CHAPTER 13

THE LEARNING PROCESS

So far in the discussion of motor learning, our major concern has been the most important empirical findings about the acquisition of skills. It is time now to consider the underlying reasons for these findings and to ask about the nature of the motor learning processes that cause the motor system to behave in the ways identified in previous chapters. A part of this process is theoretical, in that we search for a fundamental understanding—stated as theories—of how the system "works" when it learns. But part of it is practical, in that a solid understanding of the system's function provides suggestions for practical application to situations that have not actually been studied; there is nothing as practical as a good theory (Kerlinger, 1973).

In this chapter, we consider the many ways in which various people have conceptualized the motor learning process. All these theoretical perspectives have as their basic goal an understanding of the changes in skill that occur with practice. However, we will see that a phenomenon as broad and common as this can be explained in various ways and at a number of levels of analysis (biomechanical, cognitive, and so on). At the same time, we will see that the concepts basic to these various theoretical ideas are already familiar from previous chapters, having to do with such notions as the building of new motor programs, changes in attentional requirements, the development of error-detection processes, and the like.

The chapter is divided into three major sections. The first section presents some fundamental ideas about the learning process. With this information in mind, together with information from the previous two chapters, we then present various theoretical views about motor learning. Two of these, which are considered major theoretical advances in the history of motor learning research, are presented in the second section of the chapter. The third section presents different perspectives on the learning process—perspectives that in one form or another can be considered major hypotheses about learning.

Characteristics of the Learning Process

Without a doubt, the most notable thing that happens when people practice is that they demonstrate increased proficiency in the task. Sometimes this is so obvious that it hardly needs to be mentioned, while in other cases the changes are more subtle and require special methods, observation, and rationale in order to be examined. In this section we describe a number of ways in which the learning process has been characterized, in terms of the various descriptions of the ways individuals change in their capability to perform a motor skill with practice.

Stages of Motor Learning

Many have noticed that learners appear to pass through relatively distinct stages (or phases) as they practice a skill. Bryan and Harter (1897, 1899) were among the first to study the acquisition of skill in considerable detail (see "Bryan and Harter's Hierarchy of Habits"). Learning was defined as a two-stage process by Snoddy (1926). Subjects in Snoddy's research learned to make hand movements but saw their hand only in a mirror—a task that requires abilities needed by a dentist, for example. According to Snoddy (1926), the *adaptation* stage involved acquisition of the neuromuscular pattern required to perform the task. Once the pattern was learned, the *facilitation* stage involved improving the efficiency of the pattern. Other two-stage views were later suggested by Adams (1971) and Gentile (1972). A three-stage view of learning was suggested by Fitts (1964; Fitts & Posner, 1967) and later Anderson (1982, 1995). These three stages, referred to as the *cognitive, fixation,* and *autonomous stages,* are discussed in more detail in this section. As you read these explanations, however, remind yourself that these stages are not discrete and fixed stages, but have "fuzzy" borders (see Anson, Elliott, & Davids, 2005, for an excellent discussion of Fitts' stages of learning).

Stage 1: Cognitive

When the learner is new to a task, the primary problem to be solved concerns *what is to be done*—that is, what actions need to be taken in order to achieve the goal of the task? Naturally, considerable cognitive activity is required so that

Bryan and Harter's Hierarchy of Habits

A fascinating early set of studies regarding the perceptual and motor changes that occur with learning was conducted by William Lowe Bryan (a psychologist) and Noble Harter (a telegrapher and student of Bryan's). The result of their shared interests was two landmark papers regarding the acquisition of telegraphic skills (Bryan & Harter, 1897, 1899). In these papers, Bryan and Harter presented the results of experiments that compared novice and expert telegraphers, as well as data they obtained by charting the acquisition of telegraphy skill over many months of practice. These papers present many interesting findings (Lee & Swinnen, 1993), but we will focus on one in particular.

Skill, in Bryan and Harter's view, was a process of achieving a *hierarchy of habits.* At the most basic level, telegraphy involves the ability to discriminate (perceptually and motorically) between *units* of time. A dot is one "unit" of continuous auditory signal. A dash is three "units" of continuous time. One unit of no signal occurs between dots and dashes within a letter (e.g., the letter *G* is a dash-dash-dot). Three continuous units of no signal denotes that a new letter is beginning, and six units marks a new word. This "language" of telegraphy lent itself well to Bryan and Harter's view of learning as a hierarchy of habits. The discrimination of time was learned quickly.

The alphabet became the next challenge. This, too, is usually learned quickly, and performance in sending and receiving code improves rapidly. However, Bryan and Harter then noticed something peculiar about the practice curves of some of their subjects: Periods of time would go by during which little or no improvement occurred at all, which were followed later by rapid improvements. They called these periods *plateaus* in performance that occur prior to the formation of a new, advanced capability. They proposed that rather than hearing dots and dashes, with learning, the telegraphers "hear" letters. With further practice they then "hear" words, and, for the most skilled, even larger units of a sentence. Presumably, the plateaus in performance occur because the maximum performance capability of one habit places a limit on performance, which is then lifted when a higher-order habit is formed. Although some of Bryan and Harter's views have been challenged at times (e.g., Keller, 1958), many of the basic concepts of progression through stages and to higher orders of skill have been retained in a number of conceptualizations of skill acquisition that remain popular today.

the learner can determine appropriate strategies to try to get the movement in the "ballpark." Effective strategies are retained, and inappropriate ones are discarded. As a result, the performance gains during this stage are dramatic and generally larger than at any other stage in the learning process. Performance is usually very inconsistent, perhaps because the learner is trying many different ways of solving the problem. The use of instructions, models, augmented feedback, and various other training techniques (discussed in chapters 11 and 12) is most effective during this stage because they assist the learner in this problem-solving process. Probably most of the improvements in the cognitive stage can be thought of as verbal–cognitive in nature, the major gains being in terms of what to do rather than in the motor patterns themselves. Adams (1971) termed this stage the *verbal–motor stage.*

Stage 2: Fixation

The second stage of motor learning begins when the individual has determined the most effective way of doing the task and starts to make more subtle adjustments in *how the skill is performed.* Performance improvements are more gradual, and movements become more consistent in the fixation stage. This stage can persist for quite a long time, with the performer gradually producing small changes in the motor patterns that will allow more effective performance. Many writers (e.g., Adams, 1971; Fitts, 1964) think that the verbal aspects of the task have largely dropped out by this stage, with the performer concentrating on *how to do* the action rather than on which (of many) movement patterns should be produced. This stage and the next (autonomous) are equivalent to what Adams called the *motor stage.*

Stage 3: Autonomous

After many months, perhaps years, of practice, the learner enters the autonomous stage, so named because the skill has become largely *automatic* in the sense discussed in chapter 4. That is, the task can now be performed with less interference from other ongoing activities. It is easy to find examples of high-level performers engaging in secondary tasks without interference—for example, the concert pianist who can shadow digits or do mental arithmetic without interference while sight-reading and playing piano music (e.g., Allport, Antonis, & Reynolds, 1972; Shaffer, 1971, 1980). Automaticity is usually evidenced with respect to particular kinds of simultaneous tasks, primarily those that we could class as verbal-cognitive; some other motor task could in fact interfere with a performance in the autonomous stage, as discussed in chapter 4 in detail. Even so, the performer gives the impression that she is performing without having to "pay attention" to the actions. This stage has the benefit of allowing the person to process information from other aspects of the task, such as the strategy in a game of tennis or the form or style of movement in ice skating or dance.

A major problem for motor behavior research is that this stage, which is of immense importance for understanding high-level skills, is only rarely studied in experiments on motor learning. The reasons are probably obvious. In paradigms in which subjects practice on laboratory tasks, such practice should continue for months before even approaching the levels of skill shown by high-level musicians, athletes, and industrial workers. It is very difficult to convince subjects to devote this kind of effort in experiments. Alternatively, we could use other, more natural tasks that learners are practicing anyway; but it is difficult to manipulate and control the many variables that would need to be used for a scientific understanding of the learning processes.

Some efforts at understanding the principles of automaticity have been made in this direction by Schneider and colleagues (Schneider & Fisk, 1983; Schneider & Shiffrin, 1977) in reaction-time (RT) tasks, and by Logan (1985, 1988) using speeded-decision tasks. Unfortunately, research involving more complex motor tasks is rarely taken to this stage of learning (but see Jabusch, Alpers, Kopiez, Vauth, & Altenmüller, 2009, for a recent exception).

Individual Differences and Motor Learning

Some important hypotheses for motor learning are framed in the language and methods of individual-differences research (see chapter 9). Beginning with the concept that a given motor performance is based on some small set of underlying motor abilities, one hypothesis simply states that this set of abilities changes in its makeup as practice continues. The abilities themselves do not change; this would violate the assumption (discussed in chapter 9) that abilities are to a large extent genetically defined and unmodifiable by practice. But what *does* change, according to this view, is the particular collection of abilities that underlie the skill being learned.

Studies Using Individual-Difference Variables

Fleishman and Hempel (1955) and Fleishman and Rich (1963) contributed important investigations in this area. In the Fleishman-Rich study, subjects practiced the two-hand coordination task, in which two crank handles had to be manipulated to cause a pointer to follow a moving target on a target board (figure 2.5). Separate from the practice on this test, the subjects were given two additional tests. In one, they were asked to lift small weights and to judge the weight relative to a standard weight. This test was called *kinesthetic sensitivity* because it seemed related to how sensitive the person was to applied tensions. A second test called *spatial orientation* was a paper-and-pencil test related to a subject's perception of orientation in space.

First, Fleishman and Rich divided their group of people into two, on the basis of their performance on the kinesthetic sensitivity test; then they plotted the groups' performances separately for the two-hand coordination test. As seen in figure 13.1*a*, the subjects classified as high and low on the kinesthetic sensitivity measure were not different on the two-hand coordination test in early trials; but later in practice, the subjects high in kinesthetic sensitivity began to outperform those low in kinesthetic sensitivity. The interpretation of these results is that kinesthetic sensitivity is an ability that increases in importance with practice, at least for this task. Next, consider the spatial orientation measure (figure 13.1*b*). The subjects classified as high on this test were

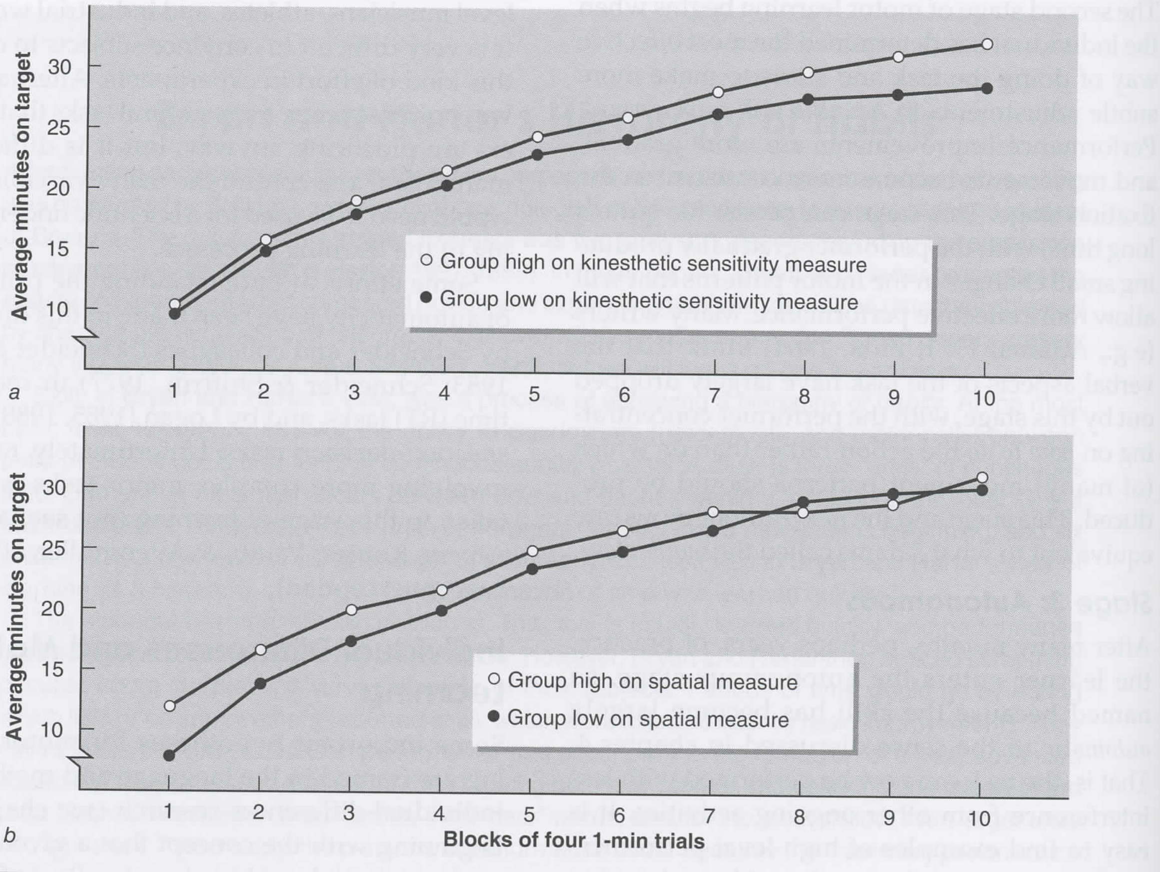

FIGURE 13.1 Performance on the two-hand coordination test as a function of practice trials. *(a)* Groups classed as high and low on a kinesthetic sensitivity test are plotted separately; *(b)* groups classed as high and low on a spatial orientation test are plotted separately.

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stronger performers on the two-hand coordination test than subjects classed as low, but only for initial performance. This result is interpreted as evidence that spatial orientation is an ability that is important for early proficiency in this task but appears to have little to do with performance in later practice.

Another way to view these results is that, for the two-hand coordination test, there is some *collection* of abilities that underlies it on trial 1. This collection includes some abilities related to the spatial orientation measure, and it does not include abilities related to kinesthetic sensitivity. As practice continues, the collection of abilities (but not the abilities themselves) changes, so that at the end of practice the task is made up of a somewhat different set of abilities. This collection could include some of the same abilities as in early practice, but it now has abilities related to kinesthetic sensitivity and does not have any abilities related to spatial orientation. Practice results in a shift in the abilities underlying a task (see also Bartram, Banerji, Rothwell, & Smith, 1985).

Practice and the Predictability of Skilled Performance

If the collection of abilities underlying a particular performance becomes rearranged systematically with practice, then the *prediction* of success in the skill will be based on different ability measures in early versus late practice. Fleishman and Rich (1963, figure 13.1) showed that, early in learning (but *not* later in learning), performance on the two-hand coordination test could be predicted (to some extent) from the spatial relations test; that is, the subjects *high* on this measure outperformed those classified as *low*. However, late in practice (but *not* early in practice), the two-hand coordination test performance could be predicted from kinesthetic sensitivity. This notion of prediction implies that the *correlation* between the two-hand coordination test and, for example, the kinesthetic sensitivity test would be zero in initial practice and larger in later practice. More generally, the hypothesis that the collection of abilities underlying some skill will change with practice says that the correlations between measures of various abilities and the criterion task performance will change with practice.

Intertrial Correlation Analyses

Take any motor task and measure a large number of subjects on each of a series of trials. Then correlate the performances obtained on every trial with those on every other trial and arrange these correlation values in an *intertrial correlation matrix*. Such a matrix is shown in table 13.1, reproduced from Jones' (1962, 1966) work on the two-hand coordination test. The bottom half of the matrix is omitted for simplicity (it is the mirror image of the top half). There are a number of interesting features of tables like this, as has been pointed out by Jones (1966).

Remoteness Effects First, notice that across any row of the table, the correlations become systematically smaller; they drop from 0.79 to 0.70 in the first row, from 0.87 to 0.82 in the second row, and so on. The top row represents the correlations of

TABLE 13.1. An Intertrial Correlation Matrix

Trial	1	2	3	4	5	6	7	8
1	—	.79	.77	.74	.73	.71	.71	.70
2		—	.87	.87	.84	.82	.82	.82
3			—	.91	.89	.87	.85	.86
4				—	.91	.88	.86	.88
5					—	.89	.90	.90
6						—	.93	.93
7							—	.94
8								—

Note. The boxed-in section forms the diagonal of the matrix, and the shaded portion is the "superdiagonal."

Adapted from Jones 1966.

trial 1 with trial 2, trial 1 with trial 3, trial 1 with trial 4, and so on up to trial 1 with trial 8. Thus, the number of trials between the two trials being correlated increases as we move to the right along any row. As a general rule, as the number of intervening trials increases, the correlation decreases. This effect is often called the *remoteness effect,* because the correlations between the trials depend on how "remote" (how far apart) the trials are from each other.

What is the meaning of the remoteness effect? First, remember that the correlation between two tests (in this case, two trials of the "same" test) is related to the number of common abilities they share. As two tests become more separated in the practice sequence, and become less correlated, the argument is that these performances are becoming dependent on fewer and fewer of the same abilities. In this sense, the remoteness effect is just another way to say that the motor abilities change with practice, as did Fleishman's research, discussed in the previous section.

Adjacent-Trial Effects Examine the data in table 13.1 again, this time concentrating on the correlations between adjacent trials—that is, between trials 1 and 2, between trials 2 and 3, and so on. These correlations can be found on what is called the *superdiagonal* (the shaded area), or the line of correlations that lies just above the diagonal of the matrix (unfilled squares in table 13.1). Notice that, as the adjacent trials are chosen later and later in the sequence, the correlations steadily increase. The correlation between trials 1 and 2 is 0.79, whereas the correlation between trials 7 and 8 is 0.94, the highest in the matrix. This is another well-known finding. The change in these adjacent-trial correlations along the superdiagonal suggests that performances become systematically more stable, in terms of their underlying ability structure, as practice continues.

Practice as a Process of Simplification An even more restrictive descriptor of the intertrial correlation matrix is what is called the superdiagonal form, for which any four arbitrarily chosen correlations within the matrix must possess a particular mathematical relationship with each other. (A discussion of the nature of this relationship is beyond the scope of this text, but see Jones, 1966.) The important point is that this superdiagonal form is derived from the hypothesis that the number of abilities systematically decreases with practice. In this sense, the task becomes "simpler" (in the sense of having fewer underlying abilities) with increased practice.

Individual Differences and Stages of Learning

A variation of Fitts' stages of learning view by Ackerman (1988, 1989, 1990, 1992; Ackerman & Cianciolo, 2000) suggests that, early in practice, performing the task should be based on abilities having to do with thinking, reasoning, mechanical knowledge, and so on. General intellectual abilities (information-processing skills) are the most important determiners of individual differences in performance during the cognitive stage of skill acquisition. Later in practice, these abilities should not be involved as much; and perhaps other abilities such as movement speed, RT, strength, and steadiness become the most important. Once the idea of the task has been acquired, the role of general intelligence as a determiner of individual differences drops off, replaced by more "motor" abilities during the fixation stage in performance.

Predicting Individual Differences During Different Stages According to Ackerman's theory, the correlation between tests of intellectual, perceptual-speed, and psychomotor abilities will differ during different stages in learning. These predictions are illustrated in the three graphs in figure 13.2. Figure 13.2*a* suggests that the correlation between general intellectual ability and task performance will be highest during the cognitive stage (stage 1) and will drop off quickly thereafter. The correlation between perceptual-speed tests and task performance should be low during the cognitive and autonomous stages (stages 1 and 3) but much higher during the fixation stage (stage 2), as presented in figure 13.2*b*. Figure 13.2*c* depicts very little contribution of psychomotor abilities until the autonomous stage (stage 3), at which point increasingly higher correlations are predicted.

Evidence for Ackerman's Integrated Model Ackerman asked subjects to perform a simple-RT task for six sessions, during which subjects pressed a key on a numeric keypad in response to the number shown on a screen (e.g., press the "1" key in response to the number "1"). As would be expected, subjects had little difficulty in figuring out what to do in this task and there-

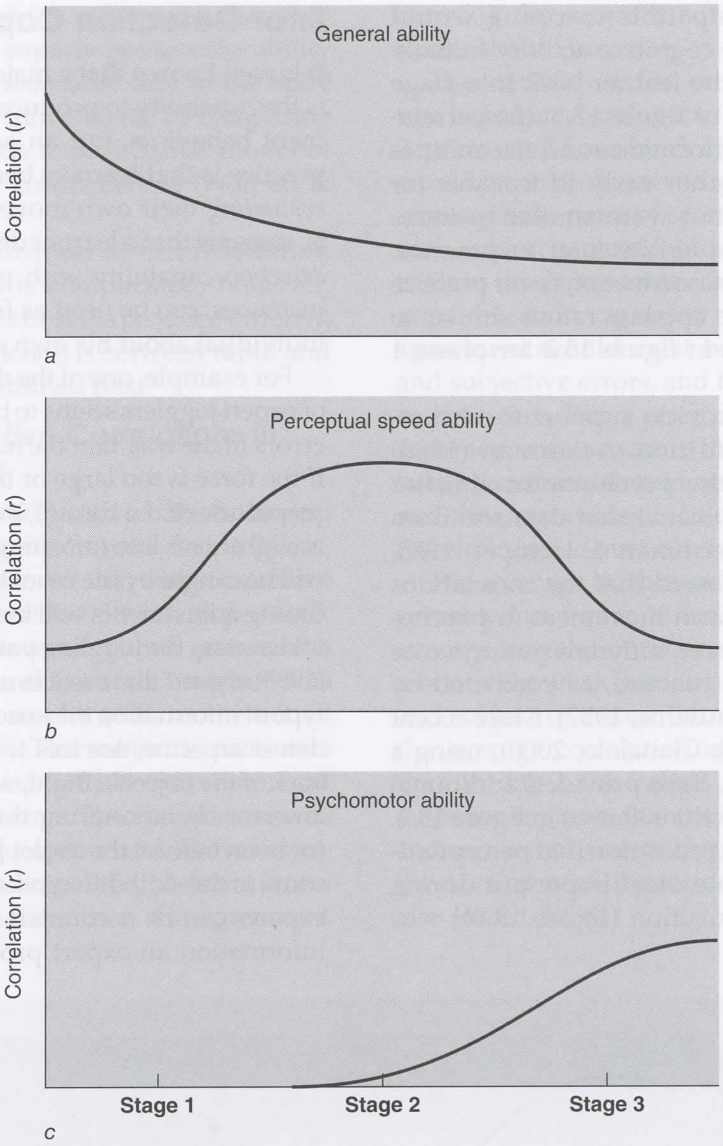

FIGURE 13.2 Predicted correlation of individual differences in general intellectual, speed, and psychomotor abilities at different stages of learning.

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fore would be expected to perform as if starting in stage 2 of practice rather than in stage 1. The correlations of task performance with general and perceptual-speed abilities are presented in figure 13.3. As can be seen, the correlations are higher for perceptual speed than for general ability in the training phase, as is predicted for stage 2. Moreover, the general trend taken by these correlations over the six sessions is similar to the predicted correlations illustrated in figure 13.2 for stage 2 of practice.

Then, in session 7, Ackerman transferred his subjects from the simple, compatible stimulus–response (S-R) mappings to less compatible mappings in which subjects pressed the key designated by a two-letter abbreviation system; the first letter indicated the numeric keypad *row* (e.g., L = lower row), and the second letter indicated the numeric keypad *column* (e.g., M = middle column). Thus, the stimulus "LM" (lower middle) indicates that the "2" key should be pressed; a "UR" denotes the "9" key. The rationale was that this incompatible mapping would require considerable cognitive activity initially in practice, forcing the learner back into stage 1. On the right side of figure 13.3, the correlations between RT performance and the abilities tests were much higher early in transfer for the general ability, but were similar to those for perceptual-speed ability later in practice. Again, the shape of these functions over practice in the transfer phase appears rather similar to the predictions seen in figure 13.2 for phase 1 of practice.

These findings provide support for Ackerman's theory. In addition, Ackerman (1988) found support for the psychomotor abilities predictions when he reanalyzed data sets from Fleishman (1956; Fleishman & Hempel, 1955, 1956). These data showed that the correlations between the rate of arm movement (a psychomotor ability) and three different performance tasks *increased* with practice, as predicted by the theory (see also Adams, 1957). More recent studies (Ackerman & Cianciolo, 2000), using a flight-simulator task, have provided additional support for the predictions shown in figure 13.2, *a* and *c*. However, the prediction that perceptual-speed abilities become most important during phase 2 of skill acquisition (figure 13.2*b*) was not supported.

Error-Detection Capabilities

It is well known that a major outcome of practice is the capability to produce more effective movement behaviors, but an additional outcome of practice is that learners become more capable of *evaluating* their own movement behaviors. That is, it seems that a learner develops a kind of *error-detection* capability with practice that, in many instances, can be used as feedback to inform the individual about his own errors.

For example, one of the distinguishing features of expert jugglers seems to be their ability to detect errors in the way that the hand releases the object. If the force is too large or too small (affecting the amplitude of the throw), or if the angle of release is slightly off line (affecting the location where it will be caught by the other hand), then spatial and timing adjustments will have to be made in order to maintain the juggling pattern. Beek and Lewbel (1995) argued that novices and experts differ in the type of information they use and how quickly they detect an error; novices tend to use visual feedback of the object in flight, while experts can detect an error by monitoring the sensory feedback as (or even before) the object leaves the hand. Thus, some of the skill differences between novices and experts can be accounted for by the "advance" information an expert processes indicating that

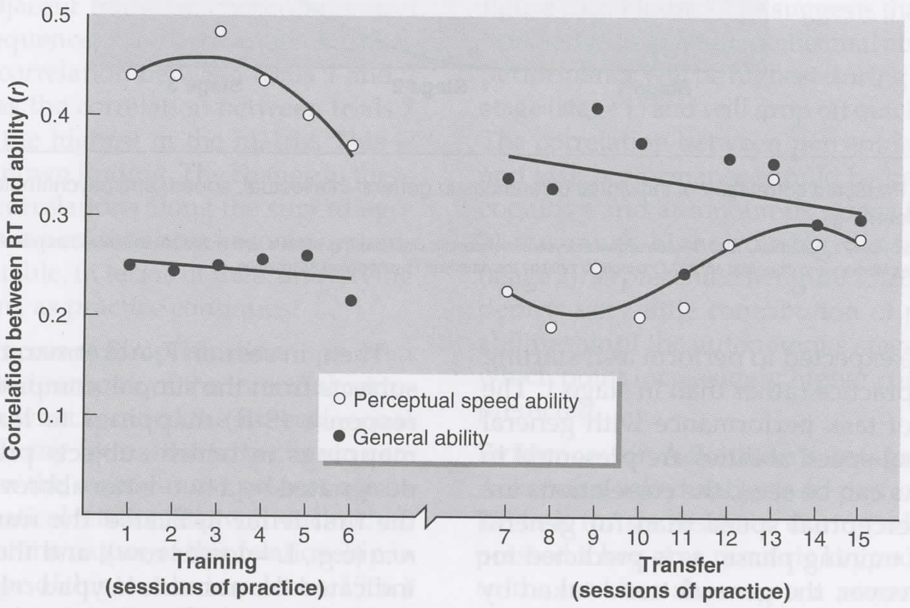

FIGURE 13.3 Test of theoretical predictions illustrated in figure 13.2.

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an error has occurred (or will occur). Another interpretation is that experts possess the ability to monitor the *motor commands* sent to the body parts that execute the movements, by comparing using these commands to an internal model of the expected sensory consequences (Wolpert & Ghahramani, 2000).

Studying the acquisition of error-detection mechanisms in skills is complicated, however, because different types of skills produce different results. A major distinction is between rapid and slow movements, examined next.

Objective–Subjective Correlations in Rapid Movements

Schmidt and White (1972) used a ballistic-timing task in which the subjects moved a slide 23 cm, with a follow-through, so that the movement time (MT) was as close to 150 ms as possible. The subject made a movement, then guessed the MT outcome score in milliseconds, and then was given knowledge of results (KR, or the actual score) in milliseconds. The subject's guess was subtracted from the subject's actual score, and was termed *subjective error*. The actual score was subtracted from the goal score and termed *objective error*. If an increased capability to detect errors is acquired with practice, then the agreement between the subject's subjective and objective scores should increase.

The statistic used to estimate this agreement was based on correlations (see section in chapter 2 for review). For a block of 10 trials, each subject would have 10 objective scores and 10 subjective scores. These pairs of scores were correlated for each subject separately for each of 17 blocks of trials in the experiment. The idea was that, if the error-detection capability was weak, almost no agreement would exist between the objective and subjective errors, and the correlation should be near zero. But if error detection increased in accuracy with practice, then the objective and subjective scores should agree to a greater extent, and the magnitude of the correlation statistic *(r)* should increase over blocks of trials.[1]

The average within-subject correlations are presented in figure 13.4. On the first block, the average correlation was about 0.28, indicating a relatively weak association between objective and subjective errors. But as practice continued, the average correlation increased to the point that on day 2 the values approached 1.0. This evidence suggests that the learners became more and more sensitive to their own errors through the development of error-detection processes (see also Rubin, 1978).[2]

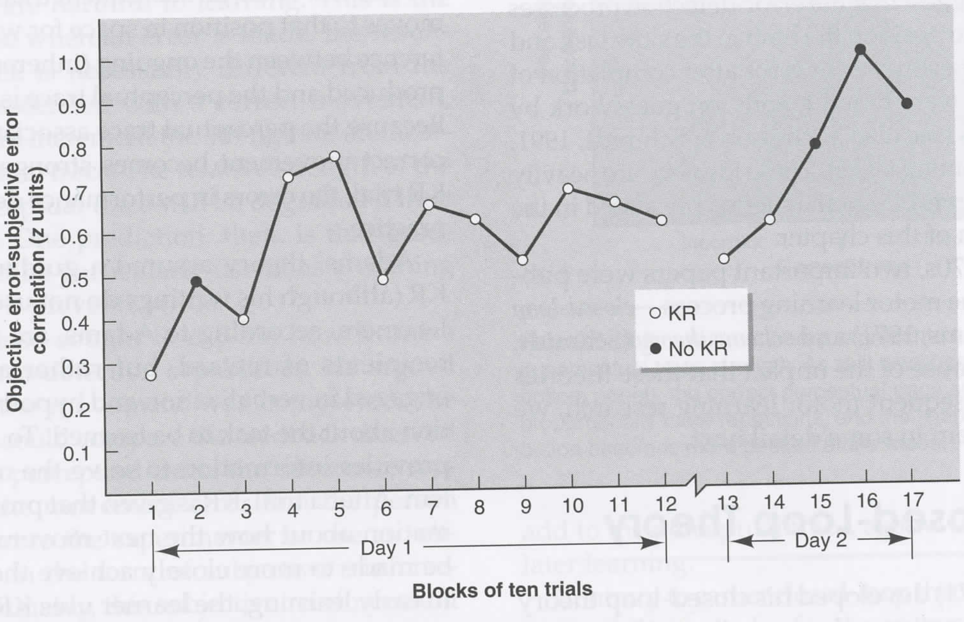

FIGURE 13.4 Average within-subject correlation between objective and subjective error as a function of practice trials. (Increased correlation is interpreted as gains in capability to detect errors; correlations are transformed to Z' units.)

Reprinted, by permission, from R.A. Schmidt and J.L. White, 1972, "Evidence for an error detection mechanism in motor skills: A test of Adams' closed-loop theory," *Journal of Motor Behavior* 4: 143-153, reprinted with permission of the publisher (Taylor & Francis Ltd, http://www.informaworld.com).

Objective–Subjective Correlations in Slow Movements

This is not so with slow movements. It appears that, for some slow movements at least, the error-detection processes may be responsible for actually *producing* the action. Because there is ample time to use feedback, it is thought that the subject in a positioning movement evaluates intrinsic feedback against the learned reference of correctness and moves to the position recognized as correct (Adams, 1971). If so, the error-detection capacity, being used to position the limb at the target, cannot then be used again after the movement as a basis for telling the experimenter about the error in positioning; if it were used, the errors would all be close to zero, as the action is based on that position that "feels like" it has minimum error. Then, if the subject is asked to report the error in positioning, she will have no idea whether or not the movement was on target.

Schmidt and Russell (1974) performed an experiment analogous to that of Schmidt and White but using a slow, linear-positioning task. In contrast to Schmidt and White (figure 13.4), Schmidt and Russell found consistently low within-subject correlations between objective and subjective errors, with most of the correlations being only about 0.20 even after 100 trials of practice. These findings suggest that the error-detection processes were used to position the limb in the slow task and that further estimates of error after completion of movement were based largely on guesswork by the subjects (see also Nicholson & Schmidt, 1991, who used timing tasks). These ideas figure heavily in the concepts of schema theory, presented in the next section of this chapter.

In the 1970s, two important papers were published on the motor learning process—*closed-loop theory* (Adams, 1971) and *schema theory* (Schmidt, 1975b). Because of the impact that these theories had on subsequent motor learning research, we describe them in some detail next.

Closed-Loop Theory

Adams (1971) developed his closed-loop theory of motor learning using a well-established set of empirical laws of motor learning, most of which were based on slow, linear-positioning movements. He believed that the principles of performance and learning that applied to these movements were the same as for any other kind of movement, and that using a well-established set of empirical laws from positioning movements would produce a solid basis for theorizing.

A Feedback Emphasis

Adams believed that all movements are made by comparing the ongoing feedback from the limbs to a *perceptual trace*—the reference of correctness, stored in memory, which is learned during practice. When the person makes a positioning movement, inherent feedback is produced that represents the particular locations of the limb in space. These stimuli "leave a trace" in the central nervous system (hence the name perceptual *trace*). With repeated practice, the person comes closer and closer to the target over trials; and on each trial another trace is laid down, so that eventually a kind of "collection" of traces develops. With practice (and KR), the learner's movements become increasingly closer to the target and with increasing consistency. Therefore, each trial provides feedback that tends to represent the *correct* movement with increasing frequency. In turn, the collection of perceptual traces comes to represent the feedback qualities of the correct movement. Then, on subsequent trials, the learner moves to that position in space for which the difference between the ongoing (inherent) feedback produced and the perceptual trace is minimized. Because the perceptual trace associated with the correct movement becomes stronger with each KR trial, the errors in performance decrease with practice.

Adams' theory assured a guidance role for KR (although his writings do not use this term). Learners, according to Adams, are not passive recipients of reward, but rather are actively engaged in verbalization and hypothesis formation about the task to be learned. To Adams, KR provides information to solve the motor problem. After a trial, KR is given that provides information about how the next movement should be made to more closely achieve the task goal. In early learning, the learner uses KR in relation to the perceptual trace to make the movement more precise, so that KR guides the movement to the target on successive trials. In such a view, KR does not produce learning directly. Rather, it creates the appropriate situation (i.e., being on target) so that the actual learning processes can operate. The movement's feedback produces an increment in "strength" for the perceptual trace.

We created the graphs in figure 13.5 to illustrate the learning process in Adams' theory. In the early stage of learning (figure 13.5*a*, top graph), the subject produces some correct movements but produces many incorrect movements, too. Thus, the movement feedback provides an increment to learning of the correct perceptual trace, but this trace is based on other, incorrect traces as well. In this stage of learning, performance is likely to be inaccurate and variable because of the spread of trace strengths among correct and incorrect perceptual traces. With the guidance of KR, the learner produces more and more correct movements, which has the effect of strengthening the correct perceptual trace and reducing the *relative* strength of incorrect perceptual traces, as illustrated in the middle and bottom graphs (figure 13.5, *b* and *c*). The reduction in relative strength of these incorrect perceptual traces improves the likelihood that the correct perceptual trace will guide the limb to the goal position with increasing frequency (i.e., less variability).[3]

One of the interesting implications of Adams' theory is that errors produced during the course of training are harmful to learning. This is the case because when an error is made, the resulting feedback is necessarily different from the feedback associated with a correct movement, and thus will increment the strength of an incorrect perceptual trace. The relative strength of the correct perceptual trace will be degraded a little bit as well. One prediction, then, is that guidance should be particularly useful as a training method, as it prevents errors.

Adams also sought to explain how learners develop error-detection capabilities. He argued that after the movement was completed, the individual could compare the feedback received against the perceptual trace, the difference representing the movement error that the person could report to the experimenter or use as self-evaluation in the form of subjective reinforcement. Presumably, this subjective reinforcement could be used to keep the movement on target without KR; and, according to the theory, keeping the movement on target can provide gains in learning because the feedback continues to add to the perceptual trace, again without KR in later learning.

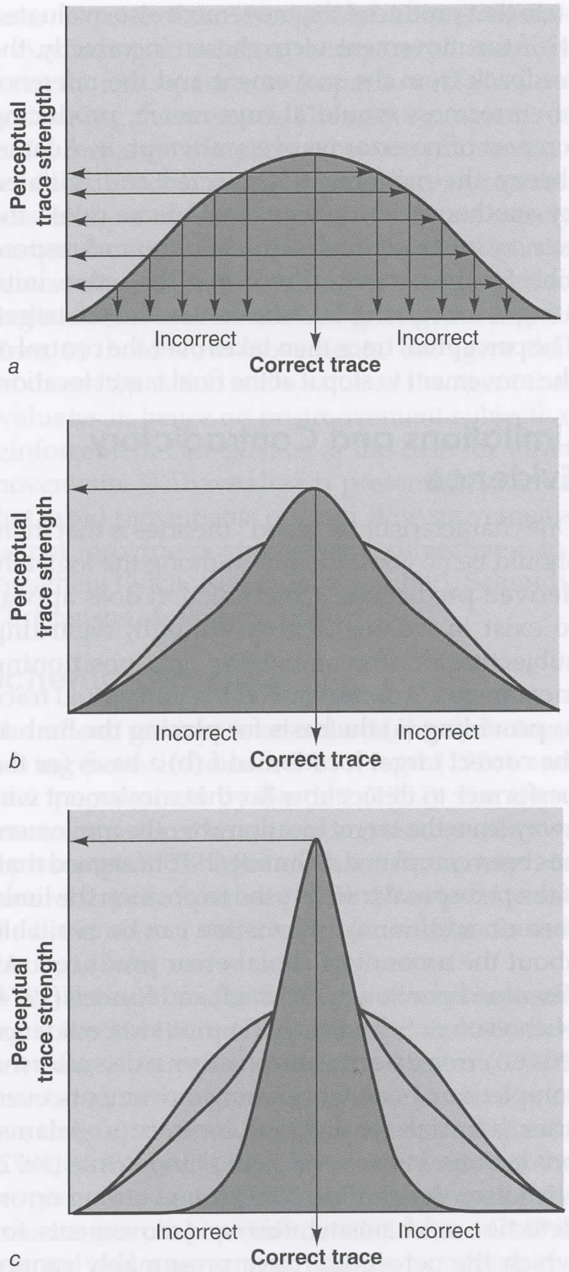

FIGURE 13.5 Adams' theory, represented as a growth in perceptual trace strength. As skill develops (from top to bottom panel), the correct perceptual trace accumulates proportionally more repetitions, and the shape of the distribution becomes more peaked at the mode.

Contrary to earlier closed-loop theorists, Adams realized that in order for the system to have the capacity to detect its own errors, two memory states must be present—one to produce the action and one to evaluate the outcome. What if the same state that produced the movement also evaluated it? If the movement were chosen incorrectly, the feedback from the movement and the reference of correctness would always match, producing a report of no error on every attempt. In Adams' theory, the movement is selected and initiated by another memory state that Adams called the *memory trace*—a "modest motor program" responsible for choosing the direction of the action, initiating it, and giving it a "shove" toward the target. The perceptual trace then takes over the control of the movement to stop it at the final target location.

Limitations and Contradictory Evidence

One characteristic of "good" theories is that there should be no contradictions among the logically derived predictions. Contradiction does appear to exist in Adams' theory, though, regarding subjective reinforcement for *slow* positioning movements. Adams viewed the perceptual trace as providing (a) the basis for placing the limb at the correct target location and (b) a basis for the performer to detect how far that movement was away from the target location after the movement has been completed. Schmidt (1975b) argued that, if the perceptual trace is used to position the limb, then no additional information can be available about the amount of actual error produced. As discussed previously, Schmidt and Russell (1974; Nicholson & Schmidt, 1991) provided evidence that no error-detection mechanism exists after the completion of slow positioning movements, even after 100 trials of practice, contrary to Adams' predictions. However, Schmidt and White (1972; Nicholson & Schmidt, 1991) found strong error-detection mechanisms after *rapid* movements, for which the perceptual trace presumably cannot be used to guide the limb during the movement. Adams did not make a distinction between these fast and slow movements, yet the evidence shows that they develop and use error-detection mechanisms very differently (e.g., Newell, 1976b).

Certainly one of the most damaging lines of evidence with respect to Adams' theory is the work on deafferentation in animals (Taub, 1976) and humans (Lashley, 1917), reviewed in chapter 6. Organisms deprived of all sensory feedback from the limbs can move reasonably skillfully, and they can even learn new actions (e.g., Taub & Berman, 1968). If the only mechanism for controlling skilled actions involved feedback in relation to a perceptual trace, then these animals should not have been able to produce the actions they did. Adams (1976b) has countered this argument by saying that the animals may have shifted to some other source of feedback, such as vision, to substitute for the lost sensations from the responding limbs. This may be the case for some of these studies, but it does not apply to all of them (e.g., Polit & Bizzi, 1978, 1979; Taub & Berman, 1968). Also, Adams' theory does not account for the data from various species showing the existence of central (spinal) pattern generators—structures apparently capable of generating complex actions without feedback from the responding limbs (see chapter 6). The failure to recognize the role of open-loop processes in movement control is a serious drawback for Adams' theory.

A second line of evidence against Adams' theory was provided by the literature on variability of practice. Because the perceptual trace is the feedback representation of the correct action, making movements *different* from the correct action (in variable practice) should not increase perceptual trace strength. Thus, Adams' theory predicts that variability of practice should be less effective for learning the criterion target than is practice at the target itself. In chapter 11 we reviewed this literature and found no clear evidence that variable practice was less effective than practice at the transfer target; and often the evidence said that variability in practice was superior to practicing the transfer target itself (e.g., Shea & Kohl, 1991). Because Adams' theory explicitly claims that experience at the target location is critical for the development of the perceptual trace, this evidence is quite damaging to his position.

Lastly, the role of KR in Adams' theory was to guide the learner to making the correct movement. However, as we reviewed in chapter 12, there is clear evidence that, when KR serves a guidance role, it has a degrading influence on learning, not the enhanced effect as would be predicted by Adams' theory.

Summary

At the time Adams' theory was proposed, it represented a major step forward for motor learning, as it presented a plausible, empirically based theory for researchers to evaluate. We believe that such evaluations have shown the theory to have a number of limitations, as outlined here, and that it no longer accounts for much of the currently available evidence on motor learning. But the theory served its intended purpose. It generated substantial research and thinking, and it paved the way for newer theories that account for the older data together with newer data. Thus, it remains as a key legacy in the growth of motor learning research.

Schema Theory

Largely because of dissatisfaction with Adams' theory, Schmidt (1975b) formulated a theory that was considered a "rival" to Adams'. The primary concern with Adams' position was the lack of emphasis on open-loop control processes, and the schema theory has a strong open-loop component. Yet, at the same time, many aspects of Adams' theory are very appealing, such as the emphasis on subjective reinforcement, the concern for slow movements, and the need to have one memory state that is responsible for producing the movement and another state that is responsible for evaluating it. Thus, schema theory borrowed heavily from Adams and others by retaining the most effective parts and replacing, changing, or eliminating defective ones. Also, the new theory was based heavily on knowledge about motor control and used these concepts in conjunction with ideas about learning processes to attempt to explain the learning of both rapid and slower movements (see also Schmidt, 1980, 2003).

Recall and Recognition Memory

Schema theory holds that there are two states of memory, a *recall memory* responsible for the production of movement and a *recognition memory* responsible for movement evaluation. For rapid, ballistic movements, recall memory is involved with the motor programs and parameters, structured in advance to carry out the movement with minimal involvement from peripheral feedback. Recognition memory, on the other hand, is responsible for evaluating the inherent feedback after the movement is completed, thereby informing the subject about the amount and direction of errors. Such structures satisfy the goal of having the memory state that produces the action be different from the memory state that evaluates its correctness, also one of the strengths of Adams' theory.

According to schema theory, recall memory is not thought to have an important role in slow positioning movements. The major problem for the learner is the comparison between movement-produced feedback and the reference of correctness. In these movements, the recall state merely pushes the limb along in small bursts, with the person stopping when the movement-produced feedback and the reference of correctness match. Here, in these slow movements, the agent that produces the action is the same as the agent that evaluates it; hence no postmovement subjective reinforcement can exist as is the case for rapid movements. We have already presented evidence that rapid movements do, and slow movements do not, provide postmovement subjective reinforcement (Nicholson & Schmidt, 1991; Schmidt, Christenson, & Rogers, 1975).

Schema Learning

The *schema* concept is an old one in psychology, having been introduced by Head (1926) and later popularized by Bartlett (1932). For these researchers, the schema was an abstract memory representation thought of as a rule, concept, or generalization. Schmidt (1975b) attempted to use the basic idea of the schema (or rule) to form a theory of how motor skills are learned.

At the heart of Schmidt's view of schema learning is the idea that movements are made by first selecting a generalized motor program (GMP), structured with invariant features (such as relative timing), then adding parameters as required in order to specify the particular way that the program is to be executed for any one particular instance (see chapter 6 for details). After a GMP is selected and a movement is made by adding the parameters, four types of information are available for brief storage in short-term memory: (1) information about the initial conditions (bodily positions, weight of thrown objects, and so on) that existed before the movement was made; (2) the parameters assigned to the GMP, (3) augmented feedback about the outcome of the movement; and (4) the sensory consequences of the movement—how the movement felt, looked, sounded, and so on. These four sources of information are stored only long enough that the performer can abstract two schemas. These abstract rules of how the sources of information are interrelated are called the recall and recognition schemas.

Recall Schema

The first of these relationships is termed the *recall schema* because it is concerned with movement production. Figure 13.6 represents the kind of process that occurs, according to the recall-schema idea. On the horizontal axis are the outcomes in the environment, such as the distance a ball traveled after being thrown. On the vertical axis are the parameters that an individual assigned to the GMP. The co-occurrence of the parameter and the movement outcome produces a data point on the graph. With repeated movements using different parameters and producing different outcomes, other data points are established. As the number of throws accumulates, a *relationship* between the size of the parameter and the nature of the movement outcome is established; this relationship is represented by the *regression line* drawn through the points.[4] With each successive movement using the program, a new data point is produced and the relationship is refined slightly. After each new movement, the various sources of information are lost from working memory, so all that remains of the movement is the updated rule, termed the recall schema in LTM.

But this is not the entire story. The relationship also includes information about the initial conditions of the movement, shown in figure 13.7. Here, the relationship between the parameters used and the outcome produced will depend on the nature of the initial conditions, such as different objects to be thrown. These different initial conditions are represented as different regression lines in figure 13.7.

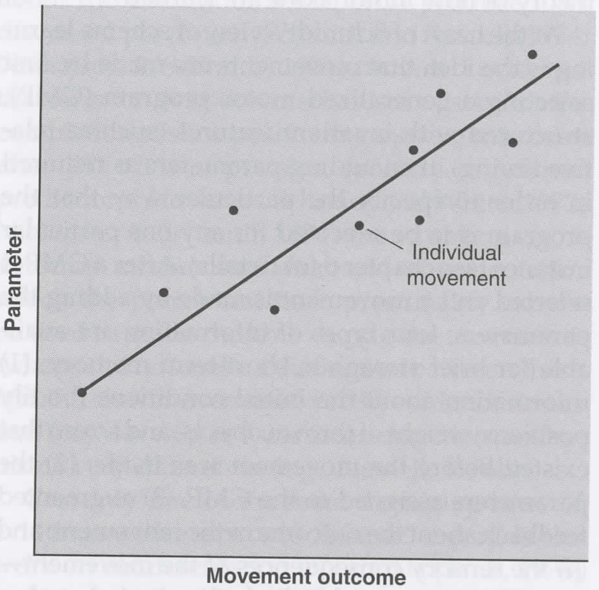

FIGURE 13.6 The hypothetical relationship between movement outcomes in the environment and the parameters used to produce them.

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How does the individual use the recall schema? On a future trial using this GMP, the person sets as a goal the desired environmental outcome, labeled point A on figure 13.7. Also, the particular initial conditions are noted (e.g., the weight of the object to be thrown), which might fit into the category represented by line 2 in figure 13.7. Then, with use of the relationship established by past experience, the rule is employed to select the parameter (labeled point B) that will come closest to accomplishing that goal. The value of this parameter is then applied to the GMP to produce the action.

Recognition Schema

The recognition schema, for movement evaluation, is thought to be formed and used in a way similar to the recall schema. Here the schema is composed of the relationship between the initial conditions, the environmental outcomes, and the *sensory consequences*. This relationship is represented as the

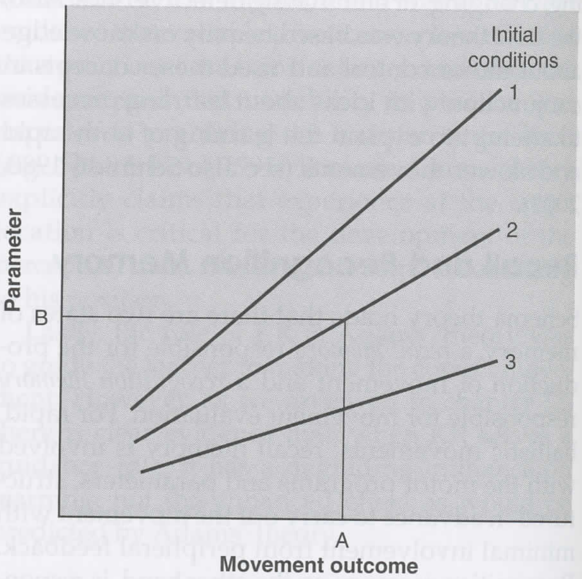

FIGURE 13.7 The hypothetical relationship between movement outcomes in the environment and the parameters that were used to produce them for various initial conditions: the recall schema.

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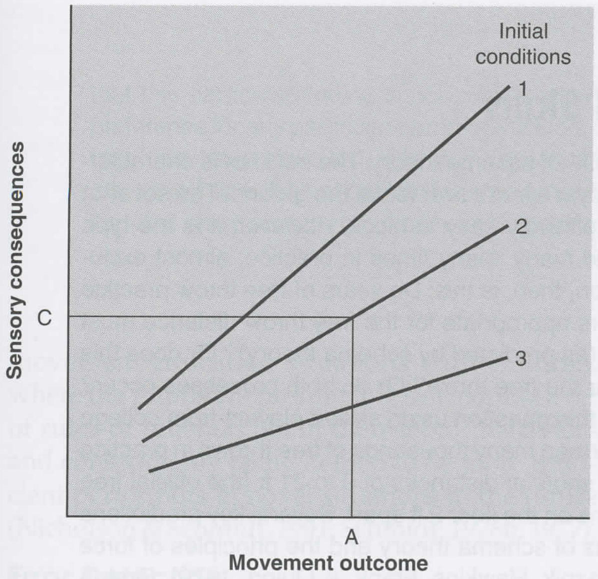

FIGURE 13.8 The hypothetical relationship between movement outcomes in the environment and the sensory consequences produced for various initial conditions: the recognition schema.

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three lines shown in figure 13.8. Before the movement, the individual selects a movement outcome and determines the nature of the initial conditions. Then, with the recognition schema, the person can estimate the sensory consequences that will occur if that movement outcome is produced. These, called the *expected sensory consequences* (labeled point C), serve as the basis for movement evaluation. The expected sensory consequences are analogous to Adams' perceptual trace.

Some Predictions About Schema Learning

The theory says that we acquire skills, at least in part, by learning *rules* about the functioning of our bodies—forming relationships between how our muscles are activated, what they actually do, and how those actions feel. Thus, movements for which any of the four stored sources of information are missing will result in degraded learning of the rules. One of the most critical of the sources is movement outcome information (augmented feedback, such as KR); if the person does not receive augmented information about the movement outcome, then even if the other sources of information are present, no strengthening of the schema can occur because the location on the horizontal axis will not be known. Similarly, if sensory consequences are missing (e.g., as in temporary deafferentation), then no recognition schema development can occur. In passive movements, no parameters are issued to the GMP (indeed, no GMP is selected to be run off), so no recall schema updating can occur.

Also, note that, according to schema theory, there are positive benefits from the production of movements whether they are correct or not. This is so because the schema is the rule based on the relationship among all stored elements, and this relationship is present just as much for incorrect movements as for correct ones. Adams' theory, you may remember, views errors as disruptive, as they degrade the relative strength of the correct perceptual trace (see figure 13.5).

Variability of Practice

The theory predicts that practicing a variety of movement outcomes with the same program (i.e., by using a variety of parameters) will provide a widely based set of experiences upon which a rule or schema can form. When the range of movement outcomes and parameters is small, all the data points such as those shown in figure 13.6 are clustered in one place, and less certainty exists about the placement of the line.[5] When a *new* movement is required, greater error will occur in estimating the proper parameters, expected sensory consequences, or both. Shapiro and Schmidt (1982) found considerable evidence that practice variability is a positive factor in motor learning, especially for children (see "Variability of Practice" in chapter 11).

Novel Movements

Schema theory also predicts that a particular movement outcome (specified by a particular value of the parameter) need not have been produced previously in order to be produced in the future. This is so because the basis for producing a new movement is a *rule* about parameter selection based on the performance of earlier similar movements. Research has shown that, after varied practice, novel movements can be produced about as accurately as they can be if the novel movement had been practiced repeatedly, and sometimes *more* accurately (see the section on variability of practice in chapter 11). This evidence suggests that motor learning may be primarily rule learning and not the learning of specific movements. Such ideas have been used for a long time in

Especial Skills

The *set shot* in basketball provides an interesting "test" of schema theory. The set shot is characterized as a deliberate shooting motion in which the player's feet never leave the ground. The set shot is not typically used in game action because it is relatively easy to block. However, it is the type of shot that is used for a free throw and is executed many, many times in practice, almost exclusively from the free throw line. An interesting question, then, is this: Do years of free throw practice establish a GMP, in which time and force parameters appropriate for the free throw distance must be generated when a free throw is to be performed (as predicted by schema theory)? Or does this practice result in a motor program that is specific for the free throw? Or do both processes occur? Keetch, Schmidt, Lee, and Young (2005) examined this question using skilled players from college basketball teams—subjects who probably had performed many thousands of free throws in practice and games. The players were asked to perform set shots at distances of 9 to 21 ft (the official free throw distance is 15 ft) from the basket, from locations on the floor 2 ft apart. Several key predictions were of interest, based on the combined predictions of schema theory and the principles of force variability (as presented in chapter 6; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). First, a negatively sloped regression line that relates the success of the shot to the distance from the basket was expected. The GMP would need to be parameterized with increased levels of force as the distance increased, thereby increasing the force variability in the movement output and increasing error. Second, schema theory predicts that the accuracy between 9 and 21 ft would fall on or very close to this negatively sloped regression line, because of the principles reviewed earlier in this section about the recall schema.

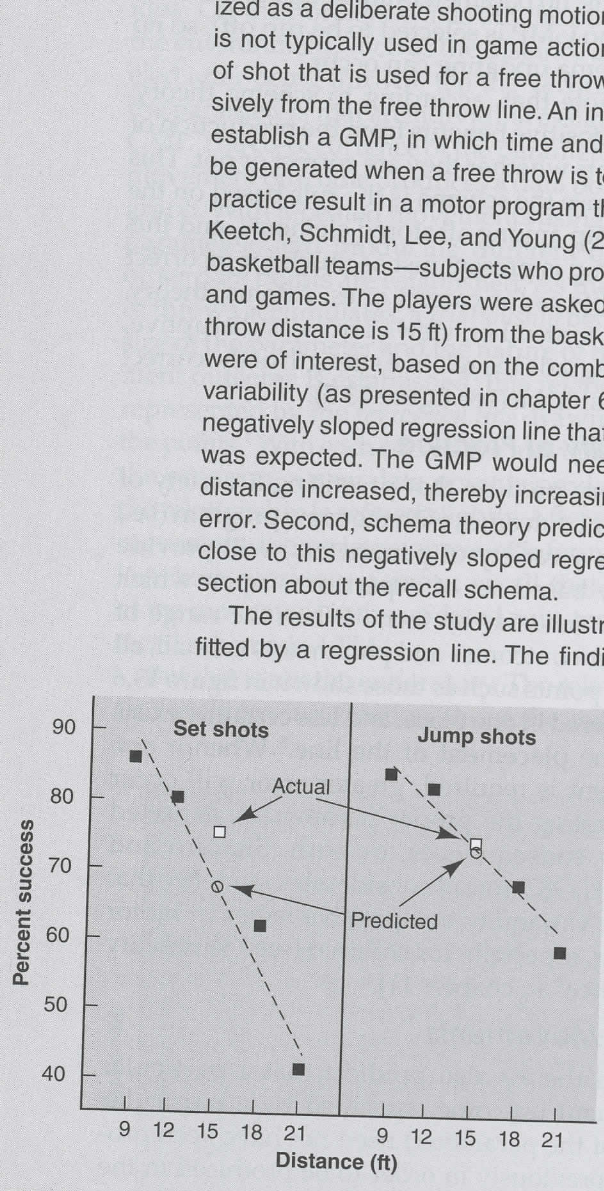

FIGURE 13.9 Schema theory accurately predicts the performance of a 15 ft jump shot (right panel) but severely underestimates the performance of a 15 ft set shot (left panel)—a free throw.

Reprinted, by permission, from K.M. Keetch, R.A. Schmidt, T.D. Lee, and D.E. Young, 2005. "Especial skills: Their emergence with massive amounts of practice," *Journal of Experimental Psychology: Human Perception and Performance* 31: 970-978. Copyright © 2005 by the American Psychological Association.

The results of the study are illustrated in the left side of figure 13.9, with the mean data points fitted by a regression line. The findings support all but one of the predictions: The regression line nicely fits four of the five data points. However, the key finding, which does not support schema theory, occurred at the distance of 15 ft—the foul line. From this distance, the players' success was considerably higher than predicted based on the schema regression. A similar effect of distance has been found in skilled baseball pitchers—who were much more accurate (than predicted) at the regulation pitching distance compared to other distances, including distances *just one foot* closer or farther from home plate than the normal pitching distance (60.5 ft; Simons, Wilson, Wilson, & Theall, 2009). But, when these basketball skills were performed by novices (Breslin et al., 2010) or by experts using jump shots (where the feet do leave the floor), all of the data points fit nicely on the regression line, as predicted by schema theory (see the right panel in figure 13.9). There was no advantage for a jump shot taken from the foul line, presumably because jump shots are not practiced more frequently at the foul line than at any other location as set shots are.

What do these results suggest? For the set shots, something specific and unique to the free throw distance had been learned through many years of practice at this distance. This specific capability facilitated performance only for the set shot and only at the 15 ft distance taken at an angle straight on to the basket, making it an "especial" skill—a rather special skill existing within a class of basketball set-shot skills. Note that this particular finding is not consistent with the schema view, as the theory gives no specific preference for any particular parameterization, regardless of the number of specific practice instances that have been executed. This study illustrates many questions of practical interest that have been discussed at a theoretical level in this and previous chapters, such as force-variability principles, variable practice, schema theory, and specificity of learning.

movement-education situations with children, where the pupils are presumably developing a set of rules or schemas about their motor behaviors and consequently being helped to be more proficient performers in novel situations in the future (Nicholson & Schmidt, 1991; Schmidt, 1976b, 1977).

Error Detection

Schema theory predicts that there should be no capability for error detection after a slow movement, whereas such capability should exist after a rapid movement. This is the case because the error-detection capability is actually used to produce the slow movement, leaving behind no capability with which to detect errors. Based on the information about closed-loop processes presented in chapter 5, if the movement was rapid (as was the case in the Schmidt & White, 1972, study), the subject would compare the feedback from the movement to the reference of correctness to define an error after the movement was completed. The error-detection process is not responsible for producing the action, and it evaluates the correctness of the action only *after* the movement has been completed. For reasons discussed before, there is insufficient time for the performer to take in the feedback, evaluate it, and make corrections before the movement is completed. According to the theory, the recall schema is thought to produce the movements, and the recognition schema is responsible for comparing the movement-produced feedback with the learned reference of correctness for evaluating the movement afterward. As mentioned during the discussion of Adams' theory, empirical evidence supports this prediction (Schmidt & Russell, 1974; Schmidt & White, 1972).

Limitations and Logical Problems

The emphasis of schema theory on the GMP concept represents both a major strength and major limitation of the theory. While we believe that the evidence strongly supports the GMP view (see chapter 6), the theory is mute in terms of how the program is formed in the first place, and this deficiency is readily acknowledged as a major problem with the theory (Schmidt, 2003). The following sections highlight other limitations.

Knowledge-of-Results Frequency

Strengthening of the schema depends on the subject's knowledge of the movement outcome, so higher levels of KR relative frequency would be expected to enhance schema learning as compared to lower levels. When relative KR frequency effects on overall learning were evaluated in chapter 12, the results appeared to contradict this schema theory prediction because reduced frequencies either had no effect on learning or in some cases enhanced it, rather than degrading it, especially so if the KR was "faded" over trials (Sullivan, Kantak, & Burtner, 2008; Winstein & Schmidt, 1990). These findings are further complicated by KR variables that appear to influence the learning of parameters and invariances in different ways, which is also contrary to schema theory (Shea & Wulf, 2005).

Contextual Interference and Cognitive Operations

One key prediction of schema theory is that variable practice would result in stronger rule learning than nonvariable (or constant) practice, and evidence supports that general prediction (but note the discussion in "Especial Skills"). However, schema theory makes no prediction about *how* the variable practice should be scheduled. Recall from the discussion of random versus blocked practice effects in chapter 11 that the amount of variable practice in these studies was equal. Because they share a common breadth of practice variability, schema theory fails to predict the learning differences that occur between random and blocked practice (Lee, Magill, &

Weeks, 1985). The explanations for contextual-interference effects stress the importance of cognitive operations during practice, which highlights a more general limitation of schema theory, as the theory provides no rationale for learning effects due to cognitive operations such as imagery, mental practice, and observational learning (Shea & Wulf, 2005; Sherwood & Lee, 2003).

Summary

Schema theory has provided an alternative to Adams' closed-loop theory of motor learning. Compared to Adams' theory, it has the advantage that it accounts for more kinds of movements; it seems to account for error-detection capabilities more effectively and seems to explain the production of novel movements in open-skills situations. Some logical problems need to be solved, and it is not clear that this can be done without discarding the entire theoretical structure (Petrynski, 2003; Schmidt, 2003; Shea & Wulf, 2005). There are some apparent failures of the evidence to agree with the theoretical predictions as well (e.g., Klein, Levy, & McCabe, 1984; Keetch et al., 2005). While the theory was a step forward, it should be clear that it does not provide a complete understanding of the data on motor learning. Even so, the theory provides a useful framework for thinking about skill learning because it is consistent with the literature on the GMP.

Differing Theoretical Perspectives of Motor Learning

The ideas presented next are probably best described as hypotheses about the learning of motor skills. They really do not satisfy the basic criteria for consideration as *theories* for a number of reasons. First, many of them are directed at only certain kinds of tasks, such as continuous tasks, positioning tasks, and tracking; and more generality is usually required for a theory. As well, some of these theoretical perspectives concern only a few experimental variables, and theories (such as closed-loop theory and schema theory) are usually thought to have more complete structures that are capable of explaining the effects of a variety of independent variables. Further, an important ingredient of a theory is that it makes testable predictions that can be falsified by experimental testing. Nevertheless, the theoretical perspectives that we consider next represent important advances in furthering our understanding of the complex interaction of processes involved in motor learning.

Cognitive Perspectives

Although both closed-loop theory (Adams, 1971) and schema theory (Schmidt, 1975) emphasized the role of memory structures in skill, the learning process depended on movement repetition and feedback. The development of the perceptual trace in Adams' theory and the recall and recognition schema in Schmidt's theory were mechanistic processes. Research conducted since these theories were published, on learning variables such as the contextual-interference effect (chapter 11) and various augmented-feedback effects (chapter 12), suggests that the role of cognitive processes in learning might be more complex than originally conceptualized in Adams' and Schmidt's theories.

Both of the major hypotheses regarding the contextual-interference effect suggest that cognitive processes play a key role. In the elaboration hypothesis, explicit contrasts and comparisons of the tasks to be learned were thought to benefit learning. In the reconstruction view, it was the process of planning a different action to be performed that boosted learning. In both hypotheses, learning was more effective if the elaboration or reconstruction was made more *difficult* (i.e., in random practice), suggesting that the *effort* with which the cognitive processes were undertaken had a critical impact on learning (Lee, Swinnen, & Serrien, 1994; Sherwood & Lee, 2003; Vickers, Livingston, Umeris-Bohnert, & Holden, 1999).

This cognitive emphasis suggested that something more was occurring during learning than executing movements and receiving inherent feedback, which could not explain the differences between random and blocked practice. In both practice conditions the subjects received the same amount of practice on the same tasks. The effects on learning of augmented-feedback variables such as concurrent feedback (chapter 12) also fit a cognitive perspective well. Movements that are produced with the assistance of concurrent feedback experience the same efferent commands and intrinsic feedback as nonguided movements. However, as argued in the KR-guidance hypothesis (Salmoni, Schmidt, & Walter, 1984; Schmidt, 1991), such variables tend to *minimize* the learner's need for evaluation of subjective information and other cognitive operations that are ordinarily undertaken in the preparation for the next trial.

The effects of these practice variables on the learning process are complex, however—they appear to have a strong dependence on the nature of the task and the experience level of the subject (Wulf & Shea, 2002). Some of these complexities were conceptualized in a theoretical framework by Guadagnoli and Lee (2004), who suggested that cognitive processing during practice is affected by the degree to which the subject is *challenged* during the practice period. The nature of the task, the conditions of practice, and the experience level of the learner interact to determine the amount of challenge present during acquisition trials. For example, random practice is considered more challenging than blocked practice and therefore should benefit learning. But, driving on a busy highway would be more challenging than driving in a deserted parking lot—and certainly much more challenging for the novice learner than the semiskilled driver. The framework suggests that variables such as random practice and concurrent feedback are effective to the degree that they challenge the cognitive processes of the learner. The framework suggests, however, that there exists a *point* at which these cognitively challenging practice conditions may not be needed. Indeed, they may be detrimental to learning if used for tasks that are already inherently challenging. Similarly, learning may be sufficiently challenged in individuals whose performance capabilities are put to the test merely by the demands of the task. In such cases, nonchallenging practice conditions (e.g., blocked practice or concurrent KR) would be expected to facilitate, rather than be detrimental to learning.

Although the Guadagnoli and Lee framework has provided an explanation for some of the complex relationships for learner, task, and practice variables that exist in the literature, it has limitations. Certainly, the concept of *task difficulty*, though frequently discussed as an important factor in the motor learning literature, remains a construct with an elusive definition. As well, the framework stops short of identifying exactly what cognitive processes are being challenged and how these processes change over the course of learning. Nevertheless, it is clear from the many studies conducted in the past several decades that the effects on learning of practice and augmented-feedback variables are much more complex than at first believed. The challenge-point framework represents an attempt to characterize the complexity of these relationships within a cognitive perspective. Some empirical explorations of the framework support its explanatory power, especially with individuals who have a compromised motor system (Lin, Sullivan, Wu, Kantak, & Winstein, 2007; Onla-or & Winstein, 2008; Sullivan et al., 2008).

Hierarchical Control Perspectives

As people learn, at least with some tasks, a change occurs such that motor control is shifted to progressively "lower" levels in the nervous system. The idea that motor behavior is hierarchical means that some "higher" level in the system is responsible for decision making and some "lower" level is responsible for carrying out the decisions. With respect to the information-processing analysis, the decision-making processes of the system are considered to be at a "higher" level in the hierarchy than the motor programming level. The hierarchical control perspective suggests that with practice, control is *shifted* from the "higher" to the "lower" levels in the system.

A good example that demonstrates research in this perspective was a study by Pew (1966), who used a tracking task in which the subject controlled the movement of a dot on a monitor by pressing one or the other of two buttons. Pressing the right button caused the dot to accelerate to the right, and the acceleration could be halted and reversed by pressing the left button, which caused the dot to accelerate to the left. If no button was pressed, the dot accelerated off the screen in one direction or another. The subject's task was to keep the dot in the center (this is called a compensatory tracking task).

A record from one of the subjects, with the velocity and position of the dot shown for early and late practice, is presented in figure 13.10. In early practice (figure 13.10*a*), the subject was making about three button presses per second, and the dot was never positioned near the center of the screen for very long. In this mode of control the subject pressed the button, waited for the visual feedback from the screen, decided that the dot was accelerating off the screen, then planned a movement to reverse it, pressed the other button, and so on. Here, the subject is using the executive (e.g., the information-processing stages) level predominantly, so that the "highest" level in the system is consistently involved in the production of every movement.

Compare figure 13.10*a* to figure 13.10*b*, which is from the same subject but later in practice. Here the motor behavior is quite different. First, the rate of responding is much faster, about eight movements per second. Next, the dot is much closer to the target because the button was pressed to reverse the direction of the dot before the dot was very far away from the target. Although we cannot be absolutely certain, the mode of control appears to have changed. It appears that now a long string of movements is prestructured as a unit, perhaps governed by a motor program. Thus, a separate decision from the executive level is no longer required for the control of each button press. Pew viewed this finding as evidence for the hypothesis that with practice, the subject shifted the control from an executive-based level to the lower-level control of the motor program, freeing the decision mechanism for other activities and making the movement more effective. Now, instead of controlling every button press, the executive level was controlling *groups* of button presses. With some subjects, the durations of the right and left buttons were adjusted, perhaps as a kind of "parameter" of the programmed activities.

It is easy to see the advantages of shifting the control from the decision-making level to the motor program level. Foremost is the freeing of the attentional mechanisms for use on higher-order aspects of the task (e.g., strategy), for doing other simultaneous tasks, or for simply resting so that the organism does not become fatigued. This freeing of attention is one of the major events that occur when people learn, and it is discussed further in later sections of this chapter.

Progression–Regression Hypothesis

Of particular relevance to tracking tasks is a hypothesis presented by Fitts, Bahrick, Noble, and Briggs (1959) about how changes in motor behavior occur with practice. In many tracking tasks, both in the laboratory and in the outside world, the movements of the track to be followed are made up of a number of components that can be described according to the physical principles of motion. At the simplest level is the position of the track at any moment. The next most complex aspect of the track is its velocity at any moment. A third and yet more complex aspect of the track is its acceleration at any moment. In designing servo systems to regulate some mechanical system, engineers can devise a simple system that responds to (a) only the position of the track,

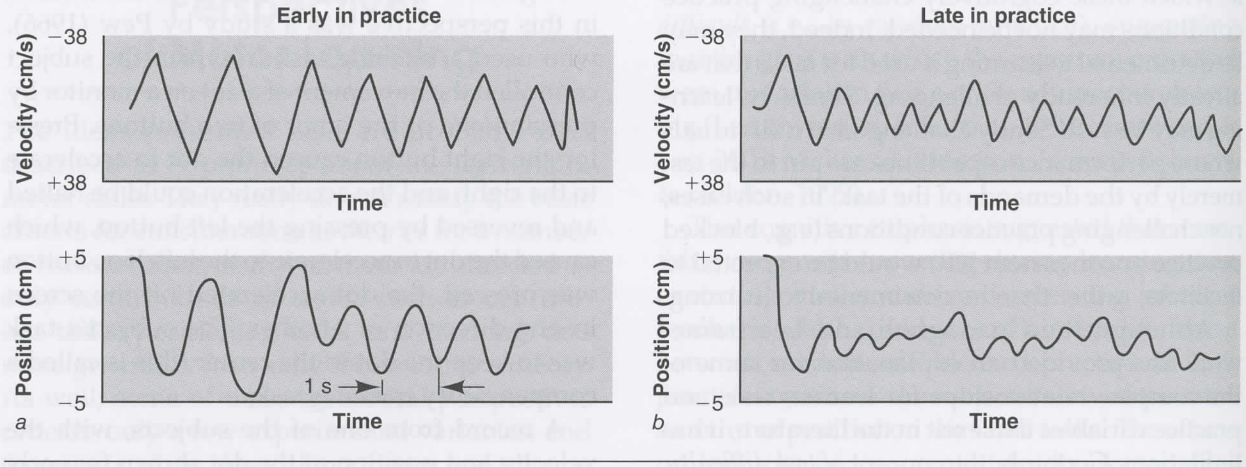

FIGURE 13.10 Performance records from a button-press tracking task in *(a)* early and *(b)* late practice. (Top records show instantaneous velocity, and bottom records show position with target represented as zero; responding is more rapid and more accurate in later practice.)

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(b) the position and velocity, or (c) the position, velocity, and acceleration. With each increase in the number of components being tracked, progressive increases are required in the complexity (and expense) of the mechanical or electronic devices that are to track them.

The *progression–regression hypothesis* for humans presented by Fitts and colleagues (1959) holds that, when the learner practices a tracking task, a progression develops in the learner's behavior in the direction of acting more and more like a complex tracking system. Early in practice, the person responds only to the simplest elements of the display (position). With increased practice, the learner becomes able to use velocity information, and even later comes to use information about acceleration as well. The regression portion of the hypothesis refers to what happens to the learner under stressful conditions or when forgetting of the movement has occurred (perhaps as a result of a long layoff). According to the hypothesis, the person regresses to a simpler level of control (from acceleration to velocity, or from velocity to position), with systematically reduced tracking performance as a consequence. Thus, the hierarchical nature of learning involves progressing to levels of more complex information, although performance effects may show reversals in the shift between levels in the hierarchy (regressing to less complex information).

A number of experimenters have studied learning in tracking tasks with respect to the progression–regression hypothesis. Fuchs (1962) found that the role of position cues in tracking decreased with practice, while the role of acceleration cues increased; and these effects were reversed when a secondary task was added to induce stress (see also Garvey, 1960). More recently, researchers have improved on the methods used in the earlier work and have provided additional evidence for a shift in movement control consistent with the hypothesis (Hah & Jagacinski, 1994; Jagacinski & Hah, 1988; Marteniuk & Romanow, 1983).

At least for tracking tasks, learners appear to respond to systematically different aspects of the track with practice and to reverse these trends with stress. We should be careful not to go too far with these conclusions, because we have no independent way of knowing exactly which stimuli were being used here. But the evidence is certainly consistent with the progression–regression hypothesis, and it contributes to an understanding of the hierarchical nature of the underlying changes in motor control when skill is achieved with practice or reduced under stress or with forgetting.

Making Movements Automatic

For more than a century (e.g., James, 1890), the idea of automaticity has been that, as a by-product of learning, skilled performers become able to perform with minimal attention cost and minimal interference from other cognitive information-processing activities. In chapter 4, we qualified this basic idea considerably, saying that "automatic" responding appears to involve a lack of interference with respect to particular secondary tasks; the notion that a given task is interference free for *all* secondary tasks is not supported by the evidence (Neumann, 1987). However, it does seem likely that the interference from many simultaneous cognitive information-processing activities is decreased, or even eliminated, with practice, thus freeing the individual to engage in other higher-order aspects of the task—such as planning strategies in tennis or race car driving, or projecting an affective emotional style in acting, music, or dance.

Automaticity can be considered in essentially two ways. First, and most common, is the idea that specialized information-processing structures are learned with practice and that they handle portions of the processing requirements of the overall task, such as feature detection and movement selection (e.g., Logan, 1988; Neumann, 1987; Schneider & Fisk, 1983; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Each process can occur when the appropriate stimulus conditions are presented and essentially triggered into action without awareness; indeed, sometimes the process cannot even be prevented (Schneider, 1985). By handling information processing in this way, the performer decreases the interference with other cognitive activities that compete for the same common resources. If, in a given task, all these processes can be so acquired, then the task can be thought of as "automatic," in the sense that the entire movement can occur without interference from particular groups of secondary tasks. In this view, the organism does not decrease the amount of environmental information processing that must be accomplished; rather, it processes this information differently—via specialized structures—and more quickly and with less interference from other simultaneous tasks.

However, another view is possible (see Schmidt, 1987). In at least some kinds of tasks (e.g., predictable and stereotyped), a major process of learning appears to be a shift from high-level conscious control to a lower-level programming control, as discussed in a previous section. With predictable tasks, the regularities of the environmental information can be learned and therefore can be anticipated during performance. If so, then the person does not have to process this information directly, but rather preprograms long sequences of action based on the prediction of the environmental information. Musicians "memorize" sheet music so that they are not dependent on it, and experienced drivers no longer have to watch their feet as they move from accelerator to brake in the car. Thus, being able to avoid processing environmental information frees those (conscious) information-processing activities for other tasks and makes the task appear "automatic," at least with respect to particular kinds of activities. In this view, the person does not necessarily process information any more effectively or faster, but rather learns to avoid having to process information by shifting to motor programming modes of control.

Of course, it could be that both of these viewpoints are correct but that each is relevant for a different class of movement tasks (e.g., those that have predictable and those that have unpredictable environmental information). Even within a particular skill, one can imagine specialized structures for detecting environmental information; then, sequences of preprogrammed output could be generated that reduce the reliance on such information for the next few hundred milliseconds. Both viewpoints provide ways of conceptualizing the acquisition of automaticity in high-level motor learning, and they present interesting issues for research in motor skills.

Creating Motor Programs

Of course, we know that many changes occur in our movements when they are subjected to practice, with actions tending to become more consistent, smoother, less effortful, and more routine or automatic with experience. These are all powerful changes, and in the next sections we consider some of the experimental evidence for them.

The Acquisition of Movement Pattern Consistency One important change in movement behavior with practice is that the movement outcomes tend to become more consistent, predictable, and certain with experience. Recall that variable error and other measures of variability (chapter 2) were devised to capture this aspect of motor behavior. In the study of these phenomena, the patterns of movement are measured by various kinematic procedures (e.g., video analysis, position–time records, computer simulation). Changes in the trial-to-trial consistency of these measures have been noted in an impressive variety of tasks, such as driving (Lewis, 1956), throwing (Stimpel, 1933), handwheel cranking (Glencross, 1973), table tennis (Tyldesley & Whiting, 1975), tracking (Darling & Cooke, 1987; Franks & Wilberg, 1984), keyboarding (Salthouse, 1986), bimanual coordination (Lee, Swinnen, & Verschueren, 1995), and many others. Such generalizations perhaps seem to be particularly appropriate with respect to the acquisition of closed skills, which have as a major goal the production of a consistent action in a stable (or predictable) environment—the kinds of skills for which stable motor programs are most highly suited. These changes in movement pattern consistency probably represent some of the most persistent phenomena in the motor learning area.

The Acquisition of Sequencing: The Gearshift Analogy Another hierarchical change in movement control with practice involves the ways in which movements are sequenced. MacKay (1976, personal communication) suggested that motor programs might be generated by stringing together smaller programmed units of behavior so that eventually this string of behavior is controllable as a single unit—such as in learning to shift gears in a car.[6] As you may remember, the act of shifting gears when you were first learning was a slow, jerky, step-by-step process; you lifted your foot from the accelerator, then depressed the clutch, and then moved the shift lever (probably in three distinct movements as well), until the entire act was completed (or until the car rolled to a stop going up a hill). Contrast this behavior to that of a race car driver, who appears to shift gears in a single, rapid action. Not only does the movement occur much more quickly, but also the elements of the action are performed with precise timing, and the actions of the hands and both feet are coordinated in relatively complex ways. In relation to the behavior of the early learner, the action seems to be controlled in a very different way, perhaps as a single programmed unit.

MacKay suggested that the various elements are learned in a progressive way to form the entire action. Figure 13.11 is a diagram of how this might work. Assume there are seven elements in the entire sequence and that these are at first controlled one at a time, each by a separate motor program. With some practice, the first two elements might come to be controlled as a single unit; the next three elements could compose another unit, and the last two could compose a third. Finally, with considerable experience, the entire sequence might be controlled as a single unit. This view is of a type of hierarchical control in that it specifies how the program is structured from the beginning, progressively growing in length by adding parts. Other possibilities exist as well (Marteniuk & Romanow, 1983).

We should be able to see evidence of the changes in these structures by using a fundamental principle of variability: The variability (inconsistency) of the elements *within* a unit should be considerably smaller than the variability between units. In figure 13.11 (middle practice), if we were to measure the interval from the end of element 2 to the beginning of element 3, the relative variability of this interval (expressed as the SD of the interval divided by the mean interval length) from trial to trial would be greater than the variability from the end of element 3 to the beginning of element 4. This is the case because the first two elements (2 and 3) are in different units (controlled by different programs), while the latter two (3 and 4) are supposedly controlled by the same program. Turning this logic around, if we found intervals in the sequence in which temporal variability was very high, this could be taken as evidence that the behaviors occurring at the opposite ends of this interval of time are members of different motor programs. This is similar to the method used by Young and Schmidt (1990, 1991) and Schmidt, Heuer, Ghodsian, & Young (1998) to investigate the acquisition of new bimanual coordination programs (see also chapter 8).

Combinations of Reflexes Another way that motor programs are thought to be formed in practice is through the combination of fundamental reflexes (Easton, 1972, 1978). According to this viewpoint, higher levels in the motor system are capable of tuning or adjusting lower spinal levels so that the existing reflexes (e.g., the stretch reflex) can be controlled in ways that result in skilled actions. Thus, rather than hypothesizing that the motor system builds a set of commands that come to exist as a stored motor program, Easton held that the "commands" are really ways of controlling the preexisting reflexes. Such emphases

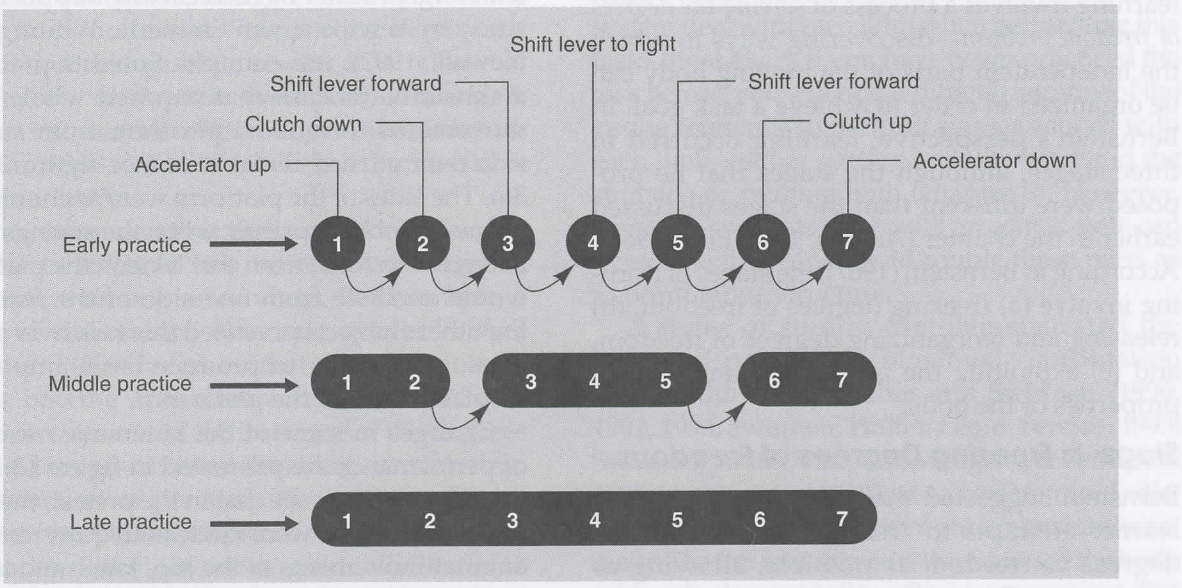

FIGURE 13.11 The gearshift analogy. (Initially, seven elements are each controlled by separate programs; later, they become grouped so that they are organized into a few units or even into a single unit.)

Adapted from MacKay, 1976, personal communication.

on reflexes are also seen in the views of Fukuda (1961) and Hellebrandt, Houtz, Partridge, and Walters (1956), as discussed in chapter 5; but here, while the reflexes are thought to be of assistance to the overall programmed action when increased force or speed is required, they are not the fundamental basis of it. But Easton's viewpoint also has a great deal in common with the ideas of Greene (1972), Turvey (1977), and others, all of whom argue that rapid movements consist of controlling structures that are constrained to act as a single unit, perhaps by tuning of spinal systems or by utilization of reflexes. These ideas share much in common with the theoretical perspectives of the Russian physicist Bernstein (see p. 8), whose ideas on learning are presented next.

The Bernstein Perspective

Suppose you were asked to throw a ball overhand with your nondominant arm. In all likelihood, your performance would look quite clumsy—the movements of the body would lack the fluid motion that characterizes a throwing motion with the dominant arm. The motions of the nondominant arm would probably be described as much more fixed and restricted in the range of motion. This example characterizes an important concept of learning initiated by the work of Bernstein (1967). The concept is that learning involves a process of *solving the degrees of freedom problem*—discovering ways in which the independent parts of the moving body can be organized in order to achieve a task goal. In Bernstein's perspective, learning occurred in three stages, although the stages that he proposed were different than the stages discussed earlier in the chapter (Adams, 1971; Fitts, 1964). According to Bernstein (1967), the stages of learning involve (a) freezing degrees of freedom, (b) releasing and reorganizing degrees of freedom, and (c) exploiting the mechanical and inertial properties of the body.

Stage 1: Freezing Degrees of Freedom

Bernstein suggested that early in practice the learner attempts to "freeze" as many of the degrees of freedom as possible, allowing as few as possible of the body parts to move independently. With practice, more and more of the degrees of freedom are "thawed out"—individual body parts appear to move either with more independence or with a different dependency. In the earlier example of throwing with the nondominant arm, one possible strategy for the performer would be to *fix* or limit the degrees of freedom involved in the act. This is done in order to reduce the contribution of their independent variability, and hence reduce the complexity of the action. In this way, the performer can achieve a relatively crude level of success at the task by reducing the number of ways in which things can go wrong. In a nice demonstration of this stage of learning, Southard and Higgins (1987) showed that people who learned a racquetball shot initially restricted the motion of the elbow and wrist and performed the shot with a more whole-arm action. A similar set of findings was reported by Hodges, Hayes, Horn, and Williams (2005) over 10 days of practice in a soccer-chip task. Participants gradually achieved more initial successes at the task as the range of motion at the hip was reduced with practice.

Stage 2: Releasing and Reorganizing Degrees of Freedom

According to Bernstein's arguments, in stage 2 of learning, the *constraints* on the degrees of freedom are loosened, allowing both for greater independent motion and for a higher level of success. Bernstein's introspections about the learning process have received support in a study by Vereijken, van Emmerik, Whiting, and Newell (1992), for example. Subjects practiced a ski simulator task that required whole-body movements to move a platform from side to side over curved metal rails (see figure 2.9, p. 36). The sides of the platform were anchored to a frame by rubber springs; when the springs were subjected to force from the "skier," the platform would oscillate from one side of the frame to the other. Subjects practiced this task over seven days, attempting to produce large-amplitude displacements of the platform.

Changes in some of the kinematic measures of performance are presented in figure 13.12. In this figure we can see that in the pretest, the platform movements were made with quite *restricted* angular movements of the hip, knee, and ankle. At this early stage of learning, subjects seemed to "freeze" the range of motion of the lower limb and trunk, perhaps just to get *any* movement of the platform at all. By the end of the first day, the

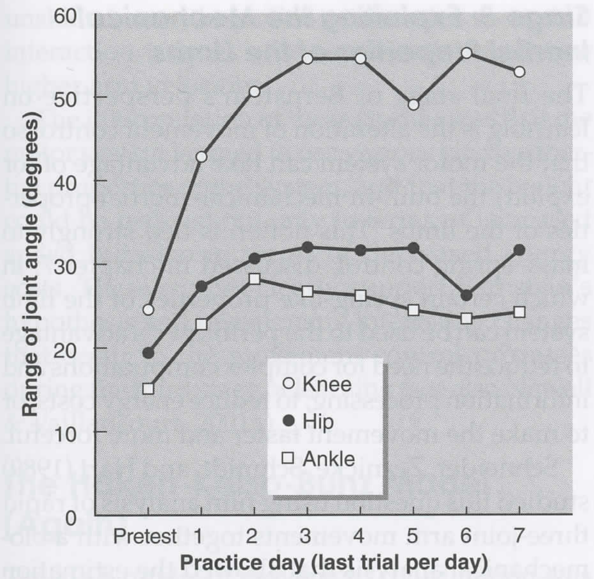

FIGURE 13.12 Changes in the frequency and amplitude of movements during practice of the ski simulator task.

range of motion of each of the joints had been extended considerably, resulting in much larger amplitudes of the platform but with reduced frequency. By the end of the seventh day, oscillation frequency had increased dramatically, along with further increases in amplitudes and joint ranges of motion. Thus, greater success in displacement and frequency of platform oscillations was achieved with greater range in the motion of the lower limbs and trunk—supporting Bernstein's suggestion that practice results in a release of the degrees of freedom (Vereijken, Whiting, & Beek, 1992; see also Arutyunyan, Gurfinkel, & Mirskii, 1968, 1969; Newell, van Emmerik, & Sprague, 1993).

Note, however, that the concept of releasing degrees of freedom has not received universal acceptance among researchers. For example, a study of violinists by Konczak, vander Velden, and Jaeger (2009) revealed that shoulder motions of the bowing arm were actually *reduced* as a function of practice, indicating that the degrees of freedom underwent freezing, not freeing, as a function of practice. We can hypothesize at least two other exceptions. First, in learning to windsurf, the performer gradually learns to freeze the degrees of freedom in the knees and hips, so that most of the controlling actions are in the shoulders and arms—actions used to manipulate the sail's orientation to the wind. Second, in learning to do a handstand on the still rings, the learner comes to freeze the degrees of freedom in the knees, hips, and trunk, so that balance control is ultimately achieved primarily by movements of the wrists. Unfortunately, very few studies have addressed this stage of Bernstein's perspective on learning, revealing a gap in empirical evidence.

Overall, we think that these ideas (about freezing and freeing degrees of freedom) form a useful description of learning's effect on movement control in *some* tasks. However, the counter-examples described here indicate that this does not provide a universal account of all motor learning.

Another key concept suggested by Bernstein was that independent degrees of freedom are assembled into functional units that act together. When two or more independently moving degrees of freedom "combine" to perform as one functional movement, the independent parts are said to be coupled—they act as *coordinative structures* (or *functional synergies*) to coordinate the independent parts to work as if they were a single unit. This is perhaps exemplified by the gearshifting concepts presented earlier in this chapter (see figure 13.11).

Another good example of coupling independent degrees of freedom occurs when you try rubbing your stomach while patting your head. In this task you are asking the two limbs to perform two different actions. How does your motor system deal with each limb when performing this task? Most likely, if you have never practiced the task before, you will find it difficult because of the strong tendency to perform similar actions with each limb—either patting both the head and the stomach or rubbing both (chapter 8). However, research suggests that with practice, you can overcome the tendency to couple these parts as a coordinative structure.

A series of studies that demonstrated the effects of practice on bimanual coordination was conducted by Walter and Swinnen (1990, 1992, 1994; Swinnen, Walter, Lee, & Serrien, 1993; Swinnen, Walter, Pauwels, Meugens, & Beirinckx, 1990). Subjects were asked to initiate rapid, discrete actions of the left and right limbs simultaneously. The left arm moved a lever toward the body with a single, rapid elbow flexion movement. The right arm also moved a lever toward the body. However, midway through the movement the right arm was required to reverse the direction of its movement twice. Thus, the subject's task was to produce a unidirectional, flexion movement of the left arm and a flexion–extension–flexion movement of the right arm, the arms starting and moving simultaneously (figure 8.9, p. 275).

As with the task of rubbing your stomach while patting your head, Walter and Swinnen found that subjects tended to perform similar actions with the two limbs: There was a *less* pronounced reversal for the limb that the subject intended to reverse, and there was evidence of a reversal in the limb that the subject did *not* intend to reverse (Swinnen, Walter, & Shapiro, 1988). Thus, neither of the limb movements was performed as intended. Rather the functional unit was of two limbs performing similar, albeit hybrid, actions of the individual goals; this was seen via high (within-subject) correlations among the kinematics of the two limbs. Learning was viewed in terms of the success with which each limb performed its own goal with practice. Learning was enhanced if it was supplemented with augmented feedback (Swinnen et al., 1990, 1993), as we would expect from our understanding of feedback effects in chapter 12.

Learning was also enhanced under *adapted* conditions, whereby the actions were performed slowly at first and then were gradually increased in speed (Walter & Swinnen, 1992). Related findings have been provided in experiments involving the acquisition of handwriting skills (Newell & van Emmerik, 1989) and dart throwing (McDonald, van Emmerik, & Newell, 1989), as well as in bimanual aiming tasks involving asymmetric amplitudes (Sherwood, 1990; Sherwood & Canabal, 1988).

One interpretation of these findings is that, by overcoming the existing coupling of degrees of freedom, the limbs are somehow *uncoupled* in a way that allows them to move more or less independently. This interpretation has some controversy, however, as others have shown that learning a new bimanual pattern actually results in an *increased* dependence between the hands: that learning results in the development of new bimanual GMPs involving tight, complex linkages between the limbs (Schmidt et al., 1998). This controversy is complicated by the evidence that the duration of the movement task has a large role in the control and learning of coordinated actions (chapter 8). More research is needed to address these issues.

Stage 3: Exploiting the Mechanical–Inertial Properties of the Limbs

The final stage of Bernstein's perspective on learning is the alteration of movement control so that the motor system can take advantage of (or exploit) the built-in mechanical–inertial properties of the limbs. This notion is tied strongly to mass–spring control, discussed in chapter 7, in which certain spring-like properties of the limb system can be used to the performer's advantage to reduce the need for complex computations and information processing, to reduce energy costs, or to make the movement faster and more forceful.

Schneider, Zernicke, Schmidt, and Hart (1989) studied this question using film analysis of rapid three-joint arm movements together with a biomechanical analysis that allowed the estimation of torques in each of the participating joints. Near the middle of this maximum-speed movement, the subject was to reverse his hand movement at a target, at which the arm was briefly extended upward at about 45°. Early in practice, the subjects tended to use a shoulder flexion torque at the target (reversal point), as if they were holding their arm up against gravity. But later in practice, the shoulder flexion torque tended to drop out, to be replaced by an *extension* torque. Now the limb appeared to be "thrown" at the target, to be "caught" by the shoulder *extensors* in order to reverse its direction and bring it back down quickly. Certainly, the structure of the GMP had changed markedly across practice, employing systematically different muscle groups for essentially the same set of positions early and late in practice. There were many other changes in movement trajectories and in the forces produced as well (see also Spencer & Thelen, 1999).

A different type of analysis was performed by Gray, Watts, Debicki, and Hore (2006), who reported on the differences between the baseball throwing motions of the dominant (skilled) and nondominant (unskilled) arms. Their analyses revealed evidence of restricted ranges of motion for the movements of the unskilled arm, providing additional support for Bernstein's stage 1 (freezing degrees of freedom). However, one of the strengths of Gray and colleagues' (2006) study was the comparison of the unskilled arm mechanics and the mechanics of the skilled arm, thereby revealing the effects of practice and learning. Their analyses showed that, compared to the unskilled arm, the skilled arm tended to exploit interaction torques at various joints to achieve higher arm velocities.

The interpretation of these studies was that the motor system learned to use various passive inertial properties of the system, and that the benefit could be realized not only in terms of increased speed but also in terms of decreased energy costs. These studies clearly support Bernstein's hypothesis and reveal many interesting changes that occur in the movement control processes during the third stage of learning (see also Newell & Vaillancourt, 2001a).

The Haken-Kelso-Bunz Model (Again)

The HKB model of movement coordination was discussed in detail in chapter 8. As mentioned there, the performance of discrete tasks appears to be fundamentally different when compared to performance of continuous tasks. We have discussed several times in previous chapters that discrete skills are dependent on a motor program for their execution. In contrast, continuous motor skills are more dependent on interactions with the environmental stimuli for their regulation. Therefore, it should not be surprising that perspectives on the learning of continuous motor tasks differ in many respects from those constructs developed to explain the learning of discrete tasks.[7]

In chapter 8 we presented evidence that there are two preferred coordination patterns by which continuous oscillations of two limbs or fingers can be reliably produced—*in-phase* and *anti-phase* coordination (the observed coordination pattern is measured in terms of the relative phase lag between the individual cycles; 0° or 180° in these two instances; see chapter 2 for review). Much of the research conducted on coordination dynamics uses the Haken-Kelso-Bunz (1985) model as a basis (see chapter 8). Basically, the HKB model states that intrinsic stabilities of the motor system attract moving degrees of freedom to perform in accordance with one of the system's naturally stable states. For the oscillating-fingers research presented in chapter 8, the strong tendency was to coordinate the fingers in an in-phase or an anti-phase pattern. Of course, theoretically, there are an infinite number of bimanual coordination patterns that can be produced. However, if the system were not amenable to change, then we would forever be locked into performing only these two patterns. But research suggests that new patterns can be learned, leading to a number of important issues about the learning process as a consequence (Swinnen & Wenderoth, 2004).

Recall from chapter 2 that studies of motor learning often devised experimental tasks that were as unique as possible to the learner. The reasons for this were straightforward—if subjects came into the laboratory with skills already learned (e.g., typing skills), then it would decrease the skill that could be gained during the earliest stages of learning. Traditional motor learning tasks such as the pursuit rotor (figure 2.5, p. 32) and the Bachman ladder (figure 2.8, p. 35) satisfied these criteria because it was highly unlikely that subjects had ever learned skills that were remotely similar to the skills required to perform these "novel" tasks. These advantages however, must be weighed against the major disadvantage that learning does not occur against the background of a "blank slate"—we can never know how learning this new task is influenced by the skills that the learner possessed prior to practice.

The self-organization approach, which was critical in the development of the HKB model, overcame some of the problems associated with "novel tasks" and provided many advantages for the study of motor learning. The approach both exploited the requirements for a learning task and provided a unique window into the influence of previously acquired skills on new learning (see also Kelso & Zanone, 2002; Schöner, Zanone, & Kelso, 1992; Zanone & Kelso, 1994, 1997). Because in-phase and anti-phase coordination are known and measurable *stable* patterns that exist prior to practice, the performance of new bimanual coordination patterns could be evaluated over the course of practice trials and compared to the performance of these existing skills.

In one experiment (Zanone & Kelso, 1992; see also Kelso & Zanone, 2002; Zanone & Kelso, 1997), subjects attempted to coordinate the relative phasing of the index fingers on both hands by rhythmically oscillating them in time to two blinking lights, which alternated in 90° relative phase. Before, during, and after each of five days of practice, Zanone and Kelso had subjects perform a type of transfer test in which the visual metronomes started by blinking simultaneously (in 0° relative phase) and then increased in phase offset by 15° after every 20 s until 180° relative phase had been reached. The main finding was that the 90° pattern was learned and became relatively stable with practice. An unexpected finding, though, was that some subjects showed a *reduced* stability for the anti-phase (180°) pattern as practice trials accumulated on the 90° pattern. This finding provided support for Zanone and Kelso's argument that learning does not involve simply adding a new skill to a subject's repertoire. Rather, learning occurs against the background of an individual's existing skills, resulting not only in the acquisition of new patterns but also in a change in the previously stabilized patterns. This latter finding is a controversial one, however, as it implies that new learning may result in the *unlearning* of previously acquired skills. Other studies suggest that the destabilization of the anti-phase pattern is only a performance bias, not a permanent destabilization in performance (Fontaine, Lee, & Swinnen, 1997; Lee et al., 1995; Smethurst & Carson, 2001), reminiscent of our previous discussions on the learning–performance distinction.

Another finding with use of this approach is also of interest. In the study by Lee and colleagues (1995), which used many of the same methods as Zanone and Kelso's (1992), when learning a 90° pattern, subjects showed strong influences of the existing stable patterns. As an example, the progress in learning for one subject is illustrated in figure 13.13. The panels in this figure represent a plot of the relative motion of the right limb together with the relative motion of the left limb. Recall that plots of this type were presented in chapter 2, for in-phase and anti-phase coordination (figure 2.13, p. 42).

For the 90° pattern investigated by Lee and colleagues, the "correct" plot was represented as an ellipse (overlaid in the top left panel of figure 13.13).[8] All subjects practiced the ellipse pattern during three days of practice. There are two observations in particular to note in this figure. First, for most subjects the initial performance trials were performed in anti-phase; much of the initial stages of learning involved "breaking away" from the attraction to perform this bimanual task as a previously acquired stable pattern. This process was revealed over the practice trials on day 1, with fewer and fewer anti-phase cycles being produced and coordination moving toward 90°. A second important finding concerned the initial trial on day 2, illustrated in the lower-left. Here, the subjects showed a short-lived performance bias that reverted to anti-phase. This result is interesting because it showed an effect that was very much like that predicted by the progression–regression hypothesis (regression to a previously mastered level of learning). It also is consistent with a phenomenon to be discussed in chapter 14 termed *warm-up decrement,* in which retention loss has a dramatic impact on performance. But, note here that the decrement was very specific, as performance reverted to a previously stable pattern, not to an *unstable* state.

The application of the HKB model and new experimental paradigm to the study of motor learning by Zanone and Kelso (1992) has generated considerable interest. Investigators have studied the role of many different variables with the purpose of discovering how new coordination patterns develop as a function of practice. For example, an existing coordination pattern may help to either stabilize or destabilize a new pattern (Fontaine, Lee, & Swinnen, 1997; Hurley & Lee, 2006; Kostrubiec & Zanone, 2002; Wenderoth & Bock, 2001; Wenderoth, Bock, & Krohn, 2002) in ways that are different than the retention of that pattern (Tallet, Kostrubiec, & Zanone, 2008). The acquisition of a stabilized new pattern appears to be greatly accelerated if movements are unpaced (Kovacs, Buchanan, & Shea, 2009), perhaps due to the influences of discovery learning processes (Hodges & Franks, 2002a; Hodges & Lee, 1999). And other factors, similar to those seen with more traditional approaches to the study of practice (chapters 11 and 12) and transfer (chapter 14), have been recast within a self-organization framework (Faugloire, Bardy, & Stoffregen, 2009; Lay, Sparrow, & O'Dwyer, 2005; Ronsse, Miall, & Swinnen, 2009), broadening the conceptual approaches to viewing these more traditional ideas.

Summary

The empirical laws of motor learning presented in previous chapters are the focus of hypotheses or theories that are directed at explaining them, and this chapter presents some of the more important of these formulations. Learners appear to pass through various stages (or phases) when they practice a skill: a *cognitive stage* in which

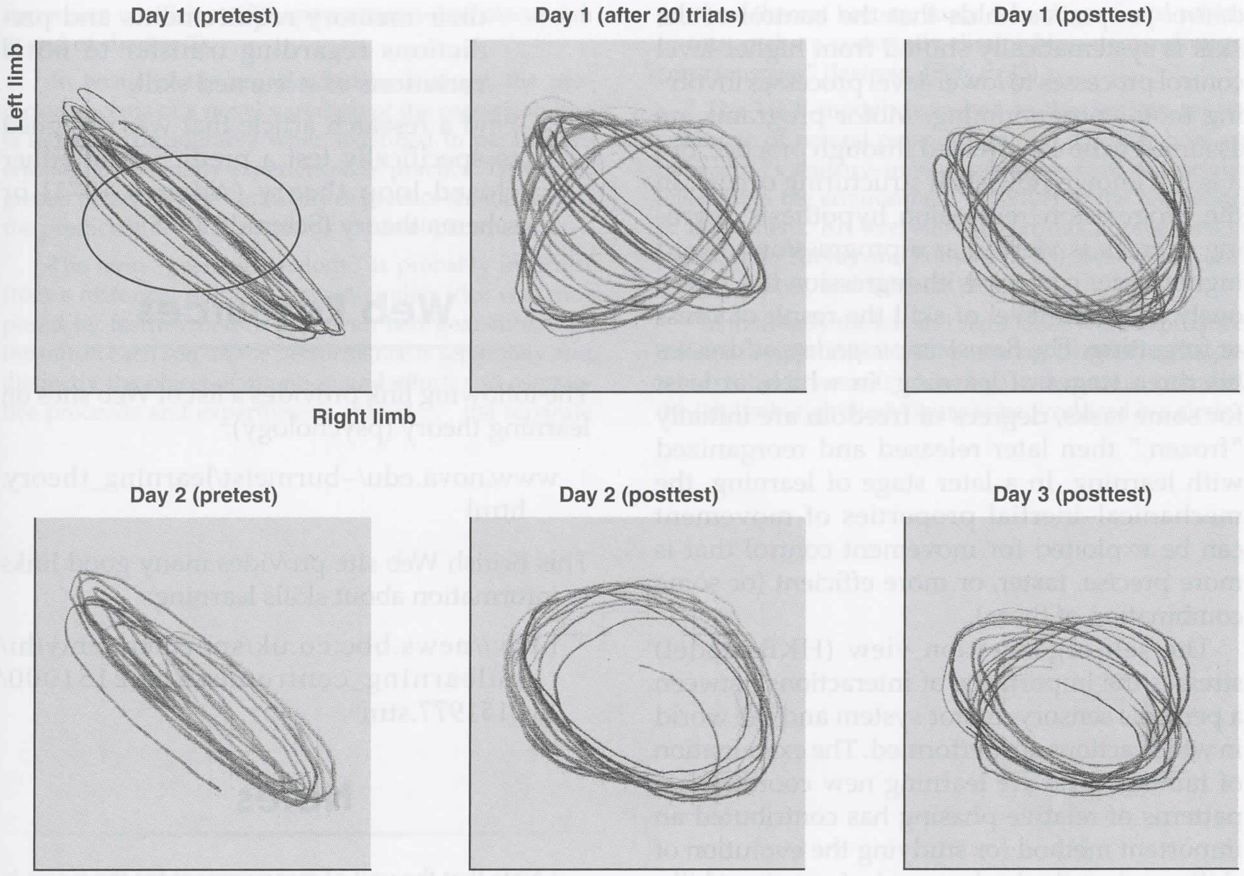

FIGURE 13.13 Effects of practice on the development of a novel bimanual timing skill. The goal is to produce a relative timing represented by an oval-shaped Lissajous figure.

emphasis is on discovering what to do, a *fixation stage* in which the concern is with perfecting the movement patterns, and an *autonomous stage* in which the attentional requirements of the movement appear to be reduced or even eliminated. A major direction for understanding skill learning has been provided by the individual-differences tradition. A significant finding is that the set of abilities underlying a skill appears to change with practice, so that the collection of abilities underlying a skill is systematically different in practiced and unpracticed subjects. The change is in the direction of less involvement of cognitive abilities and greater involvement of motor abilities with practice. These characteristics of abilities and learning provide insight into why accurate prediction of high-level motor behavior is so difficult to achieve.

Two major theories of motor learning are *closed-loop theory* and *schema theory.* Closed-loop theory holds that the learner acquires a reference of correctness (called the *perceptual trace*) through practice and that the improvements in skill result from the increased capability of the performer to use the reference in closed-loop control. Schema theory is based on the idea that slow movements are feedback based, with rapid movements being program based; with learning, the subject develops rules (or schemas) that allow for the generation of novel movements. Both theories can claim a number of lines of experimental support, but neither is capable of explaining all the evidence on motor learning.

Several other theoretical perspectives have spawned a number of hypotheses about the learning process. The *cognitive perspective* suggests that processes involved in the planning and evaluation of movement affect learning, especially so when performance difficulties challenge these cognitive processes. The *hierarchical* *control perspective* holds that the control of the skill is systematically shifted from higher-level control processes to lower-level processes involving motor programming. Motor programs are assumed to be constructed through practice, but it is not known how such structuring occurs. In the progression–regression hypothesis, learning to track is viewed as a progression toward higher-order control, with regression to a previously achieved level of skill the result of stress or forgetting. The *Bernstein perspective* addresses his three stages of learning, in which, at least for some tasks, degrees of freedom are initially "frozen," then later released and reorganized with learning. In a later stage of learning, the mechanical–inertial properties of movement can be exploited for movement control that is more precise, faster, or more efficient (or some combination of these).

The self-organization view (HKB model) stresses the importance of interactions between a person's sensory–motor system and the world in which actions are performed. The examination of humans who are learning new coordination patterns of relative phasing has contributed an important method for studying the evolution of skills against the background of existing skills. The method emphasizes changes in stabilities and instabilities, both temporary and long-term.

Student Assignments

1. Prepare to answer the following questions during class discussion:
    a. Using any sport skill, describe the skill characteristics of an athlete who is in the Fitts phases of learning: the cognitive phase, the associative phase, and the autonomous phase.
    b. Using the same sport skill as in question 1a, describe the skill characteristics of an athlete who is in the Bernstein stages of learning: the freezing degrees of freedom stage, the releasing and reorganizing degrees of freedom stage, and the exploiting the mechanical–inertial properties stage.
    c. Compare and contrast closed-loop theory (Adams, 1971) and schema theory (Schmidt, 1975) in terms of their memory requirements and predictions regarding transfer to novel variations of a learned skill.
2. Find a research article that was designed to specifically test a prediction of either closed-loop theory (Adams, 1971) or schema theory (Schmidt, 1975).

Web Resources

The following link provides a list of Web sites on learning theory (psychology):

www.nova.edu/~burmeist/learning_theory.html

This British Web site provides many good links to information about skills learning:

http://news.bbc.co.uk/sportacademy/hi/sa/learning_centre/newsid_2151000/2151977.stm

Notes

[1] Note that the unit of measurement for the *y*-axis in figure 13.4 is *Z*, not *r*. This is a typical transformation performed on correlation values prior to statistical analysis because the *r* data are not normally distributed (the scores are truncated at the two extremes, $r = +1$ and -1), which violates an assumption for analyses of variance. The *Z*-transformation provides a normal distribution to the data.

[2] Other statistics have been used to estimate error-detection capabilities as well, such as the absolute error between objective and subjective scores (Newell, 1974) and d' in signal-detection analyses (Rubin, 1978).

[3] We have assumed normal distribution here, with the mode represented as the correct perceptual trace. With learning, the shape of the distribution of incremented perceptual traces moves from platykurtic (flat) to leptokurtic (peaked). Of course, other distributions are also possible. For example, in learning to play golf, many more people have trouble with slicing the ball than with hooking the ball. In this case, the shape of the distribution would be expected to change in both kurtosis and skewness, as a function of learning.

[4] Learning in Adams' theory was represented by changes in the normal distribution—a more pronounced mode and reduced variability. In schema theory, learning is represented by a regression-line analogy. A more *powerful* regression equation is developed with learning—one that has reduced residual variability and for which the

regression coefficient (R^2) approaches 1 (see discussion at end of chapter 2).

[5] In terms of the regression-line analogy, the predicted success of a novel variation of the regression line is reduced considerably when extended to parameters *beyond* those actually experienced in practice. Therefore, greater breadth in the variability of practice should extend the predictability of the schema to novel parameters.

[6] The term "gearshift analogy" is probably incorrect from a historical point of view. A similar idea was proposed by Jastrow before cars even had gearshifts: "At the outset each step of the performance is separately and distinctly the object of attention and effort; and as practice proceeds and expertness is gained . . . the separate portions thereof become fused into larger units, which in turn make a constantly diminishing demand upon consciousness" (Jastrow, 1906, p. 42).

[7] The HKB model described in this section represents one of several perspectives that consider how an individual's sensory–motor system interacts on various levels with the environment to influence the regulation of movement. An overview of various approaches is provided in Turvey and Fonseca (2009), Beer (2009), and Latash, Scholz, and Schöner (2007).

[8] In this study the left and right limbs were to produce different amplitudes at a 90° phase lag. In other studies, in which subjects learn 90° phase lags with equal amplitudes, the left limb–right limb figure to be produced is a circle.