an effector level (motor programs and muscular system) for actually controlling or producing the patterns as they unfold. We can further distinguish these two levels by examining two distinct types of errors that can occur in performance, which we describe later in the chapter.

Motor Program Issues

So far we have discussed three lines of evidence that provide support for the notion of motor programs. First, feedback processing is slow, so that at least rapid movements will be completed before the feedback can be returned to the stages of processing and a correction determined and initiated. Some central structure seems to be handling the details of the movement in the meantime. Patterns of EMGs were unaffected for 100–150 ms after an unexpected mechanical block of the movement, supporting the view that at least this portion of the movement was controlled by central programming. Second, movements appear to be planned in advance, as evidenced by the fact that RTs increase with movement "complexity," suggesting that a response-programming stage requires more time to plan as complexity increases. Third, deafferentation studies showed that movement is possible (although degraded somewhat depending on the type of behavior) in the absence of feedback from the moving limb, implying that some central mechanism was at least partly responsible for movement organization and control.

These arguments have led to the idea of a motor program as a prestructured set of central commands capable of carrying out movement essentially open-loop. According to the original notion, which dates back to thinking by James (1890) and Lashley (1917), and more recently to Henry and Rogers (1960), Keele (1968), Schmidt (1976a), and Brooks (1979), movements are centrally structured with only a very minimal role for sensory information in movement control, at least until sufficient time has elapsed that the central information-processing mechanisms can generate and initiate modifications. An early and very clear implication for an open-loop central control mechanism was suggested by Lashley when he said that "an effector mechanism can be pre-set or primed to discharge at a given intensity or for a given duration, in independence of any sensory signals" (p. 123). Although Lashley did not use the term "motor program," this quote serves as a suitable definition for an extreme view of the concept (see also Keele, 1968).

We have already presented evidence, however, that such a view can explain only a limited set of movement situations, as many examples can be cited in which feedback processes seem to interact with open-loop processes in the production of movement. A more reasonable approach to motor programming is to ask *how* the sensory processes operate together with the open-loop processes to produce skilled actions.

Sensory Information and Motor Programs

The next sections deal with various functions of feedback in movement control. These functions operate before a movement, during a movement, and after a movement.

Prior to the Movement

One of the major roles of sensory information is probably to provide information about the initial state of the motor system prior to the action. Consider this simple example: you must know whether you are standing with your left or right foot forward in order to initiate a walking pattern (Keele, 1973). The spinal frog (figure 6.7) requires sensory information from the forelimb in order to direct the hindlimb to the elbow during the wiping response. Such information is presumably provided by afferent feedback from the various proprioceptors, and it would seem to be critical for the selection of the proper action. These processes were argued in chapters 2 and 3 to be very important for open skills, for which the nature of the environment is unpredictable or constantly changing.

Polit and Bizzi (1979), using deafferented monkeys, showed that when the initial position of the shoulder changed prior to the elbow action, a systematic error in pointing to the target position occurred. This is understandable from figure 6.11, because changing the shoulder angle as shown necessarily affects the *elbow angle* (from θ_1 to θ_2) required for pointing at a target in a given position in space. If the monkey programmed a given elbow angle, then the *equilibrium-point mechanism* (chapter 7) would achieve that angle, and the arm would not be pointing to the proper target. These monkeys did not learn to point to
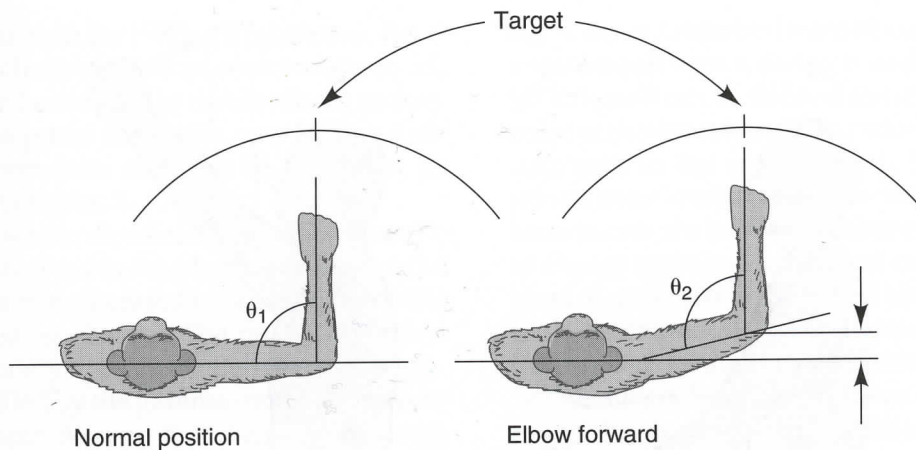
Figure 6.11.   In pointing to a target, the equilibrium point of the elbow is dependent on the angle at the shoulder. Reprinted from Plit and Bizzi, 1979.

the target, even after considerable practice. By contrast, normal, intact monkeys learned in a few trials to compensate for the shifts in the shoulder position. The interpretation is that the intact animals had feedback from the shoulder joint and could adjust the angle at the elbow to compensate for the felt change in the shoulder angle. Thus, these data suggest that to point to a position in space, feedback about the initial positions of the joints is required if the environment is not perfectly predictable.

Another role of afferent information involves what has been called *functional tuning* by a number of authors (Fitch, Tuller, & Turvey, 1982; Turvey, 1977). Recall that the spinal apparatus and resulting limb strength could be affected by changing the head position, much as would be expected on the basis of the idea that the tonic neck reflex was involved in the action (Hellebrandt et al., 1956). In this example, afferent information from the neck presumably adjusts the spinal mechanisms prior to action, thereby facilitating or inhibiting them. But a more compelling reason for assuming that premovement tuning must occur is related to some simple facts about the nature of the motor apparatus. In figure 6.12 are two diagrams of a hypothetical rapid movement. In both cases, the movement involves flexion of the elbow a distance of 45°, beginning with the arm straight. In figure 6.12a, the upper arm is positioned 45° to the vertical, so that a flexion of the elbow will result in the forearm's being horizontal at the end. In figure 6.12b, the upper arm is 45° above horizontal, so that the forearm will be vertical at the end. The same command signal delivered to the biceps muscle group will not "work" in both situa-

tions, for two reasons. First, a force is required to hold the forearm against gravity at the target position in the first situation, but not in the second. Second, more force is required to move the forearm against gravity in the first example relative to the second. A logical conclusion from this simple example is that the motor system must "know" where the shoulder position is prior to the action so that the command to the elbow flexors can produce the required 45° movement. How this happens is not entirely clear, but *that* it happens seems to be very clear.

Consider another complicating factor for the motor system to have to cope with in producing a movement. Figure 6.13 is a schematic diagram of the muscle attachments involved in a simple movement. This time, imagine that the movement is an extension movement in which the elbow is to be moved through 45°. Notice that the triceps muscle, which is the primary elbow extensor, is attached to the humerus in two places (internal and external heads) and to the scapula of the shoulder area (the long head). Thus, the triceps muscle performs two actions when it contracts: it extends the elbow and it tends to extend the shoulder joint, pulling the humerus back. Therefore, when the triceps is contracting to produce the 45°-movement, one of the muscles that flexes the shoulder must contract so that the shoulder joint is stabilized and only the elbow moves. Thus, during this simple extension movement, the motor system must "know" that there is a two-jointed muscle involved and produce some compensatory stabilization. The amount of stabilization will be dependent on the shoulder angle, because of the length-tension relation (chapter 7).
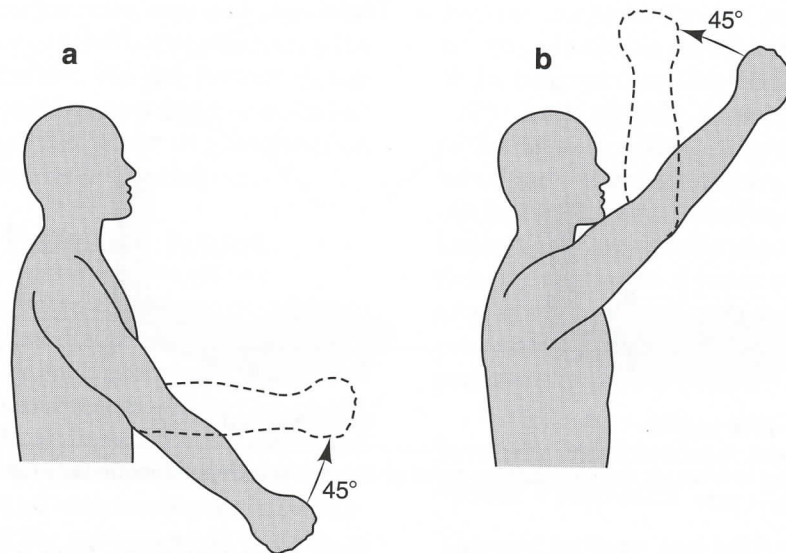
a

b

45°

45°

Figure 6.12.   Two 45° elbow flexion movements that appear to require different commands for the action and different forces at their endpoints because of the effects of gravity.
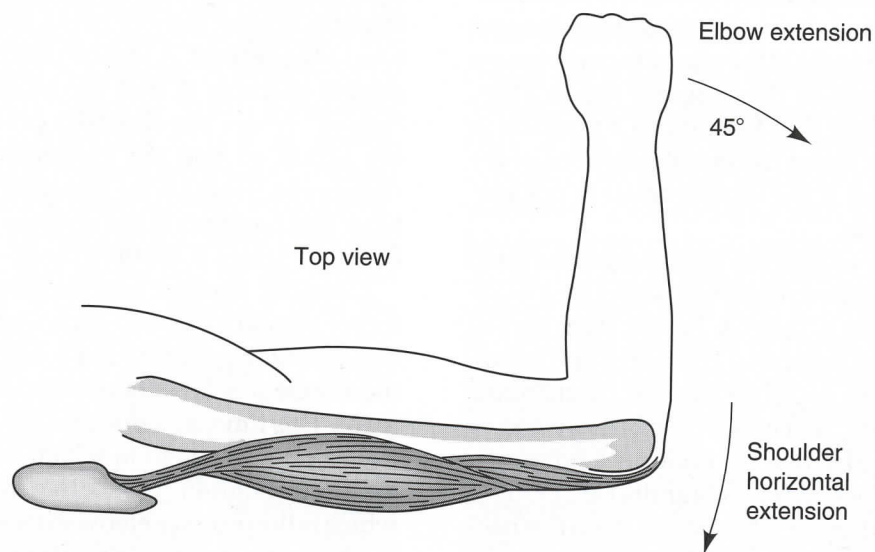
Elbow extension

45°

Top view

Shoulder horizontal extension

Figure 6.13.   Complexity in a 45° elbow extension movement caused by the fact that the triceps muscle both extends the elbow and horizontally extends the shoulder.

The picture that emerges from these observations is that a "simple" 45°-movement of the elbow joint is not really all that simple in terms of the motor system. In addition, other complicated aspects of the muscle need to be considered by the motor system, such as the nonlinear relationship between the muscle force and limb velocity, together with aspects of the contraction process that make the motor system very difficult to predict and control (Partridge, 1979, 1983). Yet our nervous system controls our limbs beautifully in these "simple" situations. How it does so is exciting to ponder.

During the Movement

One role that feedback seems to have in movement production is a monitoring function, whereby the feedback from the movement is taken in and processed but not necessarily used in the control of the action unless something goes wrong. It is probable that a long string of actions dealing with finger movements in piano playing is programmed and carried out open-loop. Feedback from the fingers is returned to the central nervous system for analysis, as if the central nervous system were "checking for" errors. If no

errors appear, then the feedback is ignored. But if the feedback indicates that an error has occurred, attention can be directed to that feedback source, and an appropriate correction may be initiated. Reflexive corrections may also be generated, as discussed in chapter 5.

A second way to view feedback is that it may be intricately involved in the physical control of the limb. We mentioned a number of examples of this in the preceding chapter. The possibility exists that a constantly changing reference of correctness is specified by the gamma motor neurons to the muscle spindles and that their actions result in a continuous set of corrections to keep the movement on the proper course. The feedback could be involved in the determination of the end location of a movement if the reference of correctness were set for this position. And in repetitive movements, the feedback from early segments of the sequence can provide adjustments for the later segments.

Following the Movement

Extensive feedback is also delivered to the central nervous system after a movement. Such information can be evaluated, presumably, by the stages of information processing in order to determine the nature of the movement just made. Information about whether or not the move achieved the environmental goal, as well as about its smoothness, its level of force or effort, or its form or style, is derived from feedback. A major role for such information is in the adjustment of the movement on the *subsequent* trial, perhaps to reduce the errors made on the previous trial. As such, this information has a considerable relevance to the acquisition of skills, as discussed in the final part of this book dealing with motor *learning* (chapters 12 and 13, in particular).

Types of Motor Program Errors

Various theories or viewpoints about motor control processes have been attempts to integrate ideas about the role of feedback with open-loop concepts. These ideas are presented in the next sections. The first task will be to define two distinct types of errors that the motor system can make, each of which uses feedback in distinctly different ways.

When a person makes a rapid movement, there are really two goals (Schmidt, 1976a). First, there is an environmentally defined goal, such as chang-

ing gears in a standard transmission car or doing a somersault from a diving board. A second goal (or subgoal) can be defined in terms of the muscular activities required to produce the desired outcomes in the environment. For example, a person must contract the muscles in the arm and torso in one of a limited number of ways in order to change gears smoothly, and only certain patterns of muscular activity will result in a somersault. Essentially, how to generate this subgoal is the problem facing the performer.

This subgoal can be considered as a pattern of action that is structured in both space and time. Thus, such a pattern of action will determine where a particular part of the body will be at a particular time after the movement starts. If this spatial-temporal pattern (the subgoal) is produced accurately, then the environmental goal will have been achieved. Of course a number of different patterns of action can be used that will result in the overall goal of changing gears (relating to how the clutch is contacted, which fingers are used to grip the gearshift, the velocity of leg and arm actions, etc.), but each of these must be produced accurately in order for the overall goal to be achieved.

Errors in Program Selection

Given the assumptions about the spatial-temporal goal, the first kind of error that the person might produce can be defined as an error in *program selection*. This kind of failure to achieve the environmental goal results from the performer's choice of action. This can happen in a number of ways (Reason & Mycielska, 1982). First, the person can produce the wrong pattern of action: for example, moving right when a left move is appropriate, or moving when it might be important to stand still. Second, an error in selection can occur if the person chooses an appropriate program (e.g., a bat swing pattern when a bat swing is required) but the spatial-temporal pattern that has been defined turns out to be inappropriate. For example, the bat swing could be too high or too low, or too early or too late, because of unexpected changes in the ball's flight. Because all these decisions about where and when to swing—as well as all the contractions that occur in the swing—must be defined in advance, the performer will have made an error because he selected the wrong pattern to produce. Another way to see this is to note that if the

person had produced a pattern with a little higher bat location and a slightly earlier swing, the results could have been a home run instead of a miss.

How does a person make a correction for an error in program selection? According to the evidence presented earlier, the person must issue a *new* motor program, as the "old" one will not achieve the goal in the environment. Hence, the information-processing stages must be reinitiated, a new program must be selected in the response-selection stage, and it must be programmed in the response-programming stage; and all these stages are relatively slow. The result is that a new pattern of action in a rapid motor skill usually cannot be selected before the movement has been completed, and the movement will be in error. If the movement has a somewhat longer MT, however, then it is possible that a correction for an error in selection can occur.

Errors in Program Execution

An error in program execution is fundamentally different from an error in program selection (Schmidt, 1976a). An error in execution can occur if the person produces a program of action appropriate for the environment, but some unexpected event occurs that disrupts the movement. This can happen, for example, if the contractions specified by the motor program are not quite achieved by the muscles, perhaps because of inconsistencies in the spinal cord where it is determined which (and how many) motor units are to be activated. Or in a tennis game on a windy day, a perfectly programmed and timed swing will be slowed by an unexpected puff of wind. If you picked up a milk carton that you thought was nearly full but that really was nearly empty, you could smash the carton into the top shelf of the refrigerator.

These influences do not make the *originally* intended movement pattern incorrect, as some compensation that will achieve the originally planned spatial-temporal goal will still result in the achievement of the environmental goal. Thus, the correction for an error in movement execution may not require a new motor program, as the original pattern of action defined by the "old" program will be correct if the motor system can compensate for the unexpected environmental influences. This implies that because the system does not have to select a new motor program,

the correction for an error in execution does not require all the stages of information processing and will be far more rapid than correcting for an error in program selection.

What is the evidence for this kind of correction, and is the correction for error in execution fundamentally different than that for an error in selection? Consider the example from Dewhurst (1967; figure 5.13) presented in the preceding chapter; recall that the subject was instructed to hold a weight with the elbow at right angles. When the weight was suddenly changed, a correction followed in the biceps EMG within about 30 ms, and a more sustained correction followed in about 50 to 80 ms. The corrections were far faster than can be explained by the production of a new program of action; hence it seems reasonable to believe that the original program of action was in some way modified. More importantly, the person did not have to select a new program of action to compensate for the added weight, as the "old" spatial-temporal goal was still appropriate. The goal as stated before the weight was added was "Hold the elbow at right angles," and the goal afterward was the same; the subject seemed only to require additional muscular tension in order to continue with the "old" goal. Thus, it appears that the corrections served the purpose of maintaining the *original* pattern of action and did not result in the generation of a new one. As a result, the corrections had a far shorter latency than would be expected if it had been necessary to produce a new pattern (see chapter 5 for other examples).

What about the role of consciousness in corrections for errors in selection? As you will recall from chapter 5, Henry (1953; figure 5.14) asked subjects to try to maintain the position of a lever in response to unexpected changes in the pressure it exerted against the hand. He showed that subjects were able to compensate for changes in position that were some 20 times smaller than changes they could consciously detect. The subjects were responding to changes in position that they could not perceive—that is, they were responding *unconsciously*. Also, Johansson and Westling (1984; Westling & Johansson, 1984) showed that if subjects began to lose grip on an object held between the fingers, compensations could be made in approximately 30 ms, apparently without conscious awareness. In these examples, the person did not have to select a new

program of action when the stimulus occurred, because the original pattern of action was still acceptable. Force changes within the context of this pattern of behavior were required, however, to maintain the movement's overall goals. These were accomplished very quickly and without awareness, and can be thought of as corrections for errors in execution.

Program Selection Errors Versus Execution Errors

Table 6.1 summarizes some of the fundamental features of these two kinds of errors, listed so that their differences can be seen more easily. These differences are important, because without testable distinctions between these error categories it would make little sense to consider these classes separate (see also classifications of reflex responses in chapter 5 for a similar analysis, especially table 5.2).

From the table, we can see that the latencies of the two kinds of corrections are quite different; the selection errors require 120–200 ms or more in order for a correction to begin, and the execution errors are corrected far more quickly, in 30–50 ms. Also, a new spatial-temporal goal is needed to correct an error in selection, whereas the original pattern of action can continue while an error in execution is being produced. We know that selecting and initiating a new movement program (needed to correct an error in selection) require attention and consciousness in the sense defined in chapter 4 and that this process will interfere greatly with certain other (cognitive) processes attempted at the same time; hence only one such correction can be done at a time. Correcting for an error in execution, on the other hand, is automatic with respect to cognitive information-processing activities, and many such corrections could pre-

sumably be done at the same time without interference—some in the arms, some in the legs, and so on. Hick's law clearly applies when one is correcting for errors in selection (chapter 3), with the latency increasing as the number of possible corrections increases. For errors in execution, on the other hand, the number of possible errors is probably not a factor, and so Hick's law would not be expected to apply.[3] All these differences, taken together, clearly argue that corrections of motor program errors are of at least two fundamental types.

Triggered Reactions

The classification scheme in table 6.1 is more than two decades old now (Schmidt, 1976a, 1983), and newer research suggests it may be somewhat too simple to account for all the evidence. One good example involves triggered reactions, as discussed in chapter 5. We saw that triggered reactions were faster than RT, did not seem to require conscious processing, and did not seem to involve the selection of a new movement program—all of which would at first glance seem to place them into the category of corrections for errors in execution. But the notion of errors in execution implies that the correction serves to bring the limbs back on the original *trajectory* after a perturbation, with the spatial-temporal goal being the particular trajectory originally selected (Cooke, 1980). Yet the evidence on triggered reactions shows that the response to various perturbations is a *new* pattern of action, with a trajectory fundamentally different from the one that was occurring before the stimulus. When a given perturbation was applied, we saw altered lip and tongue trajectories in human speech (Abbs, Gracco, & Cole, 1984; Kelso et al., 1984), new hindlimb trajectories in cat locomotion (Forssberg, Grillner, &

Table 6.1   Characteristics of Corrections for Errors in Selection and Execution

Characteristic	Selection	Execution
Latency of correction?	120–200 ms	30–50 ms
Old spatial-temporal goal OK?	No	Yes
New program selected?	Yes	No[a]
Attention required?	Yes	No
More than one at a time?	No	Yes
Hick's law apply?	Yes	No?

[a]Provided that the deviation from the spatial-temporal goal is not very large. (Adapted from Schmidt 1983, 1987.)

Rossignol, 1975), and different, coordinated patterns of elbow and finger movements in lifting tasks (Johansson & Westling, 1984; Westling & Johansson, 1984), all with very short latencies.

It is tempting to suggest that triggered reactions ensure that the *original goal* of the action is achieved—not necessarily that the *original trajectory* of the limbs is achieved. This notion implies that a particular trajectory of the limbs is not always as important as it appeared earlier. Of course, there are many ways in which the motor system can achieve a particular environmental goal; and when perturbed, the system seems to shift from one of these alternatives to another, with a very short latency. This combination of features seems to suggest that triggered reactions fall somewhere between correction for errors in execution and correction for errors in selection, sharing features of both categories, or perhaps forming a third category. It may be that when the perturbation is small, a correction for an error in execution can occur to bring the limbs back on the target trajectory; if the perturbation is somewhat larger, a triggered reaction is produced that selects another trajectory, but without the need for reprogramming the movement using the stages of information processing; and if the perturbation is even larger, a correction for an error in selection is generated, which of course involves the stages of processing. Certainly, more work is needed to clarify this issue.

Modern Motor Program Viewpoints

From the previous sections it is clear that there is considerable evidence for a central open-loop mechanism, structured before the movement is initiated, that serves to organize and control limb movements in coordinated actions. Yet substantial evidence also suggests that feedback from the responding limbs can, through a variety of mechanisms, modify the movement in various ways. Some of the lower level reflex activities serve to keep the movement "on track," and triggered reactions and "reflex reversals" alter the trajectory quickly while maintaining the overall movement goal. Also, feedback from the touch receptors in the skin can modify the ways in which the gamma loop functions in movement control (Merton, 1972).

Hierarchical Levels of Control

This large body of evidence suggests a centrally organized structure that is capable of handling most of the details of the actions but is also very sensitive to movement-produced sensory information from a variety of sources. One way to view this blending of open- and closed-loop functioning is to consider a hierarchical control, in which a higher order, open-loop control structure has "under" it a set of closed-loop processes that ensure the movement's intended goal in the face of various perturbations. If a signal appears in the environment indicating that the higher order program is no longer relevant, the highest levels in the system (the stages of processing) become involved in stopping it, or perhaps in initiating a different program. But if smaller perturbations occur that do not involve an alteration in the fundamental movement goal, these can be handled by lower levels in the hierarchy, presumably while the original higher level program continues to operate. This is a classic example of a closed-loop system embedded within an open-loop system.

These thoughts lead to a modified, less restricted definition of a motor program, one that is in keeping with the literature on feedback process yet retains the essential feature of the open-loop concept: the motor program is an abstract representation of action that, when activated, produces movement without regard to sensory information indicating errors in selection. Once the program has been initiated, the pattern of action is carried out for at least one RT even if the environmental information indicates that an error in selection has been made. Yet during the program's execution, countless corrections for minor errors can be executed that serve to ensure that the movement is carried out faithfully. Grillner (1975) has said essentially the same thing with respect to the control of gait:

> Perhaps it is useful to regard the relevant reflexes as *prepared* [italics added] to operate but without any effect as long as the movement proceeds according to the set central program. At the same instant when the locomotor movements are disturbed (small hole, a slippery surface, etc.) the reflexes come into operation to compensate. (p. 297)

This idea is similar in many ways to the concept of a *coordinative structure* discussed by Greene (1972), Fitch, Tuller, and Turvey (1982),

Turvey (1977), and Berkinblit and Feldman (1988). In both the motor program and coordinative-structure concepts, the many degrees of freedom in the musculature are reduced by a structure or organization that constrains the limbs to act as a single unit. Also, both notions involve the tuning of spinal centers, corrections for errors in execution, and freedom of the executive level from the details of what occurs at lower levels in the motor system.

Multilevel Hierarchical Control

Greene's (1972) point of view emphasized the hierarchical nature of motor control. He suggested that at the highest levels of the system, the global aspects of the movement are represented in the form of a goal (e.g., shoot a basket). The control is passed down through progressively lower levels until all the particular decisions about which motor units to fire are defined at the muscle level. The higher levels in the system do not have any direct control over muscle contractions; they have control only over adjacent levels of control that eventually result in those contractions. This idea is related to the motor program view in which only two levels exist—an executive and a program or effector. Greene's view suggests that there are more than these two levels.

Along these lines, the highest level specifies what Greene called a "ballpark" movement, which would result in any of a number of movements that were "in the ballpark" for the goal to be achieved. As the system passes control to lower levels, the individual details of the actions are defined by the initial conditions of the limbs, the posture of the performer, the relations with respect to gravity, and a host of other factors of which the highest level of the system is not aware. These lower functions then determine the ultimate movement that will result, on the basis of these lower level interactions with feedback, tuning, and other factors. In short, the "ballpark" movement becomes increasingly well specified at each lower level in the motor system.

Some Problems With the Motor Program Notion

The advantage of the motor program notion as a theory of movement control is that it provides order to a large number of separate findings, such as the inability to use certain kinds of feedback and the kinds of corrections that can and cannot be made. But the ideas about programs that have been stated so far have other logical drawbacks that must be considered. The next section deals with two of the most important: the *storage problem* and the *novelty problem*.

The Storage Problem

Given that an animal can produce a motor program "on command" and initiate it, *how many* such programs must the organism have at its disposal in order to move as it does? Recall that a motor program is thought to result in commands to muscles that define a particular pattern of action. In this view, if the pattern is to be changed (e.g., from an overhand to a sidearm throwing pattern), then a totally new program must be produced. Imagine all the ways to produce a throwing action, each of which must have a separate program.

MacNeilage (1970) pointed out this problem in the context of speech production. According to programming theories of speech, each sound (called a *phoneme*) that a human can produce is governed by a separate program; in order to speak, we simply string together these separate programs in a way that follows the "rules" of intelligible speech. This solution seemed to be a good one—since there are only about 44 sounds in English, then we should require only 44 programs. The difficulty is that the actions of the mouth, jaw, tongue, and so forth for a particular sound are different depending on the sound that precedes it. That is, to make the sound of a *t*, the musculature must make one of two different movements depending on whether the word is "eat" or "boat," as you can easily discover for yourself when you say these two words and note the actions of your own tongue. Thus, the 44 programs for tongue movement for the various sounds must now be multiplied by the number of different sounds that could precede these sounds. Furthermore, the movements of the vocal musculature depend on the sound that *follows* the sound in question. This notion of *context-conditioned variability* led MacNeilage to estimate that a very large number of programs must be stored in memory in order for us to speak as we do. Considering all the various accents, inflections, and combinations, as well as any foreign-language sounds, he estimated that about 100,000 programs would be required for speech alone.

It is possible that the brain *can* store 100,000 programs for speaking, of course, as long-term memory has a very large capacity. But when we consider the number of ways in which we move other than for speech, and the interaction of previous and subsequent states for each of these movements, there would have to be a nearly countless number of programs in long-term memory.

This postulation seems unwise for several reasons. First, many mechanical or electronic control systems have this storage problem, and it is crippling to them; examples are libraries that have to cope with tons of paper and computer systems that have to store programs for every kind of computation. They simply run out of room. A second reason is related to the belief that our motor system evolved in such a way that it was simple to operate and efficient in terms of storage. To store a complex program for every movement is not a simple and elegant way for a system to have developed (e.g., Schmidt, 1975b; Turvey, 1977). There must be a better way to conceptualize the storage of motor programs.

The Novelty Problem

The next concern about motor programming is related to the storage problem, but it takes a slightly different form. The basic issue is how we make *new* movements. Consider a movement like this: beginning in a standing position, jump up from both feet, touching your head with the right hand and your leg with your left hand before you land. Certainly, most of us could do this on the first try. If you had never done that particular movement before and if the action required a program for its execution, then where did the program come from? It is difficult to assume that the program was genetically defined (as walking might be), because such an action does not seem particularly essential. And you could not have learned it through practice, as this was the first time that you produced this action. A logical dilemma arises about motor programming for novel movements.

The same sort of problem exists for more common skills. If you were to study a series of 50 shots in tennis, examining the fine details of the feet, hands, and body, you would probably find that no two movements were *exactly* the same. This is compounded by the fact that the ball never has exactly the same velocity, the same location on the court, or the same height. Therefore, it is unlikely

that any two tennis strokes could be exactly the same. If no two shots are exactly the same, then the programs must also be different. Thus, according to this analysis at least, every shot is "novel" in the sense that it has never been produced in exactly that way before. When you make a movement, you do not simply repeat a movement that has been learned earlier.

On the other hand, a given golf or tennis stroke is certainly very similar to strokes that you have made previously. For example, some people have a certain (but very odd) style of hitting a golf ball that is characteristic of them and no one else. And your favorite touring professional's style is easily recognized. Thus, it is not fair to say that every golf stroke is absolutely new, as considerable practice and experience have led to the production of that action, and this experience tends to make the actions somewhat similar—characteristic of the individual.

Writing more than a half century ago, Bartlett (1932) made the following observation about tennis strokes: "When I make the stroke I do not, as a matter of fact, produce something absolutely new, and I never repeat something old" (p. 202). His point summarizes the issues in this section very well. When making a stroke, you do not make a movement that is absolutely new, because that movement will depend on your past learning. But you do not exactly repeat an old movement either, as any particular movement will be slightly different from all the others that you have made. In this sense, the stroke is considered novel.

One weakness of the earlier ideas about motor programming is that they do not explain how the individual can produce a novel movement or how a movement such as a particular tennis stroke is somehow slightly different from all earlier ones. If our theories about movement programs are to have an application to everyday motor behavior, then they must be able to explain these common phenomena.

The Need for Revision

These two rather persistent problems—the storage problem and the novelty problem—pose rather severe limitations for the motor programming idea as it has been stated previously. One solution has been to introduce a modification to the fundamental programming notion, one that retains all the attractive aspects of programming that have been discussed but that also provides a

solution to the two problems identified. This kind of thinking led to Schmidt's idea (1976a) that a motor program should be considered as *generalized*.

Generalized Motor Programs

The idea of a *generalized motor program* is that a motor program for a particular class of actions is stored in memory and that a unique pattern of activity will result whenever the program is executed. In order for the program to be executed, certain *parameters* must be supplied to the program that define how it is to be executed on that particular trial. Because the program's output in terms of movements of the limbs can be altered somewhat according to the parameters chosen on a particular trial, the program is said to be generalized. Before describing how such a system might operate, it will be helpful to consider an example of a generalized program for a different application.

A Computer Model

Perhaps the best example of a generalized program comes from computer science. In this field, many different statistical programs do common statistical procedures. Consider a program that calculates means and standard deviations. Such a program is generalized so that it can produce output for various numbers of subjects and for various numbers of scores per subject. In order to run the program, you must specify certain *parameters*—in this case the number of subjects to be used and the number of scores per subject. Once these are specified, the program can be executed for this particular example.

How does this kind of program solve the storage and novelty problems? First, the storage problem is reduced because, for this class of computing problem, only one program needs to be stored in the system; and this one program can accommodate a wide variety of combinations of number of subjects and number of scores. For example, if the number of subjects can range from 1 to 100,000 and the number of scores can range from 1 to 1,000, there is the potential to run this program in $100,000 \times 1,000$ different ways—100,000,000 combinations!

With respect to the novelty problem, notice that the program for means and standard deviations can produce results for combinations of subjects and scores that it has never been used for previously. One simply specifies the proper parameters, and the program is executed perfectly. In this sense, the generalized program provides one kind of solution to the novelty problem.

Invariant Features

A motor program is thought to be responsible for the production of a pattern of action, expressed in both space and time. When patterns of action are examined carefully, we see that various aspects of them are easy to change while other aspects remain almost completely fixed from movement to movement. It is not always obvious which aspects of the movement are fixed and which are easily changed; but examining the movement in certain ways, or with certain theoretical biases, can reveal these features (Schmidt, 1985).

A classic example of ways in which movements demonstrate both fixed and modifiable features is one of our most common movement patterns, *handwriting*. This demonstration was presented many years ago (independently) by Lashley (1942; Bruce, 1994) and Bernstein (1947; reproduced in Keele, Cohen, & Ivry, 1990 [their figure 3.5]), and more recently by Merton (1972) and Raibert (1977). All these demonstrations suggest basically the same thing. Figure 6.14 is a reproduction of the handwriting samples published by Lashley (1942). Two right-handed, blindfolded subjects wrote the words "motor equivalence"[4] normally (with the right hand), with the nondominant (left) hand, and with either hand attempting to produce a mirror image of the words (these have been reversed in the figure to appear as normal). The subject represented in figure 6.14a even wrote the words with the pencil held by the teeth.

These handwriting samples are obviously different in various ways. They are of different sizes and show an increased "shakiness" in some cases. The speed with which a word was produced was probably not the same either. But in all samples for each individual there are many remarkable similarities. A certain "style" is seen in all of them, such as the little curl at the start of the *m* for the subject in figure 6.14a and the way the downstroke of the *q* is made for the subject in figure 6.14b. Some aspects of these written words appear to be invariant, even when the effector used or the size or speed of the writing was changed. What is invariant is the spatial-temporal pattern, or the shapes of the letters. Lashley noted: