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 × 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:

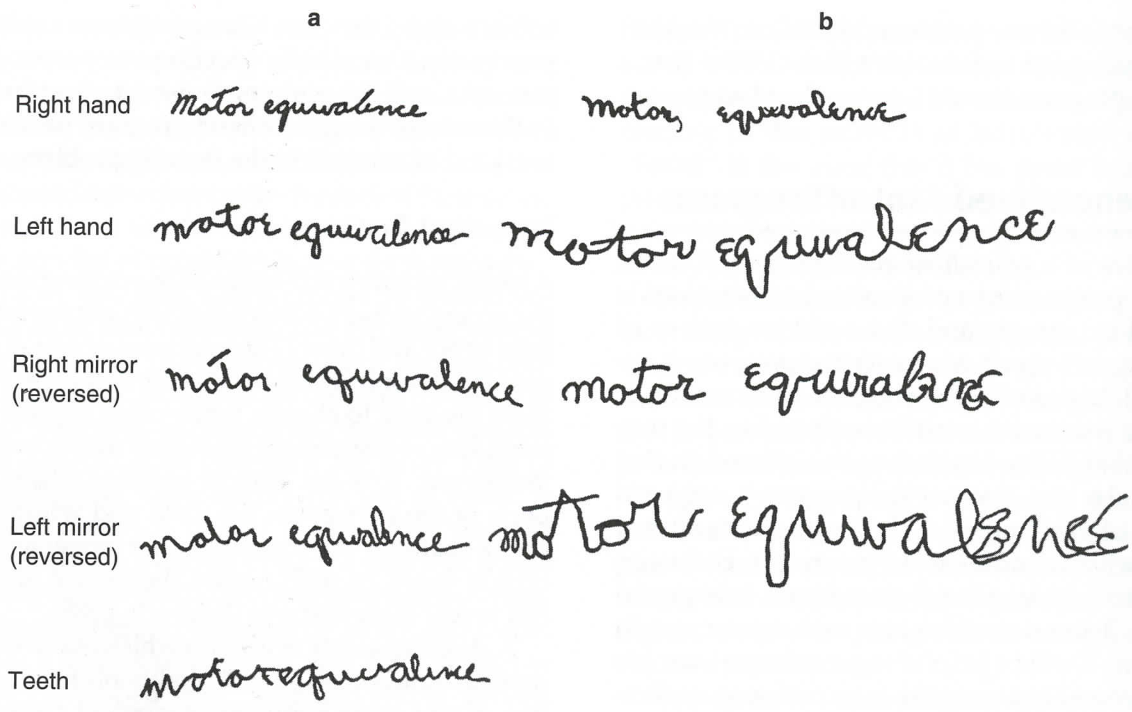

Figure 6.14. Examples from two subjects writing the words "motor equivalence" with different effectors.

> In spite of the clumsiness, the general features of the writing, individual differences in the forming of letters and the like, are characteristically maintained. The mechanics of writing is a sequence of movements in relation to bodily position, not a set pattern of special groups of muscles. (1942, p. 317)

Although the meaning of these demonstrations has been called into question (Latash, 1993), the conclusion that something in the performer's memory is common to all these handwritten words has been supported by more in-depth analyses (Wright, 1990). Some abstract structure expressed itself, regardless of the variations in handwriting speed or size or in the limb or muscles used to write the words. Schmidt (1976a) theorized that those features that are invariant, and that in some ways are *fundamental* to these written words, are structured in the motor program; those aspects of the movement that are relatively superficial (speed, effector used) are thought to be parameters of the program. Remember the computer analogy: the way in which the means and standard deviations are calculated is invariant and fundamental to the program—the numbers of subjects and scores are not, and are parameters of the program. This handwriting example seems to be showing something similar.

If these observations are correct, how can the structure of the motor program be conceptualized so that the invariant features of handwriting are held constant across a wide variety of other changes? In the next section, we consider one possibility that appears to have abundant evidence to support it—the *impulse-timing hypothesis.*

Impulse-Timing Hypothesis

One straightforward viewpoint about the structure of motor programs is the *impulse-timing hypothesis.* The fundamental idea is that the motor program provides pulses of motor neuron activity to the relevant musculature. These pulses produce patterns of contractions in the muscles that can be seen in EMG records or in records of force produced. The amount of force produced is related in a complex way to the amount of neurological activity, and the duration of the force and its temporal onset are determined by the duration of the neurological activity and the time of its occurrence. The major role of the motor program is to "tell" the muscles when to turn on, how much force to use, and when to turn off. Thus the motor program ultimately controls force and time.

Impulses

The combination of force and time generates an *impulse.* A common principle in physics is that the amount of movement produced in a limb is determined by the force(s) acting on it and the time over which the force acts; this product of force and time is called the impulse. Therefore, the impulse-timing hypothesis really means that the motor program controls impulses—bursts of force spread out over time to the appropriate muscles.

In figure 6.15 are three hypothetical, idealized records of the forces produced by a muscle over the time that this muscle is acting on the limb. At each moment of the contraction, the muscle is producing a different force against the bone; the resulting curve in figure 6.15 is called the *force-time curve*—a record of the force produced over time. The impulse is the shaded *area* under the force-time curve. From mathematics, this area is frequently called the *integral,* or *the integral of force over time.*

In the figure, notice that the impulse (the area of Impulse A) can be reduced in half by changing the amplitude of the force for a given amount of time (Impulse B), or by changing the duration of the impulse for a given amplitude (Impulse C), or both. From physics, the velocity of the limb (beginning at rest) after the impulse has ended its action will be directly proportional to the size of the impulse. Thus, Impulses B and C in figure 6.15 would theoretically produce the same velocity at the end of their respective actions (because their areas are equal). And the velocity of the limb with Impulse A would be twice as large as for the other two, because its area is twice as large. In this view, the motor program controls a feature of muscular contraction that is known to be a direct cause of movement—impulses.

If it is correct that the motor program determines impulses, it is reasonable to assume that the motor program is capable of producing a group of impulses, each one in a different muscle group and each one at a different time, resulting in a pattern of activity that produces a skilled movement. Remember, producing impulses in muscles is really nothing more than defining the time of onset and offset of the relevant contractions, as well as their forces. Once these are defined, the movement is defined. Even so, defining these impulse sizes and durations should not be seen as simple, because many factors must be considered by the central nervous system, as discussed earlier (see figures 6.12 and 6.13).

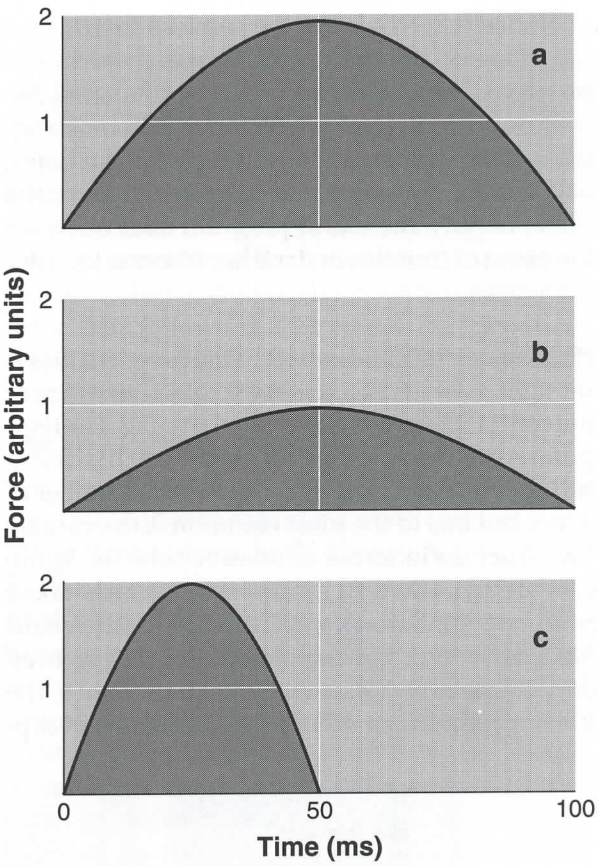

Figure 6.15. Hypothetical impulses seen as the area under force-time curves. (Impulses B and C have half the size that A does, but B is achieved by halving the force with time constant, and C is achieved by halving the time with force constant.)

Invariant Features and the Impulse-Timing View

Given a model of impulses patterned in time to produce a skill, what features of the action must remain invariant? What aspects of these impulses are the same from one handwriting sample to another, and which of them can vary while maintaining a given pattern of activity?

Order of Events. One aspect of the pattern shown in figure 6.14 that seems not to vary is the sequence or *order* of events (Lashley, 1951). In each sample, some event occurred before some other event in making a letter or word, and this order was fixed for all of the samples. We assume that the order of muscular contractions for this sequence of events is fixed in general. A basic assumption of the impulse-timing model of motor programming is that the program has an invariant order of the various elements structured in it.

Notice that this is not the same as saying that the order of *muscles* contracting is fixed in the program. Why? The muscles that produced the writing with the teeth are certainly different from those that produced the writing with the hand, and yet the sequence and the pattern were the same. Clearly, the motor program does not have the order of muscles in it; rather it seems to order the *actions*.

Phasing. A second aspect of the program that is thought to be invariant is the *temporal structure* of the contractions, usually termed *phasing*. The temporal structure of a series of events (in this case, a series of actions) can be measured in a number of ways, but one of the most common is to evaluate the structure in terms of relative time. In figure 6.16 are hypothetical examples of records taken from two similar actions. This particular record has EMGs in it, but the record could have been defined in terms of movements of the limbs, the forces produced, or other characteristics that capture in some way the nature of the movement produced. The muscles whose EMGs are shown were chosen because they act at different times in the movement sequence. The sequence begins with a strong burst of EMG from Muscle 1; then Muscle 1 appears to be turned off and Muscles 2 and 3 are activated, with Muscle 2 ceasing its activity before Muscle 3 does. How can this temporal pattern of events in these three participating muscles be described?

One method is to measure the durations of the various elements within the sequence. Shown in the figure are two similar movements, but one of them (Movement 2) has a longer MT than the other. If these two records are evaluated with respect to the durations of the relevant contractions (EMGs), then interval *a* can be defined as the duration of the contraction of the muscles in the entire action, interval *b* is the duration of contraction of Muscle 1, interval *c* is the duration of contraction of Muscle 2, and interval *d* is the duration of contraction of Muscle 3. One way to

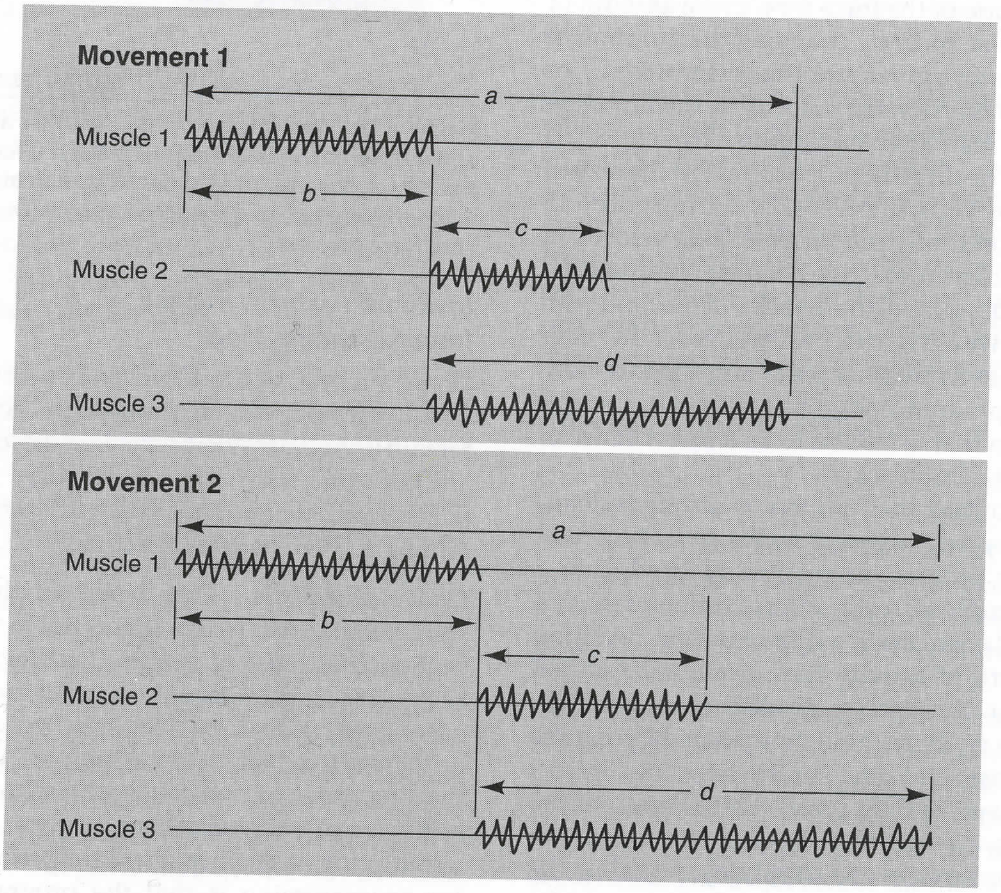

Figure 6.16. Hypothetical EMG records from two similar movements differing only in MT. (Phasing, or relative timing, is defined by the ratios of the EMG durations among various muscles, e.g., *b*/*c*, *c*/*a*, and so on.)

evaluate the temporal structure of these events is to produce ratios of these various times. The sequence for Movement 1 has a ratio of interval *c* to interval *d* of 1:2, or .50. That is, interval *d* is twice as long as interval *c*. Also, interval *b* is one and one-half times as long as interval *c*, making their ratio 1.5:1, or 1.5. Similar ratios can be computed for any two intervals in the sequence.

Another common ratio is that of an element in the sequence relative to the overall length of the sequence. For example, in the Movement 1 sequence the ratio of interval *d* to the overall length of the sequence (interval *a*) appears to be about .60; thus, Muscle 3 is contracting for about 60% of the entire movement.

The fundamental idea of these ratios is this: the temporal structure is measured by (or characterized by) the values of these ratios. If all the ratios are the same in two separate movements, then the temporal structures are the same. Thus, any two movements with the same order of contractions (perhaps that shown in figure 6.16) and the same ratios of muscle action to total MT (e.g., .45, .30, and .60 for Muscles 1, 2, and 3) have the same temporal structure (phasing). Further, these two movements are assumed to be produced by the same motor program.

Movements 1 and 2 in figure 6.16 have this characteristic. The proportion of total MT for each muscle is the same in the two movements, even though the *amount* of time that each muscle is contracting is different for the two movements. Movements 1 and 2 are thought to be governed by the same motor program, because their phasing is the same. If two movements have different phasings, then they are governed by different motor programs.

Relative Force. A third important feature of generalized motor programs is *relative force*, which simply means that the amounts of force produced by any two muscles remain in constant proportion from movement to movement. If in Movement 1, Muscle 1 produced 2 kg of peak force and Muscle 2 produced 4 kg, the ratios of these two forces would be 1:2, or .50. In another movement using the same program, these proportions should be the same, but perhaps with forces of 2.5 kg for Muscle 1 and 5 kg for Muscle 2. The ratio remains 1:2, or .50.

This feature of the movement sequence would seem to remain invariant for the patterns of handwriting in the examples in figure 6.14. This can be seen in two ways. First, in this kind of model, the height of a given letter is determined in part by the amount of force applied to the limb during the impulse applied by the motor program. But the heights of the letters remain in almost constant proportion as the various letters in a given sentence are considered. For both subjects in Lashley's example, the *t* is always about twice the height of the *o* that follows it. The forces that produced these letter heights may have been in constant proportion in the sequence as well.

The Phonograph Record Analogy

It is sometimes helpful in understanding motor control theories to consider a *model* that has many of the same features as the theory. A good model for the generalized motor program is the standard phonograph record. On the record, structured as invariant features, are three things. First is the order of the events, specifying that the drumbeat comes before the guitar, and so on. Next is the phasing structured in the record. Think of phasing as the rhythm, so that the time between any two events on the record divided by the total record time is a constant. For phonograph records, the ratios between the times of occurrence, or the durations, of any two events are always fixed. Also, the relative force is fixed. For example, the first drumbeat may be twice as loud as the second one.

What is on the record is a code that is translated into sound when the record is played on a given stereo system. It is helpful to visualize motor programs as records, because in many ways they behave the same, and the similarities allow us to visualize the motor program more vividly.

But we know that the record can be played in various ways to produce different sounds. It can be played rapidly or slowly, loudly or softly, with the treble or bass turned up, and so on. Yet a given song can still be recognized because the pattern of the sounds produced is invariant, even though some of the superficial features of the pattern may have varied. The actual muscles that produce the action (here, the particular speakers that will be driven) are certainly not on the record, because the record can be played on any stereo system. In the next section, we discuss some of these more superficial features of movements. These aspects of movement are considered to be *parameters*.

Parameters of Generalized Motor Programs

Motor program theorists have argued that there are a limited number of parameters that can be applied to a generalized motor program. Some of the parameters for which there is strongest evidence are an overall duration parameter, an overall force parameter, and a muscle-selection parameter.

Overall Duration Parameter

The basic idea of an overall duration parameter is that while the motor program contains phasing and sequencing information, it can be run off slowly or rapidly depending on the overall duration parameter assigned, just as increasing the speed of the phonograph turntable speeds up the entire sequence of sounds as a unit.

Initial evidence for an overall duration parameter is found in an unpublished study by Armstrong (1970b). Subjects were asked to learn to move a lever through a particular spatial-temporal pattern. Figure 6.17 shows a tracing of the position of the lever as a function of time in the 4-s movement. Armstrong noticed that when the subject made the movement too rapidly, the entire sequence was made too rapidly, as if the entire movement record was "compressed," with all parts of the movement being shortened in the *same proportion*. Although Armstrong did not compute the proportions suggested in figure 6.17, a critical test of the idea is that the time between peak 1 and peak 2 divided by the time for the entire movement is about the same in the two movements shown in the figure. Such findings gave initial insight into the possibility of an underlying generalized motor program, with an overall speed parameter that retained the invariant phasing in the movement pattern (see Pew, 1974a for an early discussion of this work).

Following Armstrong's (1970b) and Pew's (1974a) suggestions, Summers (1975) and Shapiro (1977, 1978) examined similar questions in tasks in which the experimenter could instruct the subject to change the overall speed intentionally, rather than incidentally as Armstrong had done. Shapiro's paradigm involved practice at a task in which precise spatial-temporal patterning of pronation/supination of the wrist was required. Thus, to be successful the subjects had to make a series of actions defined in both space and time. The temporal structure of the action for Shapiro's (1977) study is shown in figure 6.18. The proportion of the total MT (which was 1,600 ms) occupied by each of the nine wrist-twist segments is plotted as the line marked with open squares. After considerable practice, Shapiro asked her subjects to speed up the movements but to keep the pattern the same; the pattern of proportions for these "compressed" trials is shown as the line with filled circles in figure 6.18. Notice that the

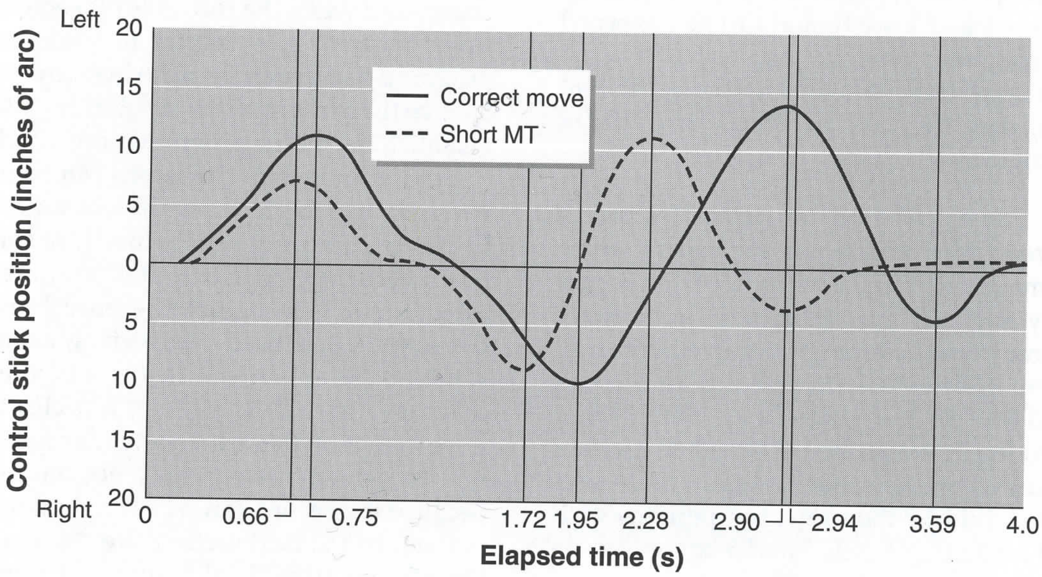

Figure 6.17. The position-time record of an arm movement task, showing the correct move and a move in which the overall MT was too short.
Reprinted from Armstrong, 1970.

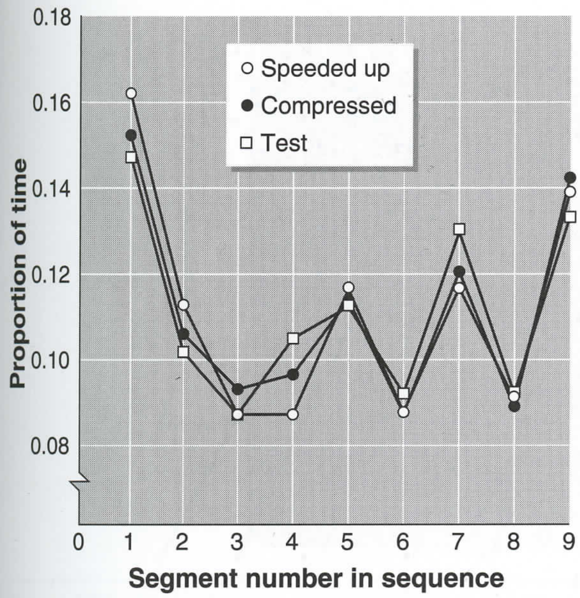

Figure 6.18. Proportion of total MT required to traverse each segment in a wrist-twist movement. (Normal trials had a goal of 1,600 ms; compressed trials were sped up using the same phasing; speeded-up trials were sped up while subjects attempted to ignore the earlier-learned phasing.)
Adapted from Shapiro, 1977.

proportions of time from segment to segment were almost exactly the same for the test trials and the "compressed" trials, but that the MT in the latter was decreased to 1,300 ms, on the average. Essentially, Shapiro showed that the subjects could decrease the time of this well-learned movement sequence as a unit, keeping the phasing in the movement (defined by the proportions) constant. This again suggests that a movement-duration parameter can be applied to some fundamental program so that the given pattern can be sped up as a unit.

Even more remarkable was another finding that both Summers (1975) and Shapiro (1977, 1978) obtained. They asked their subjects to make the movement as rapidly as possible and to *ignore* the phasing that they had learned in the earlier practice trials. In figure 6.18, the line with open circles represents these "speeded-up" trials; again, the pattern of proportions was almost identical to that for the normal trials. Subjects were able to speed up the movements, but they were apparently unable (or at least unwilling) to do so with a different phasing (see also Carter & Shapiro, 1984; Verwey & Dronkert, 1996).

There are other examples. Terzuolo and Viviani (1979) studied the typing of various words, examining the phasing characteristics. Figure 6.19 is a diagram showing various temporal records in typing the word "trouble." In figure 6.19a, the time of occurrence of each of the letters is plotted for 27 different trials. Each horizontal row of dots represents the time of occurrence for each letter for one trial. The trials are presented in the same order in which they occurred in the experimental session, and no recognizable pattern of phasing appears in them. In figure 6.19b, though, the trials have been reordered so that the trial with the shortest overall MT (845 ms) is at the top, and the trial with the longest MT (1,218 ms) is at the bottom. Notice that the onset times of the various letters "line up" on the sloped lines, as if the longest trials were simply "stretched" versions of the shortest ones. And, in figure 6.19c are the same data, but the time of occurrence of each letter is now expressed as a proportion of the total MT. Notice that the relative time of occurrence of a given letter in the word "trouble" is almost constant from attempt to attempt.

Similar findings have been produced by Shaffer (1980, 1984) in a study of typing and piano playing, as well as by Roth (1988) using an overarm throwing movement. All these data support the notion that a given overall sequence can be sped up or slowed down as a unit while the constant phasing in the sequence is maintained. These data suggest that all the different instances of typing the word "trouble" in figure 6.19 were produced by the same motor program but with a different duration parameter.

One more type of research paradigm has provided evidence that is important to consider. A series of studies by Wulf and colleagues used a research strategy in which variables that are known to affect learning produced different effects depending on what was learned or measured (much more will be described about learning variables in chapters 12 and 13). This strategy attempts to look for patterns of *dissociations* in learning, such that a particular learning variable has different effects on the learning of relative timing as compared to overall duration. These studies have shown that reducing the frequency of augmented feedback enhances the learning of relative timing (Wulf & Schmidt, 1989; Wulf, Lee, & Schmidt 1994; Wulf, Schmidt, & Deubel 1993), but has either no effect or even a degrading influence on learning to scale absolute duration (Wulf & Schmidt, 1996). Similarly, practice that encourages movement variability facilitates the

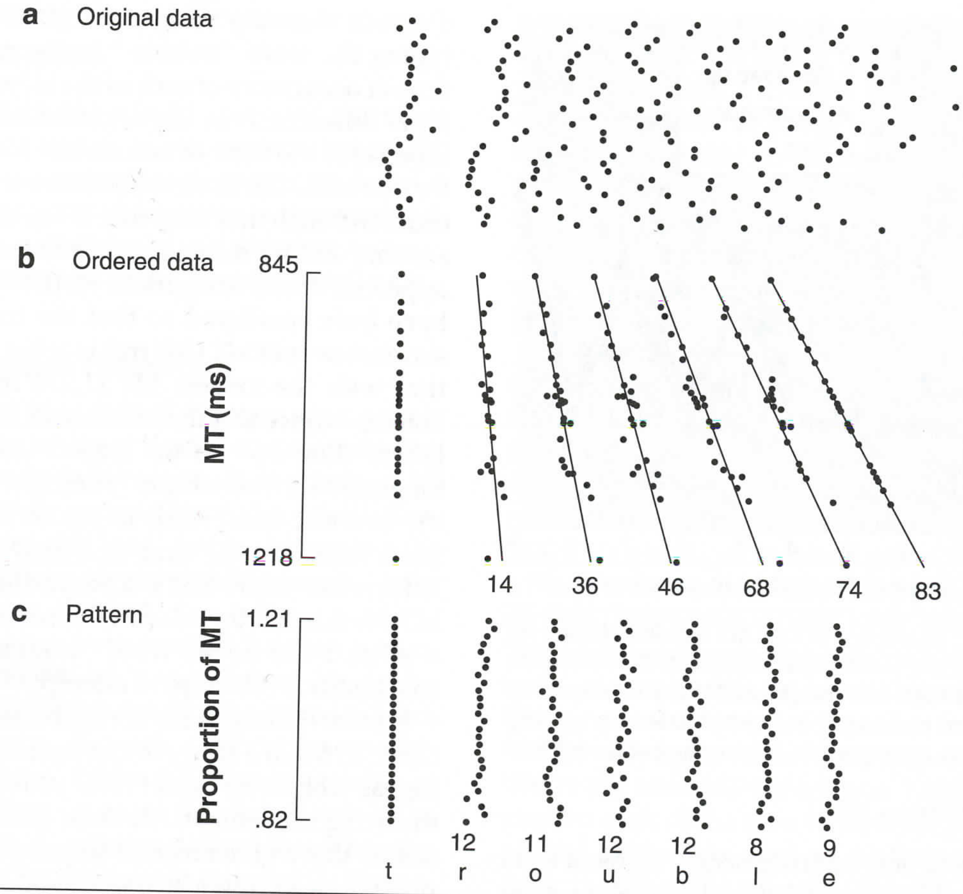

Figure 6.19. Temporal structure in typing the word "trouble." (a) Words are shown in the same order in which they were originally typed; (b) the same words are ordered in terms of their overall MT; (c) the letter durations are expressed as proportions of overall MT.
Reprinted from Terzuolo and Viviani, 1979.

learning of relative timing, but not the scaling of absolute duration (Wulf & Lee, 1993; Wulf & Schmidt, 1994b, 1997). Together, these findings support the separability of parameters and the invariant characteristics of timing skills.

Overall Force Parameter

A second parameter proposed for implementing a generalized motor program is an overall force parameter that modulates the amounts of force produced by the participating muscles. The force parameter is involved with determining how forcefully the relevant muscles will contract when they are recruited by the program. The evidence is weak that such a parameter is actually present, but logically a force parameter is included in the model.

Pew (1974a) described, as an example, a post office in which a conveyer belt carried small packages to an employee to be sorted. The person picked up the package and, with a "set shot" that might be considered good form for a basketball player, tossed the package into one of about 15 equidistant bins for later delivery. This package-sorting "system" required a number of processes on the part of the performer. First, because the bins were equal distances from the person, the final velocity (as the package left the hand) of each of the packages needed to be approximately the same in order for each package to reach its bin, regardless of its weight. But a package with a larger mass will require the application of more force at a *given* duration in order to achieve the desired terminal velocity. Thus, the performer must choose a force parameter that can be applied to the generalized "set shot" program. Presumably, the person would pick up the package, heft it to determine its mass, and then select a force parameter for the generalized program that would achieve the proper goal. The program can be run when the force and duration parameters have been selected.

Another example that supports the concept of an overall force parameter comes from Hollerbach (1978). Figure 6.20 shows the acceleration tracings from a subject writing the word "hell" two

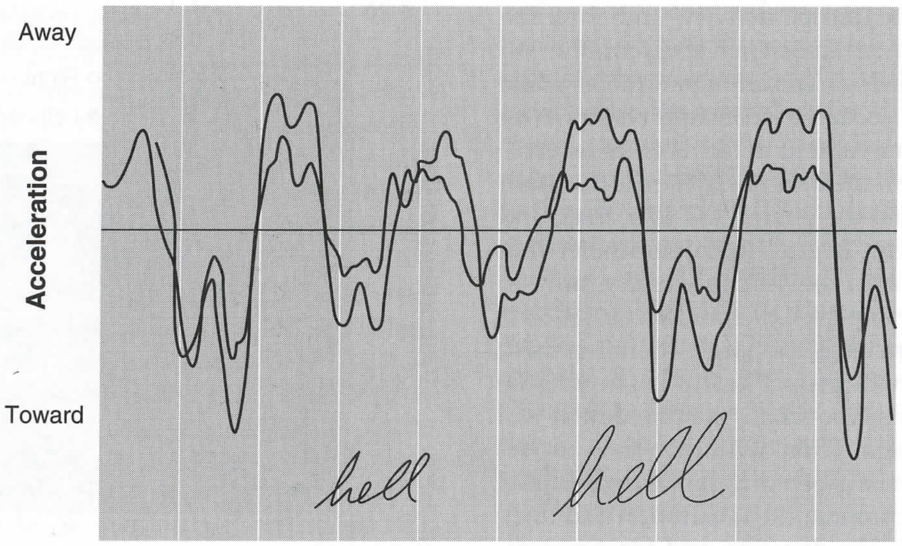

Figure 6.20. Vertical accelerations produced in writing the word "hell," with one word having twice the amplitude of the other. (The tracings show a remarkable degree of temporal agreement, with systematic differences in amplitude of acceleration.)

times, one word being twice the size of the other. The accelerations are, of course, directly proportional to the forces that the muscles are producing during the action. The tracings have the same temporal pattern, yet the accelerations in the tracing for the larger word are uniformly larger than those for the smaller word. It appears that the forces applied to the pen were simply increased while the original temporal pattern was maintained. Of course, increasing the force leads to increased distance that the pen travels; hence, the word is larger with the same spatial-temporal pattern. Similar interpretations can be made from a study of handwriting by Denier van der Gon and Thuring (1965), who showed that when the friction of the pen on the writing surface was increased, a systematic decrease in the writing size resulted but with no change in the pattern of letters produced.

In the examples just cited, the overall force parameter applies to the participating muscles proportionally, maintaining the relative forces applied to the limb proportionally. This concept is very much like the overall duration parameter, which is applied to the sequence as a unit. A less restrictive view is that the force parameter can be applied to various actions in the sequence without affecting other actions in the body. For example, carrying a heavy backpack would seem to require that more force be applied to the muscles that operate against gravity in walking, but the muscles that cause the foot to move through the air in the swing phase would not need to have extra force applied to them. Perhaps a force parameter is selected that applies only to those aspects of the program that require extra force. However, this idea has the disadvantage of requiring the motor system to do more "computing" in order to move.

Interaction of Duration and Force Parameters

There is a further argument with respect to the necessity for a force parameter, but it is less obvious than the one just given. Consider a movement in which you begin with your elbow straight, flex the elbow to 90°, and then extend it to the straight position again, completing all of the movements in an overall MT of 300 ms. The motor program presumably determines the phasing of the biceps, the cessation of the biceps and the initiation of triceps (for the reversal), and the contraction of the biceps to bring the movement to a stop. Now consider what would happen if you simply decreased the duration parameter of the program without changing a force parameter. Selecting a shorter duration parameter would cause the program to move through the biceps-triceps-biceps sequence more rapidly while keeping the forces produced by these muscles constant. What will happen to the movement? Because the impulses will be shorter in time, the impulse will be smaller, and the limb will not have moved as far in the time allowed for biceps activity, and thus the movement will reverse itself short of the 90° position. Decreasing a duration parameter while holding a force parameter constant results in an inappropriate movement in terms of its extent.

One possible remedy is to choose the duration parameter so that the overall MT is correct, and then to choose an overall force parameter that will be sufficient for the limb to actually move to 90° before reversing itself (Schmidt et al., 1979). If the force parameter is too large, the movement will go too far in the proper amount of time; if the force parameter is too small, the movement will not go far enough. Thus, with this view, movement distance for a given program is determined by a complex combination of duration and force parameters. Clearly, duration and force parameters must complement each other. The selections of the force and speed parameters are not independent, as the particular value of the force parameter will depend heavily on the chosen duration parameter.

Muscle-Selection Parameter

In the analysis of the handwriting examples shown in figure 6.14 (from Lashley, 1942), we argued that the muscles for the particular action could not be stored "in" the motor program, because the same program produced movements in entirely different limbs. Thus, the sequential ordering embedded in the motor program is considered to be *abstract* with respect to which specific joints and muscles are to be added during the *implementation* of the program. In this case, it is reasonable to think of the specification of muscles (or joints) as another parameter of the motor program.

Additional evidence for this view comes from numerous experiments using a *bilateral-transfer* paradigm. For example, Shapiro (1977) used a wrist-twist task similar to that described earlier, having subjects practice this sequence with the right hand for 5 days. Then she asked the subjects to make the same movements with the left hand, which had never been used for this pattern before. She found a pattern of activity shown in figure 6.21, in which the well-practiced right-hand pattern is indicated by the open circles and the novel left-hand pattern is indicated by the closed circles. The two patterns are nearly identical, and the case can be made that the program that was generated by practice with the right hand could be produced with the left hand. Further evidence for the preservation of sequence

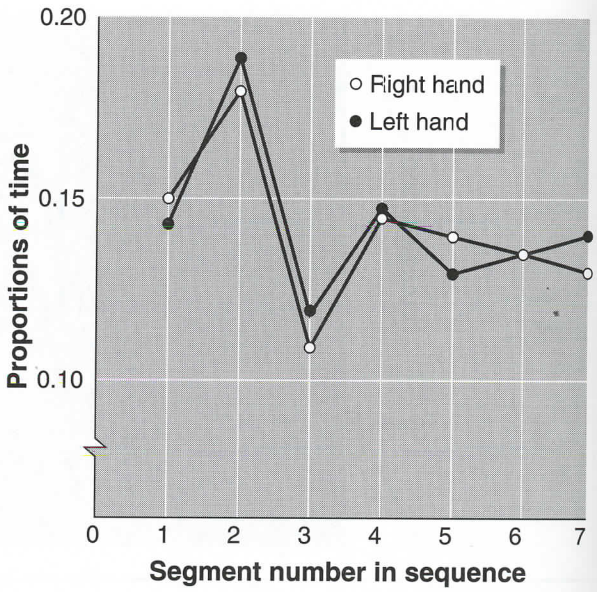

Figure 6.21. Proportions of total MT required to traverse various movement segments in a wrist-twist task. (The pattern is similar for the practiced right hand and for the unpracticed left hand.)
Reprinted from Shapiro, 1977.

learning during transfer to different effectors has been shown by Keele, Jennings, Jones, Caulton, and Cohen (1995; see also Jordan, 1995; Keele, Cohen, & Ivry, 1990).

The Phonograph Record Analogy (Again)

Earlier we presented the analogy between a motor program and a phonograph record, with information about order, phasing, and relative force structured "in" the motor program to define a given pattern. To complete the analogy, add the ideas about parameters just discussed. The overall duration parameter is analogous to the speed of the turntable. When the record turns more rapidly, the overall duration of the record's activity decreases, but the phasing of sounds remains invariant. Next, the overall force parameter can be thought of as the volume control, whereby the same pattern of action can be produced either loudly or softly. This is very much like writing in small or large letters with the pattern of the writing remaining the same. Muscle-selection parameters are analogous to the operation of speakers. If you have one set of speakers in one room and another set elsewhere, you can choose which ones will play the music. If the speaker is analogous to an effector, then this is an example in which the same pattern is produced in two different set of "muscles."

Changing Parameters and Programs

Additional evidence supporting the generalized motor program comes from experiments in which some aspect of the movement has to be changed during the movement. For example, Quinn and Sherwood (1983) had subjects make elbow flexion or extension movements, following through past a switch near the end, such that the time from the beginning of the movement to the switch was 400 ms. Occasionally an auditory signal, administered in different blocks of trials, would instruct the subject to either (a) move faster or (b) reverse the movement. The findings, similar to those from earlier studies in this same general paradigm (Gottsdanker, 1973; Vince & Welford, 1967), showed that the latency of the corrections (the interval from the auditory stimulus until the first EMG change) was 100 ms shorter when the movement had to be sped up than when it had to be reversed. Theoretically, with a reversal, the subject has to stop running a given program and select, parameterize, and initiate a different one that will reverse the movement. However, when the movement is sped up, the existing program can be retained, and only a reparameterization must be done (e.g., with adjusted overall duration and force parameters); the stages involved in program selection and initiation can be bypassed.

Roth (1988) has shown that these principles hold for sport skills studied in the laboratory. For example, the RT to change a tennis ground stroke to a lob (presumably requiring a different program and different parameters) was estimated to be about 600 ms, whereas the RTs to change the direction or length of the ground stroke (presumably requiring only new parameters) were estimated to be about 200 ms less. Analogous results were provided for table tennis and volleyball skills, suggesting that the difference between program *plus* parameter selection versus only parameter selection is general across a variety of movement behaviors.

Concerns About Invariant Relative Timing

The generalized motor program theory was first proposed over 20 years ago, and there have been numerous empirical and theoretical examinations of its predictions since then. In general, the theory has held up well. However, as with all theories, some data and analyses do not provide support.

The most contentious issue with regard to generalized motor programs has been the concept of *invariance,* especially as it relates to relative timing. We argued earlier that in order for a timed segment to be considered invariant, its proportion of time, relative to the total duration of the activity, must be constant over a series of separate executions of the program. But have another look at the phasings for each letter of the word "trouble" that are illustrated in figure 6.19c (from Terzuolo & Viviani, 1979). Although the relative durations for each letter show rather consistent phasings, there are still some deviations. The questions that arise are these: Are these deviations meaningful? And how do you decide whether they are or not?

Statistical Invariance

A qualitative answer is to draw a straight line through the center of the data points plotted in figure 6.19c (this has already been done with the absolute timing data in figure 6.19b). If the data were perfectly invariant, then all the individual data points would fall exactly on vertical lines—and the more they fall off the line, the weaker is the evidence for invariance. In reality, there is very little chance that motor behavior will ever show true, perfect invariance. Therefore, the question is how much deviation from perfection can be tolerated before we begin to *reject* a description of the data as being invariant.

A partial solution to this debate was provided by Gentner (1987). He proposed two statistical methods for assessing relative invariance in a set of data. One method, called the *constant-proportion* test, uses statistical *regression* to assess whether or not a set of ordered phasings has a slope that deviates from zero. The amount of invariance is indicated by expressing relative time as a linear function of the total time. If there is a systematic increase or decrease in the relative proportion accounted for by a segment, then the slope of the regression line will deviate significantly, either positively or negatively from zero, indicating that the relative timing of the segment was not invariant across different absolute durations.

The other approach proposed by Gentner (1987), called the *interaction* test, uses the statistical method of *analysis of variance.* Basically, the method is an analysis showing whether the timing of components that make up the action, combined with other experimental factors (such as instructions to go slow or fast), results in variances that are additive or interactive. Additive (or main) effects in the *absence* of interactions suggest that the component's relative timing does not change as a function of the other conditions in the experiment—that is, that the timing of the components is invariant across the levels of the other factor(s). The presence of interactions, however, suggests that specific invariances (as indicated by the factors that are interacting) do not exist.

Gentner's (1987) analysis provided an objective, statistical solution to the problem of assessing invariance. Using these methods, Gentner reanalyzed some previously published data sets and found that, while some studies continued to support invariant relative timing, many others did not. More recent experiments, using the methods suggested by Gentner, have also produced evidence that is weighted heavily against perfect statistical invariance (Burgess-Limerick, Neal, & Abernethy, 1992; Maraj et al., 1993; Wann & Nimmo-Smith, 1990; but see also Franks & Stanley, 1991).

Do these statistical tests constitute rejection of the idea that relative timing can be invariant? The answer is unclear. Several questions can be raised from a statistical point of view, such as (1) the appropriateness of accepting the null hypothesis when significant effects are not found (which would be evidence in support of invariance) and (2) the level at which to set the cutoff point for the rejection of the null hypothesis. Gentner suggested that a level of $\alpha = .05$ is appropriate; however, a case could be made for more or less stringent levels.

Central Versus Peripheral Invariance

Heuer (1988, 1991) has raised another important issue to consider. He suggested that even in the absence of *measured* invariance, there may still be *central* invariance. Heuer's argument uses as a basis the Wing and Kristofferson (1973a, 1973b) distinction between central and peripheral timing. The idea is that the timing observed at the output or peripheral level is a combination of a central mechanism that periodically triggers an effector into action and the motor delays (such as neural delays and muscle recruitment) that occur following a central trigger. Heuer (1988) demonstrated that, given a central timing signal with perfect invariance in relative timing, a variable motor delay can result in an absence of invariance at the peripheral level.

Thus, perhaps because of complexities in the muscle properties in fast movements (e.g., Heuer & Schmidt, 1988; Gielen, van den Oosten, & ter Gunne, 1985; Zelaznik, Schmidt, & Gielen, 1986), it is possible that invariance at the level of the generalized motor program might not be detected by searching for invariances in motor output. Perhaps this issue will be resolved only by future research analyzing the brain potentials of action prior to movement output. We will return to the discussion of invariant relative timing when we discuss how the system regulates the coordination of two or more activities at the same time (in chapter 8).

Summary

The response-chaining hypothesis proposed by James (1890) was the first open-loop theory for motor control. It held that each action in a sequence is triggered by the movement-produced feedback from the immediately preceding action. Research on the role of feedback in movement performance under various deafferentation conditions has tended to show that sensation from the moving limb is not *essential* for motor performance, although it contributes to the smooth control of many actions. Thus, the response-chaining hypothesis cannot be universally correct, as it states that feedback from the responding limb is required for the control of a movement sequence.

Motor control scientists have three reasons for believing that movements are controlled by programs: (a) the slowness of the information-processing stages, (b) the evidence for planning movements in advance, and (c) the findings that deafferented animals and humans can show only slight decrements in skill. This is not to say that feedback is not used in movement. Feedback is used (a) before the movement as information about initial position, or perhaps to tune the spinal apparatus; (b) during the movement, when it is either "monitored" for the presence of error or used directly in the modulation of movements reflexively, and (c) after the movement to determine the success of the response and contribute to motor learning.

The earlier definition of motor programs as structures that carry out movements in the absence of feedback was found to be inadequate to account for the evidence about feedback utilization during movement. Also, problems were associated with the requirement for storage of many different motor programs (the *storage* *problem*) as well as with the means by which the motor program could create a novel action (the *novelty problem*). For these reasons, the motor program is thought of as *generalized*—containing an abstract code about the *order of events*, the *phasing* (or temporal structure) of the events, and the *relative force* with which the events are to be produced.

These generalized motor programs require *parameters* in order to specify how the movement is to be expressed. Such parameters are the *overall duration* of the movement, the *overall force* of the contractions, and the *muscle* (or limb) that is used to make the movements. With such a model, many different movements can be made with the same program (reducing the storage problem), and novel movements can be produced through selection of parameters that have not been used previously (reducing the novelty problem).

Notes

[1] Four of Taub's monkeys were reexamined 12 years after their surgery, and all revealed considerable functional reorganization of the brain structures responsible for sensory representation (Pons et al., 1991). Thus, it seems that motor and sensory systems may have both short- and long-term methods for adapting to the loss of peripheral feedback.

[2] This view could also be related to the reflex-chaining hypothesis. The difference is that the closed-loop model would have the feedback evaluated against a reference of correctness, whereas the reflex-chaining view would have the feedback from the movement trigger the next action directly.

[3] The generalizations that errors in execution can be corrected (a) without interference from other similar corrections and (b) with latencies unaffected by the number of possible corrections have not been studied carefully and should be considered with caution.

[4] Lashley probably had a good reason for choosing these particular words to be written; the term *motor equivalence* refers to the idea that different effectors can be used to achieve the same goal.