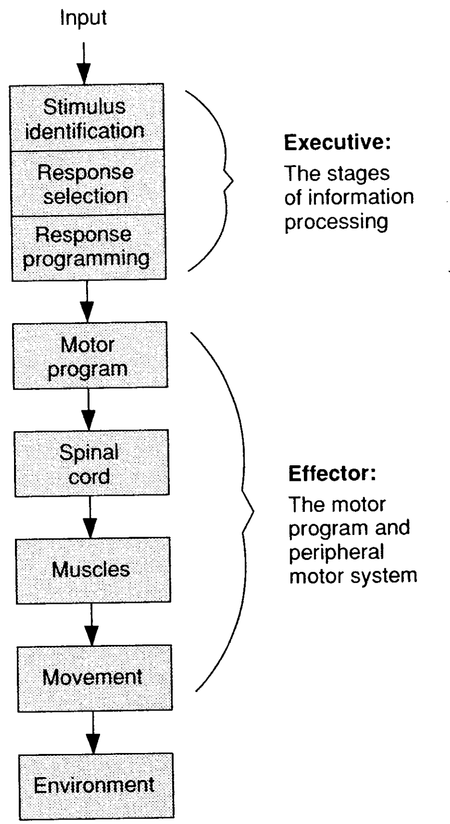


Figure 4.2 An expanded open-loop control system for human performance. The executive level contains the stages of information processing.

Practice leading to learning skilled actions is thought of as building new, more stable, more precise, or longer-operating motor programs. Initially a program might be capable only of controlling a short string of actions. With practice, however, the program becomes more elaborate, capable of controlling longer and longer strings of behavior, perhaps even modulating various reflexive activities that support the overall movement goal. These programs are then stored in long-term memory (see chapter 2) and must be retrieved and prepared for initiation during the response-programming stage (see Figure 2.13).

One major advantage for the performer using motor programs is that various conscious, attentional processes are used less for movement production. One problem for attention discussed in chapter 2 was movement organization and initiation in the bottleneck in the response-programming stage (review Figures 2.9 and 2.10). But if, after continued practice, the programs run longer and control more skilled behavior, then the response-programming stage is involved less often. This frees various attentional processes to perform other higher-order activities, such as monitoring form or style in gymnastics or dance or attending to the strategic elements in tennis.

PRACTICAL APPLICATIONS

1. The quicker an action, the more a learner should be encouraged to plan the movement in advance and produce it as a single unit.
2. In such an action, the learner should be discouraged from trying to intervene in the movement with feedback processes.
3. The more stable and predictable the environment, the more the movement should be organized in advance, produced as a single unit, and feedback-based modulations discouraged.
4. In serial skills, especially where the environment is stable, encourage the learner to combine smaller elements into longer sequences controlled as single units.
5. Encourage the learner to generate longer sequences of elements in order to free attention for other higher-order aspects, such as strategy or style.

OPEN-LOOP CONTROL WITHIN THE CONCEPTUAL MODEL

How does this concept of open-loop control and the motor program fit with the conceptual model of human performance? Figure 4.3 shows the conceptual model used in chapter 3 (Figure 3.9), now with the portions shaded that comprise the open-loop components seen in Figure 4.2. The conceptual model can now be thought of as an open-loop control system with feedback added (not shaded) to produce corrections through the other loops discussed previously. This more complete conceptual model has two basic ways of operating, depending on the task. If the movement is very slow, the control is dominated by the feedback processes. If the movement is very fast, though, then the open-loop portions tend to dominate. Motor behavior is not either open- or closed-loop alone but a complex blend of the two.

For very fast actions, the theory of motor programs is useful because it gives a set of ideas and a vocabulary to talk about a functional organization of the motor system. If a given movement is said to be "a programmed action," it appeared to be organized in advance, triggered more or less as a whole, and carried out without much modification from sensory feedback. This language describes a style of motor control with central movement organization, where movement details are determined by the central nervous system and then sent to the muscles, rather than by peripheral control involving feedback. Of course, both styles of control are

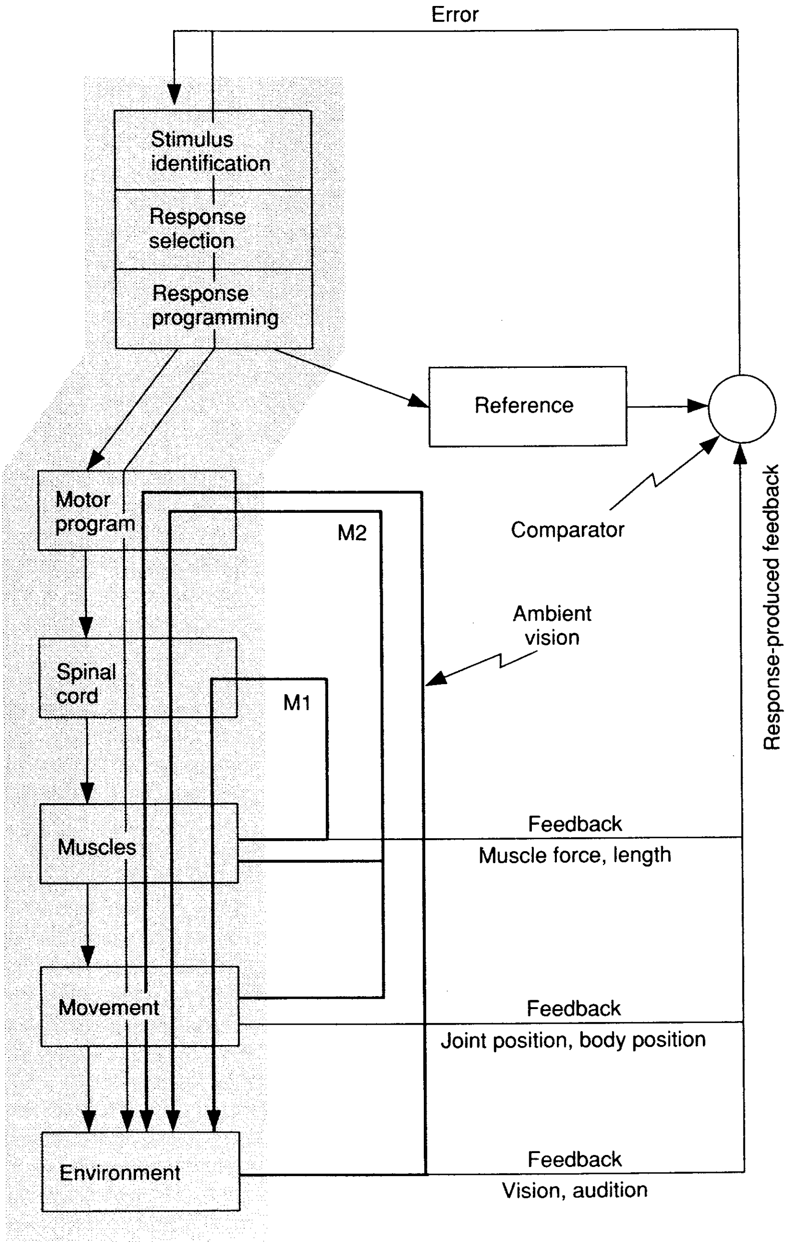


Figure 4.3 The conceptual model of human performance, with the open-loop components highlighted.

possible, depending on the nature of the task, the time involved, and other factors.

Three Lines of Evidence for Motor Programs

Essentially three separate lines of evidence converge to support the theory of motor program control of fast actions. This evidence involves the role of movement complexity for reaction time, experiments on animals with feedback removed, and analysis of electromyographic patterns when the movement is unexpectedly blocked.

Reaction Time and Movement Complexity

When subjects in reaction time situations are asked to respond to a stimulus by initiating and carrying out a predetermined movement as quickly as possible (as discussed in chapter 2), the reaction time depends on the complexity of the *movement* (Henry & Rogers, 1960; see Highlight Box). Recall that reaction time is measured from the presentation of the stimulus until the movement begins, so any added time for the movement itself does not contribute directly to elevated reaction time. However, several features of the movement contribute to its complexity, all of which still affect RT.

- RT increases when additional elements in a series are added to the action: A unidirectional forward stroke in table tennis would likely require a shorter RT than a backswing plus a forward stroke.
- RT increases when more limbs must be coordinated. A one-handed piano chord has a shorter RT than a more complicated two-handed chord.
- RT increases when the duration of the movement becomes longer. A fast swing of a bat taking 100 ms would have a shorter RT than a slower bat movement taking 300 ms.

The interpretation is that when the movement is more complex in any of these ways, reaction time is longer because more time is required to organize the motor system before the initiation of the action. This prior organization occurs, as discussed in chapter 2, in the response-programming stage. The effect on RT by the nature of the movement to be produced is evidence that some of the action is organized in advance, just as a motor program theory expects.

Deafferentation Experiments

Chapter 3 mentioned that sensory information from the muscles, the joints, and the skin are collected together in sensory nerves, which enter the dorsal (back) side of the spinal cord at various levels. A surgical technique termed **deafferentation** involves cutting such an afferent nerve bundle where it enters the cord, so the central nervous system no longer receives information from some portion of the periphery. Sensory information from an entire limb, or even from several limbs, can be eliminated by this procedure.

What are experimental animals capable of when deprived of feedback from the limbs? I have seen films of monkeys with deafferented upper limbs. They are still able to climb around, playfully chase each other, groom, and feed themselves essentially normally. It is indeed difficult to recognize that these animals have a total loss of sensory information from the upper limbs (Taub, 1976; Taub & Berman, 1968). The monkeys are impaired in some ways; they have difficulty in fine finger control, as in picking up a pea or manipulating small objects. On balance, though, it is remarkable how little impaired these animals are in most activities.

HIGHLIGHT

The Henry-Rogers Experiment

One of Franklin Henry's many important contributions was a paper he and Donald Rogers published in 1960. The experiment was simple, as many important experiments are. Subjects responded as quickly as possible to a stimulus by making one of three different kinds of movements. Only one of these movements would be required for a long string of trials, so this was essentially simple RT. The movements, designed to be different in complexity, were (a) a simple finger lift, (b) a simple finger lift plus a reach and grasp for a suspended ball, and (c) a movement requiring a simple finger lift followed by several reversals in direction to targets.

Henry and Rogers then measured the RTs to initiate each of these actions, that is, the interval from the presentation of the stimulus until the beginning of the required movement. They found reaction time increased with added movement complexity. The finger-lift movement (a) had an RT of 150 ms, the grasping movement (b) had an RT of 195 ms, and the movement with two reversals in direction (c) had an RT of 208 ms.

Notice that in each case the stimulus to signal the movement (processed during stimulus identification) and the number of movement choices (response selection) are constant. Thus, because the only factor that varied here was the complexity of the movement, the interpretation was that the elevated RT with movement complexity was caused by increased time for movement programming prior to the action, during the response-programming stage. This notion has had profound effects on the understanding of movement organization processes, and has led to many further research efforts to study these processes more systematically. Most importantly, these data support the idea that movement is organized in advance, which is consistent with the motor program concept.

Sensory information from the moving limb is certainly not absolutely critical for movement production, and it is clear that many movements can occur without it. This evidence suggests that theories of movement control must be generally incorrect if they require sensory information from the responding limb. Because feedback-based theories cannot account for the monkeys' movement capabilities, many theorists have argued that the movements must be organized centrally in motor programs and carried out in an open-loop way, not critically dependent on feedback. In this sense, this deafferentation evidence supports the idea that movements can be organized centrally in motor programs.

This thinking is similar to ideas presented in chapter 3, where some actions were thought to be too fast to allow feedback to be used in their control. For example, in Figure 3.6 a very quick movement is completed before the feedback from that movement can have an effect. Thus, if the movement is quick enough, the motor program controls the entire action; the movement is carried out as though the performer were deprived of feedback. The capability to move quickly thus gives additional support to the idea that there is some central program that handles the movement control, at least until feedback from the movement can begin to have an effect.

Effects of Mechanically Blocking a Limb

A third line of evidence supporting motor program control comes from experiments in which the performer is instructed to make a quick limb action (moving a lever) and the patterns of muscle activity are examined. Figure 4.4 shows an integrated electromyogram (EMG) from a quick elbow-extension movement (Wadman, Denier van der Gon, Geuze, & Mol, 1979). In the normal movement (heavy lines) there is first a burst of the agonist (triceps) muscle, then the triceps turns off and the antagonist muscle (biceps) is activated to decelerate the limb, and finally the agonist comes on again near the end to stabilize it at the target area. This triple-burst pattern is typical of quick movements of this kind.

On some trials the subjects had the movement unexpectedly mechanically blocked by the experimenter so no movement of the lever was possible. Notice what happens to

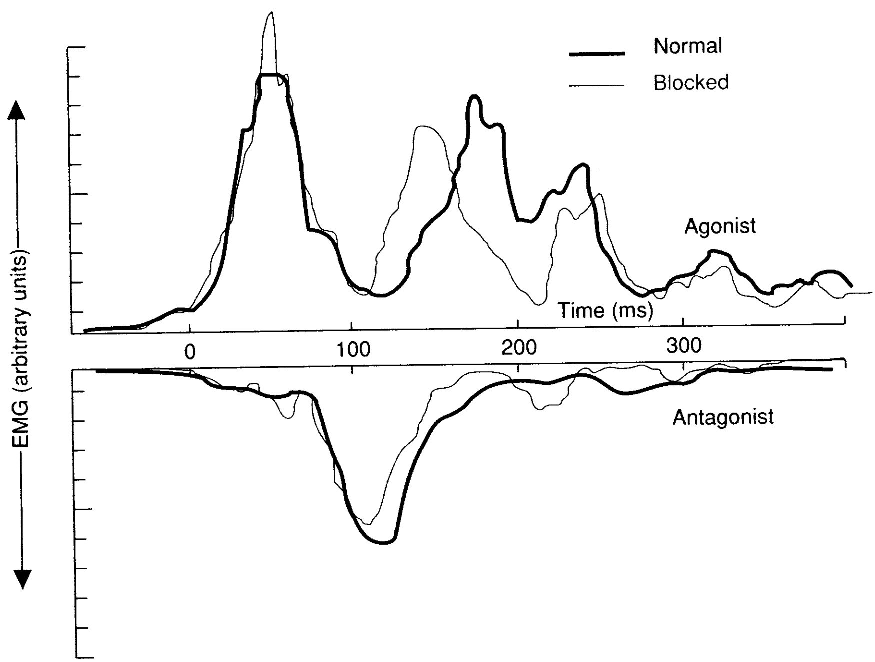


Figure 4.4 Agonist (triceps) and antagonist (biceps) EMG activity in a rapid elbow-extension movement. The lighter traces are from a movement which was mechanically blocked at the outset. (Reprinted from Wadman, Denier van der Gon, Geuze, & Mol, 1979.)

the EMGs (lighter traces). Even though the limb does not move at all, there is a similar initial pattern of muscular organization, with the onset of the agonist and the antagonist occurring about the same times as when the movement was not blocked. Later, after about 120 ms or so, there is a slight modification of the patterning, undoubtedly caused by the reflex activities (e.g., stretch reflexes) discussed in chapter 3. But the most important findings were that the antagonist (biceps) muscle even contracted at all when the movement was blocked and contracted at the same time as in the normal movements.

The feedback from the blocked limb must have been massively disrupted, yet the EMG patterning was essentially normal for 100 ms or so. Therefore, these data contradict theories that feedback from the moving limb (during the action) acts as a signal (a trigger) to activate the antagonist muscle contraction at the proper time. Rather, these findings support the ideas that the movement program organizes EMG activities in advance and that it is run off unmodified by sensory information for 100 to 120 ms, at least until the first reflexive activities can become involved.

Summary ◇ Break

Here are summarized the three most important lines of evidence for the prior organization of movements via motor programs:

1. Reaction time is longer for more complex movements, suggesting organization in response programming prior to action.
2. Movement capabilities of deafferented animals shows that feedback from the limbs is not critical, suggesting central organization of action.
3. EMG patterning in unexpectedly blocked limbs is essentially normal for 120 ms, suggesting that patterning is not dependent on feedback.

How and When Do Programs Contribute to Actions?

Particularly in rapid movement, open-loop control occurs primarily to allow the motor system to organize an entire action without having to rely on the relatively slow information feedback presented under a closed-loop control mode. Skilled performers appear to organize movements in advance to get it right from the beginning rather than having to modify and correct an initially faulty movement as it unfolds. Several processes must be handled by this prior organization. At a minimum, the following must be specified in the programming process in order to generate skilled movements:

- The particular muscles that are to participate in the action
- The order in which these muscles are to be involved
- The forces of the muscle contractions
- The relative timing and sequencing among these contractions
- The duration of each contraction

Most theories of motor programs assume that a movement is organized in advance by the program's setting up some kind of neural mechanism, or network, that contains time and event information. A kind of movement script specifies certain essential details of the movement as it runs off in time. Therefore, scientists speak of performers "running" a motor program, which is clearly analogous to the processes involved in running computer programs.

A particularly useful analogy or model for a motor program is the common phonograph record. The record defines which sounds are to occur and in what order, the durations and timing (rhythm) of those events, and the relative intensities of the sounds. Not every aspect of the movement is specified in the program as it would be on the phonograph record, however, because there could certainly be reflexive activities that modify the final commands, as discussed in chapter 3. But if you conceptualize a motor program as operating more or less like a record, you have the general idea.

PRACTICAL APPLICATIONS

1. To prevent the disruption of the preprogrammed sequence, avoid asking a learner to attend to various aspects of a rapid action.
2. Encourage the learner to let the movement run its course "automatically," let it flow, in order to facilitate the learning of effective open-loop capabilities.
3. In an unstable environment, abandon open-loop strategies in favor of closed-loop control, emphasizing the processing of environmental information during the action.
4. In sport situations involving simple reaction time, have the performer concentrate on the whole action (which facilitates its programming) rather than on the stimulus.

Postural Adjustments Before Action

Imagine standing with your arms at your sides and an experimenter gives you a command to raise an arm quickly to point straight ahead. What will be the first detectable muscular activity associated with this movement? Most would guess that the first contraction would be in the shoulder musculature, but in fact these muscles' activity occurs relatively late in the sequence. Rather, the first muscles to contract, some 80 ms before the first muscle in the shoulder, are in the lower back and legs (Belen'kii, Gurfinkel, & Pal'tsev, 1967).

This order may sound strange, but it is really quite a "smart" way for the motor system to operate. Because the shoulder muscles are mechanically linked to the rest of the body, their contractions influence the positions of the segments connected to the arm—the shoulder and the back. That is, the movement of the arm affects posture. If no compensations in posture were first made, raising the arm would shift the center of gravity forward, causing a slight loss of balance. Therefore, rather than adjust for these effects after the arm movement, the motor system compensates before the movement through "knowing" what postural modifications will soon be needed.

There is good evidence that these preparatory postural adjustments are really just a part of the movement program for making the arm movement (W.A. Lee, 1980). When the arm movement is organized, the motor program contains instructions to adjust the posture in advance as well as the instructions to move the arm, so that the action is a coordinated whole. Thus, do not think of the arm movement and the posture control as separate events but simply as different parts of an integrated action of raising the arm and maintaining balance. Interestingly, these preparatory adjustments vanish when the performer leans against a support because postural adjustments are not then needed.

Central Pattern Generator

The idea of motor programs is very similar to that of the **central pattern generator** (CPG), which was developed to explain certain features of locomotion in animals, swimming in fish, chewing in hamsters, and slithering in snakes (Grillner, 1975). Some genetically defined (inherited) central organization is established in the brainstem or the spinal cord.

When this organization is initiated by a triggering stimulus from the brain, sometimes called a command neuron, it produces rhythmic, oscillating commands to the musculature as if it were defining a sequence of right-left-right activities, such as might serve as the basis of locomotion. These commands occur even if the sensory nerves are cut (deafferented), suggesting that the organization is truly central in origin.

An example of a simple network that could account for the alternating flexor-extensor patterns in locomotion is shown in Figure 4.5. Here, the input signal activates Neuron 1, which activates the flexors as well as Neuron 2. Then Neuron 3 is activated, which activates the extensors. Neuron 4 is then activated, which activates Neuron 1 again, and the process continues. This is, of course, far too simple to account for all of the events in locomotion, but it shows how a collection of single neurons could be connected to each other in the spinal cord to produce an alternating pattern.

The notion of the CPG is almost identical to that of the motor program. The main difference is that the motor program involves learned activities that are centrally controlled (such as kicking and throwing), whereas the CPG involves more genetically defined activities, such as locomotion, chewing, and breathing. In any case, there is good evidence that many genetically defined activities are controlled by CPGs.

Integration of Central and Feedback Control

Although it is clear that central organization of movements is a major source of motor control, it is also very clear that sensory information modifies these commands in several important ways, as seen in the revised conceptual model in Figure 4.3. Thus, the question now becomes how and under what conditions these commands from programs and CPGs interact with sensory information to define the overall movement pattern. This is one of the most important research issues for understanding motor control.

Reflex Reversal. In addition to the various classes of reflexive activities discussed in chapter 3 that can modify the originally programmed output (Figure 3.5), another class

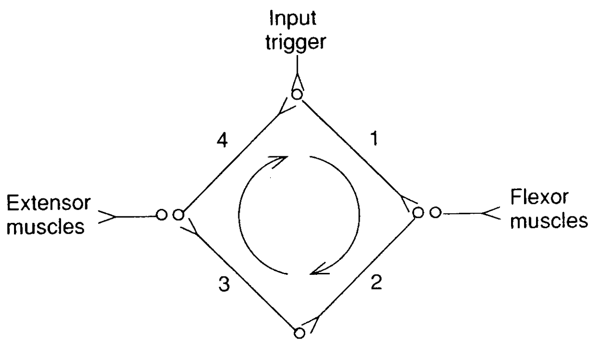


Figure 4.5 A simple network of neurons that could result in alternating flexor and extensor muscle movements in activities like locomotion. Such a network could form the basis of central pattern generators (CPG).

of reflexive modulations has a very different effect on the movement behavior. Several experiments show how reflex activities are integrated with open-loop programmed control. While a cat is walking on a treadmill, the experimenter applies a light tactile stimulus to the top of a foot. This stimulus has different effects when it is presented at different locations in the step cycle. If this stimulus is applied as the cat is just placing its foot on the surface in preparation for load bearing, the response is to extend the leg slightly, as if to carry more load on that foot. This response has a latency of about 30 to 50 ms and is clearly nonconscious and automatic. If exactly the same stimulus is applied when the cat is just lifting the foot from the surface in preparation for the swing phase, the response is very different. The leg flexes upward at the hip and the knee so the foot travels above the usual trajectory in the swing phase.

These alterations in the reflex, reversing its effect from extension to flexion (or vice versa) depending on where in the step cycle the stimulus is applied, has been called the reflex reversal phenomenon (Forssberg, Grillner, & Rossignol, 1975). It challenges our usual conceptualizations of a reflex, usually defined as an automatic, stereotyped, unavoidable response to a given stimulus: Here the same stimulus has generated two different responses.

These variations in response must occur through interactions of sensory pathways and the ongoing movement program for locomotion, the CPG. As just discussed, the CPG is responsible for many of the major events, such as muscle contractions and their timing, that occur in locomotion and other rhythmical activities. In addition, the CPGs are now thought to be involved in the modulation of reflexes, producing the reflex reversal phenomenon. The logic is that the CPG determines whether and when certain reflex pathways can be activated in the action, as diagrammed in Figures 4.6a and b. During the part of the action when the cat's foot is being lifted from the ground (swing phase), the CPG inhibits the extension reflex and enables the flexion reflex (i.e., allows it to be activated). If the stimulus occurs, it is routed to the flexion response, not to the extension response. When the foot is being placed on the ground, the CPG inhibits the flexion reflex and enables the extension reflex. It does this all over again on the next step cycle and so on. Finally, notice that if no stimulus occurs at all, there is no reflex activity at all, and the CPG carries out the action "normally" without the contribution of either reflex.

Enhancing Movement Flexibility. These complex reflex responses are only beginning to be understood, but they undoubtedly play an important role in the flexibility and control of skills. The cat's reflexes are probably organized to have an important survival role. Receiving a tactile stimulus on the top of the foot while it is swinging forward probably means that the foot has struck some object and that the cat will trip if the foot is not lifted quickly over the object. However, if the stimulus is received during the beginning of stance, flexing the leg would cause the animal to fall because it is swinging the other leg at this time. These can be thought of as temporary reflexes in that they exist only in the context of performing a particular part of a particular action, ensuring that the goal is achieved even if a disturbance is encountered.

This feature of a movement program provides considerable flexibility in its operation. First of all, the movement can be carried out as programmed if nothing goes wrong. If something does go wrong, then appropriate reflexes are allowed to participate in the movement to ensure that the goal is met. Also important is the fact that certain reflexes

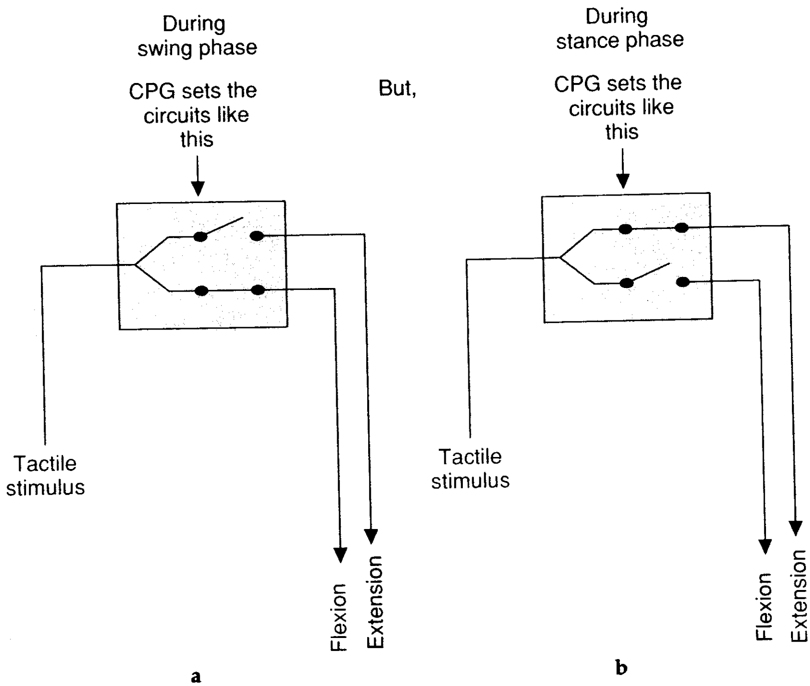


Figure 4.6 In addition to controlling the leg motion during locomotion, the CPG can inhibit or enable flexion and extension reflexes, depending on the phase of the step cycle.

are *not* allowed to participate in a particular action because the motor program has been organized to exclude them, similar to the reduction of the M2 response by instructions to ''let go'' (chapter 3). For example, when the tactile stimulus is presented when the cat has just placed its foot down on the support surface, the leg flexion response is not allowed because it would disrupt the system's goal of providing support for the body while the other leg is in the swing phase.

Analogous findings have been produced in speech, where unexpected tugs on the lip musculature during the production of a sound cause rapid, reflexive modulations, with the actual responses critically dependent on the particular sound being attempted (Abbs, Gracco, & Cole, 1984; Kelso, Tuller, Vatikoitis-Bateson, & Fowler, 1984). The critical goals for the motor system in such situations seems to be to ensure that the intended action is generated and that the environmental goal is achieved.

Here are some important generalizations from this section:

- Fast, nonconscious, reflexlike compensations can be triggered by appropriate stimuli during movements.
- The nature of the response can depend on the location of the stimulus in the movement cycle (reflex reversal phenomenon) or on the overall goal of the movement.

- These reflexes are not permanently structured but are organized only as long as that movement is being produced.
- These reflexes are either enabled or inhibited by the motor program or the CPG.

Motor Programs and the Conceptual Model

Motor programs are a critical part of the conceptual model seen in Figure 4.3, operating within the system, sometimes in conjunction with feedback, to produce flexible skilled actions. The open-loop part of these actions provides the organization, or pattern, that the feedback processes can later modify if necessary. Some of the major roles of these open-loop organizations follow:

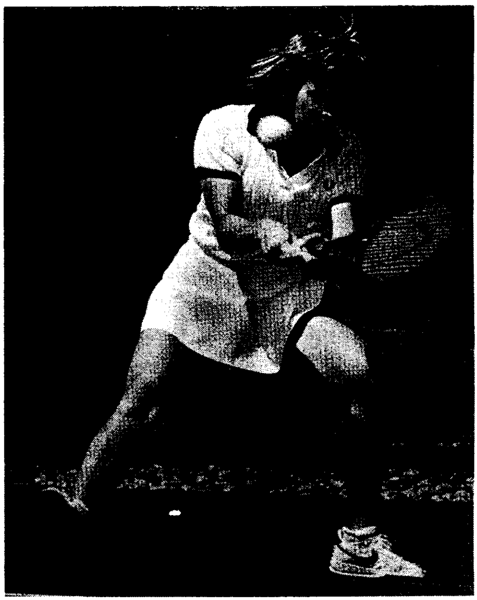
- To define and issue the commands to musculature that determine when, how forcefully, and which muscles are to contract
- To organize the many degrees of freedom of the muscles and joints into a single unit
- To specify and initiate preliminary postural adjustments necessary to support the upcoming action
- To modulate the many reflex pathways to ensure that the movement goal is achieved

GENERALIZED MOTOR PROGRAMS

The theory of motor programs is very useful for understanding the functional organization of certain kinds of movements. However, motor program theory, at least as developed so far in this chapter, does not account for several important aspects of movement behavior. Perhaps its most severe limitations are the failure to account for novel movements and for the performer's capability to produce flexible movement patterns.

How Is a Novel Movement Produced?

When I watch a champion tennis player, I am often struck by the amazing capability to produce actions that appear completely novel. The player may be out of position yet return the opponent's shot acceptably with a shot that is completely unorthodox and almost certainly could never have been practiced previously. Even on any play, given the immense number of possible combinations of ball speed, angle of flight, and overall trajectory, as well as the positions on the court of the player and the opponent, each shot must be considered essentially novel in that it has never been performed exactly that way



Sometimes, skilled players make movements they have never made previously.

HIGHLIGHT

Counterpoint: The Dynamical Perspective

The notion of the motor program is not the only theory to deal with movement control. Several investigators have been critical of the program concept on various grounds and have offered an alternative that is generally termed the Bernstein perspective (after Russian physiologist N.I. Bernstein) or the dynamical perspective (e.g., Bernstein, 1967; Kelso, 1982; Kelso & Kay, 1987; Kugler & Turvey, 1986; Turvey, 1977). These critics argue that the program notion assumes too much organization, neural computation, and direct control by brain and spinal cord mechanisms, so that every movement must have an explicit representation stored in the central nervous system. Also, they argue that the program concept does not consider many features of movement dynamics, such as the springlike properties of contracting muscle and preferred frequencies of oscillation of the limb segments.

Investigators from the dynamical perspective hold that the regularities of movement patterns are not represented in programs but rather emerge naturally (that is, physically) out of the complex interactions among many connected elements. This is analogous to the ways in which many complex physical systems achieve organization and structure without having any central program or set of commands, such as the sudden transformation of still water to rolling patterns as it begins to boil and the organization among molecules to form crystals. Just as it would make little sense to postulate a central program for governing the patterns in boiling water, they argue that it is incorrect to think that complex patterns of human motor activity are controlled by such programs.

There is a healthy scientific debate about these issues at present (see Schmidt, 1988a, for my side), and we will probably not see their resolution very soon. Perhaps some combination of these viewpoints will best explain the nature of movement organization. Even so, thinking of the motor system acting as if it were driven by motor programs helps integrate many different findings into a unified structure.

before. Yet, performers make these novel movements with great style and grace, as if producing well-practiced actions.

This raises problems for the simple motor program theory. Recall that in this view a given movement is represented by a program stored in long-term memory. Therefore, each variation in the movement, associated with variations in the height and speed of the ball, the position of the opponent, the distance to the net, and so on, would need a separate program because the instructions for the musculature would be different for each variation. There is literally a countless number of variations; therefore, according to this view, the performer must have a countless number of motor programs to play tennis. Adding to this the number of movements possible in all other activities, the result would be a very large number of programs stored in long-term memory. This leads to what has been called the **storage problem** (Schmidt, 1975, 1988b), which concerns how all of these separate programs could be stored in memory.

There is also the **novelty problem**. Try this: From a standing position, jump up and turn one-quarter turn to the left, touching your head with your right hand and your leg with your left hand while in the air. You have probably never done this movement before, yet you can probably perform it effectively on the first try. Where did the specific program for this action come from? You could not have learned it because you have never practiced this movement. And it is not likely that it was genetically determined because such a movement would have little biological significance in evolution, unlike locomotion or chewing, for example. Motor program theory is at a loss to explain the performance of such novel things.

To summarize, these observations raise two problems for understanding everyday movement behavior:

1. Storage: How (or where) do humans store the nearly countless number of motor programs needed for future use?
2. Novelty: How do performers produce truly novel behavior that cannot be represented in an already stored motor program?

How Can Motor Program Output Be Modulated?

These problems for program theory have motivated a search for alternative ways to understand motor control. There was a desire to keep the appealing parts of motor program theory but to modify them to solve the storage and novelty problems. The idea that emerged in the 1970s was that movement programs can be generalized. The **generalized motor program** consists of a stored pattern, as before. However, this pattern can be modulated slightly when the program is executed, allowing the movement to be adjusted to meet the altered environmental demands.

Over a half century ago, the British psychologist Sir Fredrick Bartlett (1932) wrote about tennis,

> When I make the stroke, I do not . . . produce something absolutely new, and I never repeat something old. (p. 202)

The first part of his statement means that even though a movement is in some sense novel, it is never totally brand new. Each of his groundstrokes resembles quite strongly his other groundstrokes, possessing his own style of hitting a tennis ball (you can probably very easily pick out your favorite sports performer from a film because of his or her unique patterns). The second part of Bartlett's statement conveys the idea discussed in the previous section, that every movement is novel in that it had never been performed exactly that way before.

Variation in Movement Time

What are some of these features that seem to carry over from movement to movement, even though many of the details of the action are different? There are many, but a very important start in answering this question was made by Armstrong (1970) in analyzing the patterns of movements that subjects made in one of his experiments. In Armstrong's experiment learners attempted to produce a pattern of movement at the elbow joint that was defined as a space-time pattern, as graphed in Figure 4.7. The goal movement (solid line) had four major reversals in direc-

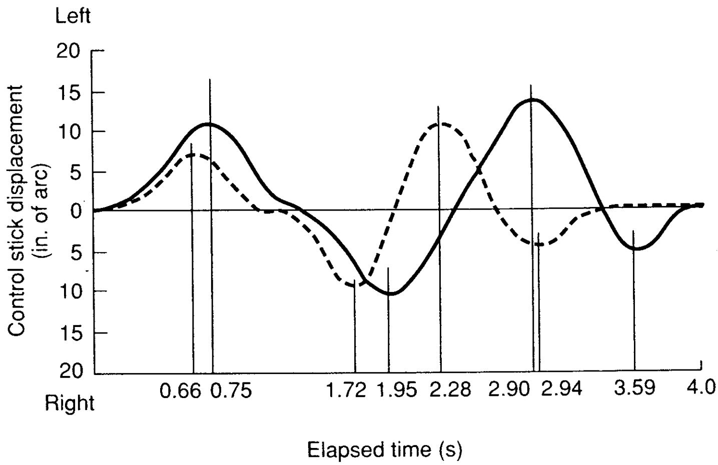


Figure 4.7 The position-time record of performance in an arm movement task. The solid trace is the goal move, whereas a movement that is uniformly too rapid is shown in the dotted trace. (Adapted by permission from Armstrong, 1970.)

tion, each of which was to be produced at a particular time in the action, with the total movement occupying about 4 s.

Armstrong noticed that when the learner made the first reversal movement too quickly (dotted trace), the whole movement was done too quickly. Notice that the graph's first peak (at reversal) was just a little early, with the other timing errors increasing as the movement progressed. This gives the impression that every aspect of the movement pattern was produced essentially correctly but that the entire pattern was simply run off too quickly.

Another way to think of this relationship is this: If you drew the dotted trace on a rubber sheet and stretched the sheet so the final peak lined up with the final peak of the solid trace, then all the other peaks would line up with their respective peaks, too. This aspect of movement control is consistent with the phonograph record analogy of movement programs discussed earlier, where the various features of the action (the left-right-left pattern) were programmed on the record. However, there is an important modification: In this case the record has been played too fast, as if the speed of the turntable were accidentally too great. This also agrees with the common experience that we seem to have no trouble speeding up and slowing down a given movement, such as throwing a ball at various speeds.

This indicates that when the movement time is changed, the new movement preserves the essential pattern features of the old movement. Therefore, both movements are represented by a common underlying temporal (and sequential) pattern that can be run off at different speeds.

Variation in Movement Amplitude

The amplitude of movements can also be modulated easily in a way much like varying the time. For example, you can write your signature either on a check or five times as large on a blackboard, and in each case the signature is clearly yours (Merton, 1972). Making this size change seems almost trivially easy. Similarly, the football quarterback throws passes of various distances, which seem to differ mainly in amplitude (and/or speed) of a fundamental throwing action.

The handwriting phenomenon was studied more formally by Hollerbach (1978), who had subjects write the word *hell* in different sizes and measured the accelerations of the pen produced by the forces exerted by the fingers during the production of the word. These accelerations are graphed in Figure 4.8, where a trace moving upward indicates acceleration away from the body and a downward trace indicates acceleration toward the body. Of course, when the word is written larger the overall magnitude of the accelerations produced must be larger, seen as the uniformly larger amplitudes for the larger word. But what is of most interest is that the patterns of acceleration over time are almost identical for the two words, with the accelerations having similar modulations in upward and downward fluctuations.

This leads to an observation similar to the one just made about movement time. Movements can easily be increased in amplitude by uniformly increasing the accelerations (forces) applied while preserving their temporal patterning. Therefore, two words written with different amplitudes are based on a common underlying structure that can be run off with different forces to produce movements of different sizes.

Variation in Limb Used

A performer can also modulate a movement by using a different limb to produce the action. In the signature example, writing on a blackboard involves very different muscles and joints than writing on a check. In blackboard writing the fingers are mainly fixed, and the writing is done with the muscles controlling the elbow and the shoulder. In check writing the elbow and the shoulder are mainly fixed, and the writing is done with

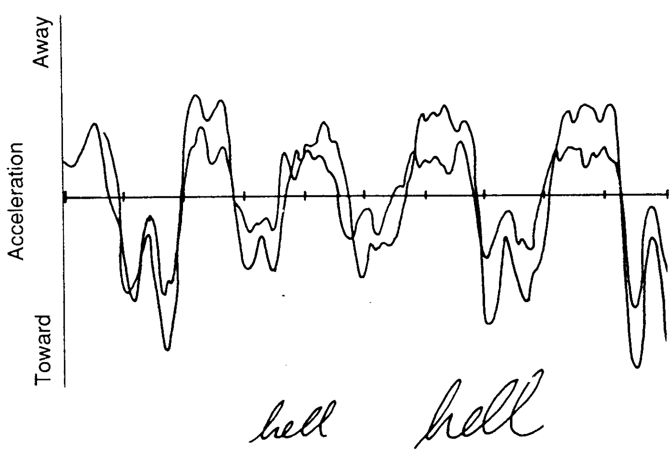


Figure 4.8 Similar patterns of acceleration produced during the writing of the word *hell*, even though one example has twice the amplitude of the other. (Adapted by permission from Hollerbach, 1978.)

the muscles controlling the fingers. Yet, the writing patterns produced are essentially the same. This indicates that a given pattern can be produced even by varying the limb and muscles used as the effector.

These phenomena were studied by Raibert (1977), who wrote the sentence "Able was I ere I saw Elba" (a palindrome, spelled the same way backward as forward) with different muscles. In Figure 4.9, Line A shows his writing with the right (dominant) hand, Line B with the right arm with the wrist immobilized, and Line C with the left hand. These patterns are very similar. Even more remarkable is that Line D was written with the pen gripped in the teeth, and Line E with the pen taped to the foot! There are obvious similarities among the writing styles, and it seems clear that the same person wrote each of them, yet the effector system was completely different for each.

This all indicates that changing the limb and effector system can relatively easily preserve the essential features of the movement pattern. There is some underlying temporal structure common to these actions, which can be run off with different effector systems.

Summary ◇ Break

There are many more examples that could be mentioned, all of which point to the same general ideas, summarized in the following points:

- Movements can be modified along several dimensions, such as the movement time, the movement amplitude, and the limbs or effector system used for movement production.
- Such modifications seem very easy, suggesting that the novel organization is somehow already available to the performer.
- Even though these changes create differ-

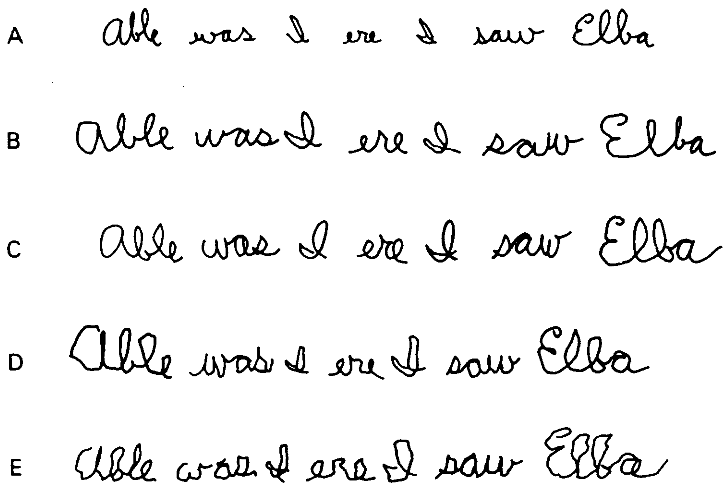


Figure 4.9 Similarities in writing with different effector systems. Line A was written by the right (dominant) hand, Line B with the wrist immobilized, Line C with the left hand, Line D with pen gripped in the teeth, and Line E with pen taped to the foot. (Reprinted by permission from Raibert, 1977.)

ent movements, the underlying temporal pattern can remain remarkably consistent.
- The temporal regularity implies a single underlying structure that can be run off in different ways to modulate movement output.

Identifying Movement Parameters

The theory of generalized motor programs holds that these various movement modulations represent relatively superficial, or surface, features of the movement. The speed of a baseball throw and the spoken volume of a word involve superficial variations of a fundamental pattern. These surface features are specified by quantities called parameters.

Movements are thought to be produced as follows. Based on sensory information processed in the stimulus-identification stage, a generalized motor program for, say, throwing (as opposed to kicking) is chosen during the response-selection stage. This generalized motor program is then retrieved from long-term memory storage, much the same as you retrieve your friend's telephone number from memory. During the response-programming stage, the motor program is prepared for initiation.

One of the necessary processes here is to define how to execute this program. Which limb to use, how fast to throw, and how far to throw must be decided upon, based on the environmental information available just prior to action. These decisions result in the assignment of a few **parameters**, characteristics that define the nature of the program's execution without influencing the overall temporal pattern of movement production. Some parameters include the speed of movement, its amplitude, and the limb used. Once the parameters have been selected and assigned to the program, the movement can be initiated and carried out with this particular set of surface features.

PRACTICAL APPLICATIONS

1. Stress that the learner can easily modify an already learned movement pattern to meet many new movement goals, without having to learn a new movement pattern.
2. Try having the learner speed up or slow down a given movement to reinforce the idea of movement flexibility.
3. Have the learner shorten the overall amplitude of the golf swing to produce a swing suitable for very short shots.
4. Make the learner aware of the relationship between the amplitude or speed of the action and the outcome in the environment.
5. Knowing the relationship between parameters and outcome is useful for determining movement speed values for future movements.

To summarize, quick movements are organized in several steps:

1. Processes in the response-selection stage, based on sensory information, define which movement must be made (throw or kick).
2. The generalized motor program for the chosen action is retrieved from long-term memory.
3. Parameters are specified and assigned to the program in the response-programming stage, and the movement is readied for initiation.
4. The movement is executed according to a relatively rigid temporal pattern,

with surface features tailored to meet specific environmental demands.

CHAPTER SUMMARY

In a person's most rapid actions, where there is no time for the system to process feedback about errors and correct them, a movement is organized in an open-loop fashion—planned in advance and executed with minimal involvement of sensory information. The structure that supposedly carries out this action is the motor program. Several lines of experimental evidence argue for such programs: Reaction time is longer for more complex movements, animals deprived of sensory information by deafferentation are capable of relatively effective movement, and a limb's muscular activity patterns are unaffected for 100 to 120 ms when the limb is unexpectedly mechanically blocked.

Even though the motor program is responsible for the major events in the movement pattern, there is considerable interaction with sensory processes, such as the organization of various reflex processes to generate rapid corrections, making the movement flexible in the face of changing environmental demands. Finally, motor programs are thought to be generalized to account for a class of actions (such as throwing), and parameters must be supplied to define the way in which the pattern is to be executed (such as either rapidly or slowly).

Checking Your Understanding

1. What are the major elements in an open-loop system? Describe the differences between this and closed-loop systems (discussed in chapter 3).
2. Summarize the three lines of evidence for the existence of motor programs.
3. What are reflex reversals? How does the phenomenon tell us about the interaction of open-loop and closed-loop control?
4. How do humans produce novel movements? Are such movements really novel? Explain.
5. What is a generalized motor program? Explain how this idea accounts for the production of movements tailored to environmental demands.

Key Terms

Definitions of the following terms appear on the page(s) shown in parentheses:

central pattern generator (p. 88)
deafferentation (p. 84)
generalized motor program (p. 94)
motor program (p. 78)
novelty problem (p. 94)
open-loop control (p. 79)
parameters (p. 98)
storage problem (p. 94)

Suggestions for Further Reading

Further reading about the evidence for motor programs in humans can be found in Schmidt (1988b, chapter 7), and a treatment of the central pattern generator concept in animals has been contributed by Grillner (1975). Taub (1976) provides a good review of the literature on deafferentation and movement performance. An early discussion of the role of parameters for motor programs is available in Keele (1981) and Schmidt (1975), and a more modern treatment can be found in Schmidt (1988b, chapter 6). A readable account of the dynamical perspective as a rival to the motor program view can be found in Kelso (1982, chapters 10, 11, and 12); a recent treatment of this approach can be found in Jeka and Kelso (1989) and Kugler (1988).