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A Schema Theory of Discrete Motor Skill Learning

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A number of closed-loop postulations to explain motor skills learning and performance phenomena have appeared recently, but each of these views suffers from either (a) logical problems in explaining the phenomena or (b) predictions that are not supported by the empirical evidence. After these difficulties are discussed, a new theory for discrete motor learning is proposed that seems capable of explaining the existing findings. The theory is based on the notion of the schema and uses a recall memory to produce movement and a recognition memory to evaluate response correctness. Some of the predictions are mentioned, research techniques and paradigms that can be used to test the predictions are listed, and data in support of the theory are presented.

The field of motor behavior has become extremely interesting in the past few years, probably as a result of some rather severe changes in the way in which researchers have tackled their problems. Prior to about 1960, the area seemed to be dominated by the "task-oriented" approach (Pew, 1974). This approach emphasized "global" motor learning theories, such as that of Hull (1943), or emphasized no theories at all, and the area was dominated by experimenters who were testing the effects of a large number of independent variables on the overall learning and performance of motor tasks. Scoring was usually in terms of some very gross index of responding, such as time on target for 30 sec, and there was little concern for the events that changed within the individual that enabled him to perform or to learn the motor task.

Since 1960, however, there has been a considerable shift in emphasis in motor skills research. Motor behaviorists have begun to ask questions about the kinds of processes occurring as the individual performs and learns the motor response. The tasks used have tended to shift from those that could only be scored with global measures to those that enabled the isolation of various processes and strategies and provided information about contributions of various subsystems. A number of researchers took the lead from the new directions provided by Fitts and his colleagues (e.g., Fitts, 1954) concerning the processing of information in skills. Examples of these new concerns were the time to process visual information (Keele & Posner, 1968), the development of error detection mechanisms (e.g., Schmidt & White, 1972), and the locus of attentional requirements in simple movements (Ells, 1969). Questions such as these were not popular under the earlier traditions.

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A part of the reason for this shift in emphasis has been the inadequacy of the earlier theories in providing reasonable explanations for motor learning and performance; this is well documented by the controversy about Hull's (1943) theory that raged in the late 1950s and early 1960s (see Adams, 1964, for a review) and finally resulted in an almost total loss of interest in these points of view. The lack of adequate theories for guiding research in motor behavior caused motor behaviorists to reach out in other directions for explanations of motor learning. Of course, an important event in a number of fields was the arrival of the information processing and cybernetic ideas that led to closed-loop theory, and the application of these notions to psychology and motor skills was welcomed with great vigor.

Of the closed-loop theories, some were quite old, for example, Bernstein (1967) in essays originally published in 1934 and 1957, but there have been a number of widely discussed recent additions. The closed-loop models of Sokolov (1969), Anokhin (1969), and Konorski (1967), plus the work of Adams (1971) and Laszlo (1967), were most recent additions to the thinking in this area. While these theories differed a great deal from one another, they had the essential features of closed-loop theory in common: There was provision for the receipt of feedback, the feedback was checked against some reference of correctness, any discrepancy resulted in an error, and the error was subsequently corrected.

As many closed-loop theories as there were, it was surprising that there were so few serious attempts to test them against one another experimentally. It is not because the theories did not produce an interest among the workers in the field, because these ideas have been used as explanations for various experimental results by numerous authors. Rather, it is because most of these theoretical ideas are not strictly theories, but are more properly termed *models* (see Lachman, 1960, for a discussion of the distinction between models and theories). Often, such models are very easy to construct, as seemingly all one needs to propose a new model is a few appropriately labeled boxes, supposedly representing processes in motor performance, with connecting arrows, and a new model is born. What has often resulted are models that are not tied to experimental data for their formation and that do not provide ways for conducting tests of them. The result is a diagram that is useful perhaps in visualizing what might be happening in skills and learning, but which has little basis in fact and cannot be verified (or, more properly, disproved) by experiment. This kind of model building has been taken far too seriously by students of motor behavior.

A notable exception to this statement was the closed-loop theory proposed in 1971 by Adams. This theory was generated in a way quite different from that of the earlier closed-loop ideas. First, the original focus was an existing body of carefully controlled basic research in motor learning—that dealing with the learning of slow, graded, linear-positioning tasks. Focusing on these data, Adams attempted to explain the various findings with the aid of closed-loop notions of error detection and correction. Most important, Adams ensured that his ideas would be testable by providing operational definitions for all of his constructs, by suggesting experimental variables that, when appropriately manipulated, should produce certain changes in particular measures, and by suggesting experimental paradigms for testing various aspects of the theory. The results of this effort were seen immediately with the appearance of approximately 20 articles testing the Adams theory in the first two years after it was introduced—already more than for all of the earlier closed-loop theorists combined. Clearly, the production of a theory that was so easily testable by researchers was appealing, and the Adams theory became a most important article for the field of motor learning in a very short time.

THE ADAMS THEORY

Adams' (1971) theory proposes that there are two states of memory, termed the *memory trace* and the *perceptual trace.* The memory trace, analogous to recall memory in verbal learning, is a "modest motor program" responsible for initiating the movement, choosing its initial direction, and determining the earliest portions of the movement. Its strength is developed as a function of knowledge of results (KR) and practice. The perceptual trace, on the other hand, is analogous to recognition memory in verbal tasks and is responsible for guiding the limb to the correct location along the trackway. The perceptual trace is formed from the past experience with feedback from earlier responses and comes to represent the sensory consequences of the limb being at the correct endpoint. During the movement, the subject compares the incoming feedback (from the eyes, ears, proprioceptors, etc.) against the perceptual trace to determine if the limb is in the correct final location; if it is, he stops responding, and if it is not (i.e., an error is signaled from the perceptual trace), he makes a small adjustment and the comparison is made again until the limb is in the correct location. With increased exposure to feedback and KR, the perceptual trace is strengthened, and the individual becomes more accurate and confident in his responding.

Some Strengths of Adams' Theory

Adams' theory has a number of characteristics that are generally considered desirable attributes. Some of these, in each case representing improvements over early closed-loop theories, are as follows.

Concern for learning. Almost every one of the early closed-loop theories has dealt with the processes thought to occur in the *performance* of already-acquired skills. In addition to this concern, the Adams theory is directed toward the *learning* of novel motor tasks, which was not a consideration in the earliest work.

Reduced scope. Adams has begun modestly, attempting to limit his theoretical predictions to the body of data dealing with the learning of linear positioning. Thus, the theory is very close to the data and attempts to explain them with the theoretical constructs proposed. To be sure, the theory probably does have applicability to response classes other than linear positioning, but a limited focus provides the most solid beginnings for further theoretical developments.

Empirical support for constructs. The processes postulated in Adams' theory are all known processes, in that there is considerable evidence, either directly from motor behavior or inferred from other response classes, for each. This has not been the case for many of the earlier positions, in which processes were proposed without either behavioral or neurological support. Adams' approach has been to insist that the model postulate only those kinds of processes or mechanisms that have a reasonable probability of empirical reality.

Simplicity. The Adams theory is quite simple, postulating a minimum of hypothetical states to account for the learning of positioning tasks. Some of the earlier models are extremely complex, with many times more states postulated, and it is encouraging to think that motor learning might be explained by fewer postulations than seemed necessary before.

Some Criticisms of Adams' Theory

With all of the research and thinking that has developed since Adams' theory was published, it is not surprising that some shortcomings in the theory have appeared. Some of these result from logical difficulties with the theory as stated, and others result from recent data that do not follow the theory's predictions.

Limitations to positioning responses. Although this is not a serious criticism, some researchers are worried that positioning responses are not representative of the wide range of behavior that one would like to term *skilled,* and that the theory cannot explain the learning of other types of responses. It should be reiterated that the theory was deliberately limited in scope because of the lack of good evidence in other types of responses, but it would be a desirable goal to have a theory that predicts performance and learning in other tasks as well. Specifically, the generalization to more rapid responses (e.g., kicking and throwing) would be important, as would attention to open and closed skills or to skills in which the major goal is other than accuracy (e.g., pole vaulting). The author and his colleagues (Schmidt & White, 1972; Schmidt & Wrisberg, 1973) have attempted to extend Adams' theory to simple accuracy tasks requiring rapid movement (approximately 30 cm in 150–200 msec), but the theory was not specifically designed to handle these tasks and tests using such tasks are not strictly tests of Adams' point of view. Some revision seems clearly necessary in order to extend the theory to more rapid movements.

The error detection mechanism. The major feature of Adams' theory is that it provided a means for the subject to determine, in the absence of KR, his error for the response just produced, to use this information (termed *subjective reinforcement*) as a means for maintaining performance, or even to continue to learn without KR. The author has argued before (Schmidt, 1974, Schmidt, Note 1) that learning without KR does not follow logically from Adams' theory. Theoretically, the subject uses the perceptual trace and feedback during the movement to guide the limb to the proper location, and he moves to that position he recognizes as correct; thus, the movement endpoint is that position for which the error signal (the difference between the perceptual trace and incoming feedback) is zero. After the subject has removed his hand from the lever, how can he generate an additional error signal that is sensitive to the difference between the position on the trial and the correct position? The answer is that he cannot. When asked what the error was on that trial, the subject can provide a guess, but that guess is probably uncorrelated with the actual error for the trial, because his error signal at this point is necessarily zero. Thus, it would seem that the theory cannot provide subjective reinforcement that would enable the individual to continue to learn without KR.

In a study by Schmidt and Russell (unpublished study, 1972),[1] subjects were given 100 positioning trials, with KR after each trial. A paradigm was used in which the subject responded, was asked what he thought his error was (in the units of the positioning task), and was then provided KR. The measure of the error detection mechanism was the correlation, computed within subjects, between the actual and judged error on the last 20 trials. The highest correlation was .40, and many of the *r*s were negative, with the average being .21. Had there been a strong error detection mechanism operating after the movement, larger correlations, similar to those found by Schmidt and White (1972) for a rapid movement task ($r = .90$), should have been found. The Schmidt and Russell findings agree with the prediction that there should be no error detection mechanism after the movement in slow positioning.

Learning without KR. Another important prediction of the Adams theory is that later in learning, when the perceptual trace is well established, the subject should be able to continue to learn without KR. There is no evidence that individuals can continue to learn positioning tasks after KR withdrawal, and the best approximation seems to be that they can maintain performance reasonably well after KR withdrawal (e.g., Bilodeau & Bilodeau, 1958). But in spite of the lack of evidence, the theory cannot predict this no-KR learning. If, on the first no-KR trial, the movement is not perfect, the perceptual trace will be degraded somewhat because of the feedback from that response. The next response will be less accurate because the perceptual trace has been slightly weakened, and the perceptual trace will be degraded further, and so on. Eventually, the perceptual trace becomes increasingly weak, with a corresponding decrement in accuracy, and performance is increasingly inaccurate. Clearly, the theory cannot predict learning without KR for positioning responses.

Generalization to rapid responses. While the Adams theory was not intended to be explanatory for rapid responses, a number of experimenters (e.g., Newell, 1974; Newell & Chew, 1974; Schmidt & White, 1972; Schmidt & Wrisberg, 1973) have used Adams' closed-loop ideas to generate predictions for this response class. The reasoning was that in slow positioning responses the memory trace and perceptual trace become

[1] Requests for information concerning this and other unpublished studies cited in this article should be sent to Richard A. Schmidt, Department of Physical Education, University of Southern California, Los Angeles, California 90007.

experimentally confounded, with positioning tasks not providing measures that could be ascribed to the variations in the memory-trace strength. One solution was to use rapid movements, usually the movement of a slide for 10–15 in. (25.4–38.1 cm) with a goal of 150–200 msec, where the movement would be carried out by the memory trace (in this case a motor program without feedback involvement), with the perceptual trace strength evidenced by how accurately the subject could guess his movement time after the movement.

Many of the predictions that seemed to come from Adams' theory were supported. The strength of the error detection mechanism (the perceptual trace measured as the within-subject correlation between actual and judged error) increased as a result of practice (Schmidt & White, 1972), the error detection mechanism was sensitive to the amount of experience with feedback stimuli (visual and auditory) present in the task (Newell & Chew, 1974; Schmidt & Wrisberg, 1973), and ratings of the subject's confidence increased with practice as well. But there were some instances of nonsupport. Shea (unpublished study, 1972) failed to confirm that the interresponse interval was a factor in development of either the memory trace or the perceptual trace. Also, Adams states clearly that the delay of KR should not be a factor in the development of the perceptual trace, and yet a study by Schmidt, Christenson, and Rogers (in press) indicates that delaying KR by 25 sec versus 5 sec caused a drop in the correlation (from .92 to .61) between actual and judged error; the interpretation was that KR delay retarded the development of the perceptual trace.

Perceptual trace development. Adams' theory holds that the perceptual trace is formed from feedback traces associated with having moved to the correct location, and that without this experience at the correct location, the perceptual trace cannot develop. Williams and Rodney (in press) had subjects practice a linear positioning task under a variety of conditions, and two of these conditions test this prediction. Group TO (target only) moved 16 times to a stop that defined the criterion location, while Group IR (interpolated random) moved to 16 randomly ordered stops (not at the criterion location), after being told that the criterion location was in the center of these positions. When subjects then attempted to move to the criterion position without the stop for 20 trials without KR, the absolute errors (see Figure 1) for the two groups were nearly equal on the first block of 4 trials; also Group IR maintained performance over blocks, whereas Group TO regressed significantly. The finding that subjects who had never experienced the correct location (Group IR) could move as accurately (and maintain accuracy more effectively) as those subjects who had the conditions necessary for the development of the perceptual trace (Group TO) is very damaging to Adams' position.

The storage problem. Most existing theories, whether they stress the open-loop (programmed) aspects (e.g., Henry, 1960) or the closed-loop aspects of movement control (e.g., Adams, 1971), implicitly postulate that for each movement that is to be made there must be either a motor program or a reference against which to compare feedback (depending upon the type of theory), and that there is a one-to-one mapping between stored states (either programs or feedback states) and movements to be made. This presents problems for the central nervous system in terms of the amount of material that must be stored, as discussed recently by MacNeilage and MacNeilage (1973) in the speech production area and by Schmidt (in press) for motor skills. They estimated that for the English language, considering inflections and accents, there were some 100,000 phonemes required, and thus the same number of stored states. When we add to this the nearly countless additional ways (other than speech) in which individuals move their musculature, the individual must have a nearly countless supply of either programs or feedback states in storage. While this may be possible—and there is no evidence that it is not possible—it would seem desirable to postulate mechanisms that do not require this level of storage. Recently, a number of attempts at

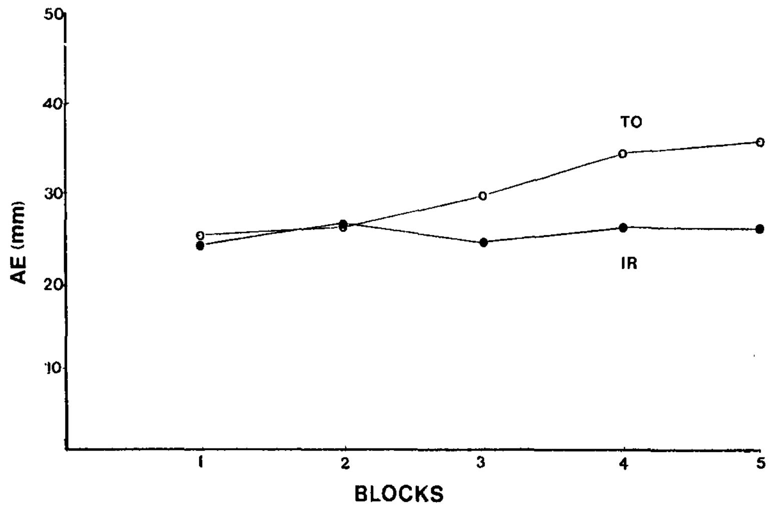

FIGURE 1. Absolute error (AE) in linear positioning as a function of variability of prior experience (from Williams & Rodney, in press). Abbreviations: TO = target only group; IR = interpolated random group.

alternatives to the earlier program or feedback theories have been proposed that do not require this volume of material to be stored, such as the MacNeilage (1970) target hypothesis and the use of reflexes by Easton (1972).

The novelty problem. A companion to the problem of one-to-one storage of programs or feedback states is the problem of how the performer produces a "novel" movement. It has seemed clear to investigators for many years—for example, Bartlett (1932) and Bernstein (1967) in essays originally published in 1934 and 1957—that when we make a motor response in a game, for example, we do not execute the movement exactly as we have made it before, and this is borne out by recent biomechanical analyses of movements (e.g., Higgins & Spaeth, 1972). If the response is to be programmed, for example, the sequence of muscle commands would be appropriate for only one movement, beginning with the body in a specific position, and with an identical goal; and it is probably true that the same response is never made twice when one considers the number of possibilities there are, for example, in shooting a basketball. Therefore, motor-learning theory must be able to account for the generation of such novel movements to overcome the shortcomings of existing theories in this regard.

THE GOAL OF THIS ARTICLE

The research and thinking that Adams' (1971) theory, and other closed-loop theories as well, have generated in the last few years has revealed a number of shortcomings —both logical and empirical—as outlined in the previous sections. The goal of the present article is a theory that contains the strong points of the Adams view but is considerably different in a number of important ways, so that it will be consonant with the experimental literature. The theory attempts to deal with discrete tasks, that is, those that have a recognizable beginning and end and are usually quite short in time (e.g., less than 5 sec in duration). A number of types of discrete tasks are considered. In addition to the linear positioning responses with which Adams dealt, the theory is aimed at rapid "ballistic" tasks with very short movement times (e.g., less than 200 msec), tasks that are "open" as well as "closed" (Poulton, 1957), tasks that demand accuracy, and tasks that have maximum speed, height, etc., as goals. Tracking and other continuous tasks are deliberately excluded from this article because of the rather complex simultaneous interaction between sensory input and motor output, although there is the possibility that the ideas presented here will be useful at some future time for tracking (see Pew, 1974, for an up-to-date review of the tracking literature).

THE THEORY

In order to correct for the shortcomings of existing open- and closed-loop theories in accounting for the recent motor learning and performance data, a somewhat marked departure from these original points of view seems essential. As with any new theory, there is probably not very much really new, with many of the ideas borrowed from earlier points of view. Such is the case here. As the theory is explained in the next few sections, it will become obvious that the lineage of the major ideas can be traced to Bartlett (1932) in terms of the notion of the schema, to Adams (1971) for his application of closed-loop theory to learning of motor skills, to Pew (1974) for the suggestions about the application of the schema to motor skills, and to Lashley (1917) for his lead in characterizing man as controlling his movements centrally with "motor programs." It is to the open-loop control ideas and the motor program that we turn next.

The Motor Program

The idea that the human being has a set of stored muscle commands ready for action at any time has probably been with us for a very long time, but the first important documentation that movement was centrally controlled was provided by Lashley (1917) in describing the movements of a patient with a gunshot wound in the back. Because of the wound, the patient had lost all sensation from his lower limbs, but had not lost the efferent pathways that enabled him to move. Even though he could not feel movement in his leg, he was nevertheless able to position it with surprising accuracy, not unlike a normal control subject. This finding led Lashley to argue for a position in which movement was controlled centrally, since there was little possibility that the wounded patient could have been using feedback to guide his movements.

This idea has been restated many times, both formally and informally, and with the advent of the electronic computer the centralist notion became couched in terms of the programs used by the machines; Henry's (1960) "memory-drum theory" was such an idea, using the notion of the memory drum element in the earlier computers as an analogy to the human system. One of the more recent statements is that of Keele (1968), who defined the motor program as a sequence of stored commands that is "structured before the movement begins and allows the entire sequence to be carried uninfluenced by peripheral feedback" (p. 387).

The primary evidence for the motor program notion has been that the processes involving the generation of sensory error information, perceiving it, and initiating corrections in response to those errors was quite slow, requiring from 120–200 msec (about one "reaction time") to initiate the corrections. While it is true that there is some variance in the speed with which the various sensory channels operate, with proprioception being fastest, at about 110 msec (Chernikoff & Taylor, 1952), and vision being the slowest, at about 190 msec (Keele & Posner, 1968), there is still the problem that many movements can be carried out in far less time than is required for the feedback loop to operate. In fact, the strongest human evidence for the motor program notion seems to be that subjects can initiate, carry out, and stop a limb movement within 100 msec, implying that decisions about when to stop the movement must have been made prior to the initiation of the movement. These results have provided a serious dilemma for the closed-loop performance theorists, and have provided the support needed for the program notion to become popular.

The idea of the motor program is largely a default argument, as pointed out by Pew (1974). There is really no direct human evidence of a motor program; centralists reason that there is no other known means of producing the movements; thus programs must be the explanation. Actually, it should be shown either (a) that feedback is present in movement but is not used, or (b) that feedback is not present and movement can still occur. Strictly, neither of these two possibilities has been shown experimentally.

There are, however, data from subhuman species that provide support for the program notion. The most convincing is the report from Wilson (1961), who totally deafferented the wing musculature and related joints of locusts. When a ganglion near the head was stimulated electrically, the locust would produce movements of the wings closely resembling flying (although the movements were decreased in amplitude somewhat), and these movements would continue for an extended period of time without further stimulation. Thus it appears that there are motor programs, and that they are capable of carrying out movement in the absence of sensory feedback. Similar data have been collected by Nottebohm (1970) with birdsongs. The limitation of these findings for human motor behavior is that these subhuman motor programs can probably be considered innate, and as yet there are no data showing that learned acts can be programmed, as we would like to believe in terms of learning a program for kicking a football. Even so, the notion seems to have sufficient direct and indirect support to warrant its inclusion here.

The motor program notion is modified slightly in the present situation, however. The original form of the motor program implies that every movement must have a separate motor program associated with it, and such a postulation brings in the storage problem mentioned earlier. The notion has therefore been changed somewhat to mean that there are generalized motor programs for a given class of movement. For example, there might be a single program for the many ways of throwing a baseball. How wide this category of movements governed by a single program might be has been the subject of some debate, as some would hold that the movement category is quite narrow (e.g., Henry, 1960), while others, referring to the "overarm pattern," imply that the program might govern all movements in which something is propelled overhead (e.g., Broer, 1973). How big the category actually is does not matter a great deal, however, as long as it can be postulated that there is not a one-to-one match between the program and each specific movement that the individual can produce, in order to avoid the storage problem.

These generalized motor programs are assumed to be able to present the prestructured commands for a number of movements if specific response specifications are provided. Thus a motor program for throwing a ball could be modified by specific instructions to throw fast or slow. These specifications can be thought of as parameters that can be varied before the movement begins to enable the execution of the program at a different speed, a different force, and so on. Thus, the performer's problem in choosing a movement is the determination of the response specifications that will modify the existing stored motor programs.

According to the current literature in the neurological control of movement (e.g., Granit, 1970), the output from the motor program consists of two sets of signals. The alpha efferent signals innervate the extrafusal fibers in the main body of the musculature, while the gamma efferent signals innervate the intrafusal fibers in the muscle spindles. Through the servo-action of the muscle spindles, the alpha and gamma activity is coordinated, so that minute variations from the intended spatial–temporal pattern of movement are corrected very rapidly—within 30–50 msec—via the rapid, spindle-initiated feedback loops. These servo-type corrections control for unplanned variation in the fatigue state, unexpected forces occurring in the limbs, etc., so that the movement takes on the intended path (i.e., the path intended when the program was chosen). Thus, strictly speaking, it makes little sense in view of the evidence to claim, as Keele (1968) and Schmidt (1972b) have done, that movements with durations less than 200 msec take place "without involvement from peripheral feedback," because the spindle system operates much more quickly than this. What is meant by this definition of the motor program is that when the program is initiated, it carries itself out as planned, correcting for deviations from the intended path of the movement, but that if something happens in the environment that requires that some new movement (a new goal) be planned, the performer cannot accomplish any such changes until the program has run its course for approximately

200 msec. Thus, control is open loop because stimuli from the periphery cannot initiate a new program until the present one has run its course for one reaction time (see Schmidt, in press).

Actually, the time over which a program must run its course without change is probably far longer than the lower limit of 200 msec usually specified. If the movement time is only 200 msec, any signal that the subsequent movement is about to be incompatible with the environmental conditions must occur very early in the movement; being able to correct for errors occurring this early seems unlikely, because the initial portions of the movement must usually be made in order for the subject to perceive that it is going to be incorrect. Depending upon the type of response, it is reasonable to believe that the program could carry itself out for nearly 400 msec before it could be changed. The amount of possible feedback involvement in a movement longer than one reaction time is probably dependent primarily upon the movement time, and seems independent of the movement velocity so long as the movement time is constant (Schmidt & Russell, 1972).

A primary focus of the present theory is on the development of motor programs and their response specifications, an emphasis shared by a number of motor skills researchers. Perhaps this point is made best in a passage from a recent article by MacNeilage and MacNeilage (1973):

> The *need* for peripheral sensory feedback can be thought of as inversely proportional to the ability of the central nervous system to predictively determine . . . every essential aspect of the following acts. (p. 424)

Because of the lags in processing feedback, the subject becomes less and less dependent upon feedback for performance, and the emphasis shifts from feedback-controlled, jerky performances to the smooth execution of almost completely open-loop movements. Thus, the problem for the subject in learning motor skills is to develop these open-loop programs for his movements to free himself from feedback involvement. Pew (1966) has shown, in a task requiring alternate finger-tapping movements to keep a dot centered on a screen, that there was a shift in control from closed-loop to open-loop control. Schmidt and McCabe (Note 2) also found less feedback involvement in a discrete timing task with a 750-msec movement time, using the index of preprogramming discussed by Schmidt (1972b).

The Schema

The notion of the schema is not a new idea at all, as the first formal statement of the idea was made by Head in 1926, and the ideas were subsequently modified considerably and presented in a book by Bartlett called *Remembering* (1932). The idea, usually stated with respect to perception, is that in order to perceive a set of visual stimuli (e.g., a dog) and to classify these stimuli correctly in the category "dog," we need not have previously received the particular set of stimuli in question. Through our past experiences with seeing dogs, we store these stimuli in recognition memory and also abstract these stimuli into a concept related to dogs for additional storage. This concept forms the basis of a *schema* or rule for determining whether a new set of visual stimuli should be classified into the category "dog" or not. Thus to recognize an animal as a dog, we need not have ever seen that particular animal before, and with the use of the schema for dogs, we correctly identify the animal's category. This rule for determining the category membership of a set of stimuli forms the basis for the definition of the schema, as defined by Evans (1967b):

> A schema is a characteristic of some population of objects, and consists of a set of *rules* serving as instructions for producing a population prototype (the concept). (p. 87)

Thus, given the schema for "dog," which consists of a set of rules for determining if a set of stimuli should be classed as a dog or not, the individual comes to the decision about the category membership of the stimuli.

While the notion of the schema has been in existence for a long time, it has been limited in its usefulness theoretically because there have been a number of ways of thinking about the same idea (e.g., Head, 1926, versus Bartlett, 1932), the ideas were somewhat too "mentalistic" for the behavioristic leanings of psychology until recently, and there have not been attempts to operationalize the concept so that it could be tested experimentally. Recently, however, a number of researchers have invoked the notion to explain nonsense pattern recognition, and Evans and his colleagues (Edmonds & Evans, 1966; Edmonds, Evans, & Mueller, 1966; Edmonds & Mueller, 1966; Edmonds, Mueller, & Evans, 1966; Evans, 1967a, 1967b; Evans & Edmonds, 1966) and Posner and Keele (1968, 1970) have provided strong operational definitions and tests of the concept. The descriptions of the Posner and Keele studies indicate how the schema has been tested for pattern recognition tasks.

Posner and Keele (1968, Experiment III) presented a series of random dot patterns on a screen to subjects. They had three basic 9-dot patterns (the "prototypes"), and they produced variations (called "distortions") of these prototypes by randomly moving the dots in the original patterns. In training, 24 of the distortions were presented, and the subjects learned with practice and knowledge of results (KR) to categorize them correctly (Edmonds, Mueller, & Evans, 1966, have shown that KR is not necessary for this categorization to occur). The original prototypes from which the distortions were created were not shown. Following training, a transfer test was given, consisting of the 3 original prototypes (not seen previously), 6 distortions shown in training, 12 distortions not previously shown, and 3 new, unrelated, random patterns.

On the transfer test subjects classified the distortions they had seen previously most accurately (13.0% error), but they correctly classified the prototype patterns nearly as well (14.9% error). Classification of the distortions not previously seen was not as accurate (26.9% and 38.3% error, depending upon the degree of distortion). These data indicate that subjects can correctly classify dot patterns that they have never seen before, implying that they generated an abstraction (a schema) of the dot patterns of a given category, stored it, and were able to use this stored abstraction to recognize the prototype pattern when it was later presented. A subsequent study by Posner and Keele (1970) showed that when the transfer test was provided 1 week after the original learning, the recognition of the prototype did not decrease over the retention interval, whereas the recognition of previously seen distortions of it did. This implies that the schema for the dot-pattern classes was retained nearly perfectly, while the actual patterns seen previously could not be stored as effectively. These data clearly suggest that subjects store both the patterns seen and the schema (the abstraction) of the pattern (although at different strengths), and that the schema allows subjects to recognize the prototype pattern without ever having seen it previously. These data, in addition to the Evans experiments cited previously, provide an experimental paradigm and rather strong evidence for the schema concept, at least for stimulus recognition. The next sections deal with the extension of the schema to the area of motor response production and motor response recognition, respectively.

The Motor Response Schema

Bartlett (1932) discussed the notion of the schema as a means of solving the storage problem for response production and as a means of generating novel responses. He was quite clear that some such mechanism must exist, as evidenced by the following:

> How I make the [tennis] stroke depends upon the relating of certain new experiences, most of them visual, to other immediately preceding experiences and to my posture, or to balance of postures, at the moment. (p. 201)

Then, after one takes in this information about the present state of the body and environment, Bartlett says,

> When I make the stroke I do not, as a matter of fact, produce something absolutely new, and I never merely repeat something old. (p. 202)

He was not very clear concerning precisely how the schema would operate and how learning would be handled, but recently Pew (1974) has provided some additional thinking about the schema. While the views expressed in this article are not exactly like

Pew's, they clearly had their origin in Pew's thinking.

The notion of the schema as an abstraction of a set of stimuli requires some modification to allow application to response production. Basically, when the individual makes a movement that attempts to satisfy some goal, he stores four things: (a) the initial conditions, (b) the response specifications for the motor program, (c) the sensory consequences of the response produced, and (d) the outcome of that movement. The next section explains each of these constructs.

Initial conditions. A number of writers (e.g., Keele, 1968; Pew, 1974) have indicated that in order for the subject to move effectively, he requires information about the preresponse state of his muscular system and of the environment in which he is to move. The initial conditions, then, consist of the information received from the various receptors prior to the response, such as proprioceptive information about the positions of the limbs and body in space, as well as visual and auditory information about the state of the environment. After the movement, the initial conditions used to plan the movement are stored.

Response specifications. Since the motor program for generation of the muscle commands is assumed to be rather general, with variations of the basic pattern possible by changing such important elements as the speed with which it is run off, the forces involved, etc., the subject must specify these elements before the movement can be run off. After the movement, these specifications are stored along with the other information received after the movement. These serve as a record of the specifications of the movement produced.

Sensory consequences. The third type of information stored after the movement is the response-produced sensory information. This information consists of the actual feedback stimuli received from the eyes, ears, proprioceptors, etc. Thus, the sensory consequences are an exact copy of the afferent information provided on the response.

Response outcome. The fourth source of information stored after the movement is the success of the response in relation to the outcome originally intended. The desired outcome (or goal) of the movement is potentially a verbalization, such as, "throw the dart very hard at the center of the target" (although the desired outcome need not actually be verbalized), and the response outcome is in these same terms, such as, "you threw 23 mm to the left." Thus, the actual outcome of the movement is stored, not what was intended. This outcome information arises from information the subject receives after the movement, and consists of KR (when present) and subjective reinforcement that the subject obtains from other sources of feedback. The accuracy of the outcome information is thus a direct function of the amount and fidelity of the feedback information, and a subject without any feedback information does not have outcome information to store.

Schema formation. The above four sources of information—initial conditions, response specifications, sensory consequences, and response outcome—are stored together after the movement is produced. When a number of such movements have been made, the subject begins to abstract the information about the relationship among these four sources of information in a way suggested by the dot-pattern discrimination experiments. The schema notion requires some extension from the original pattern-perception idea, however, in that in the motor case it is the relationship among the arrays of information that is abstracted rather than the commonalities among the elements of a single array. The strength of the relationship among the four stored elements increases with each successive movement of the same general type and increases with increased accuracy of feedback information from the response outcome. This relationship is the schema for the movement type under consideration and is more important to the subject than is any one of the stored instances, which, according to Posner and Keele (1970), are forgotten more quickly over time than is the schema. Figure 2 diagrammatically shows how these sources of information are associated to form the schemata.

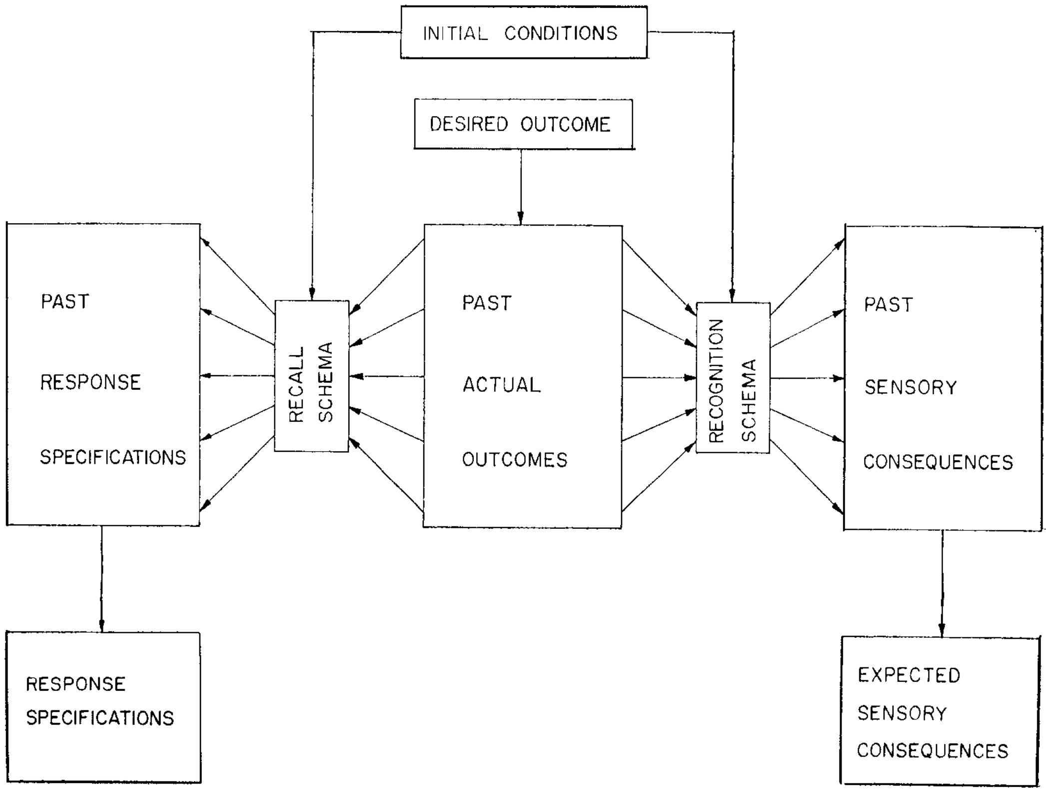

FIGURE 2. The recall and recognition schema in relation to various sources of information.

Response production. When an individual is required to make a response of a type for which he has a schema already developed, he begins with two inputs to the schema: the desired outcome for the movement and the initial conditions. From the relationship between the past outcomes and response specifications (the recall schema), he determines what set of specifications will achieve the desired outcome. The subject need never have produced those specifications previously, because they are determined from a combination of initial conditions and an outcome that might never have been present earlier; nevertheless, with the schema rule between the outcome and response specifications, as modified by the initial conditions, the specifications can be determined as interpolations among past specifications. When the specifications are determined, the subject executes the motor program with the particular set of specifications, and the movement is carried out. Because the specifications may have never been used in exactly this way before, the movement that results may be novel, in that it may, strictly speaking, never have been executed before.

Response recognition. At the same time that the subject uses the schema to generate the response specifications, he also generates the expected sensory consequences of the movement. Because the schema also contains a relationship between the past outcomes and the past sensory consequences, given the desired outcome, the subject can generate two types of sensory consequences, modified by the particular initial conditions. The first expected sensory consequence is the expected proprioceptive feedback, which should result if the desired outcome is achieved, and which consists of the anticipated feedback from the various proprioceptors in the muscles and joints, as well as the anticipated information from the vestibular apparatus. Second, the anticipated exteroceptive feedback consists of anticipated vision, audition, etc., of the environment and of the limb and the objects moved by it.

During and/or after the movement, each of these expected sensory consequences is compared with the respective inflow of sensory information (the proprioceptive and exteroceptive feedback, respectively), and a resulting mismatch in the expected and actual sensory consequences produces an error that is fed back to the schema, providing information (subjective reinforcement) as to the outcome of the response produced. These processes are symbolized in Figure 3, in which the recall and recognition schemata are combined (i.e., the "motor response schema") to increase the clarity of presentation.

Since the expected sensory consequences are dependent upon the developing relationship between the response outcome (as determined by KR or other subjective reinforcement) on previous trials and the sensory feedback actually received, the strength of the recognition memory should increase as a function of both KR in initial practice and the quality and amount of feedback received on each trial. This portion of the schema rule is the basis of recognition memory for the movements of the type governed by the schema. This recognition memory is assumed to be analogous to recognition memory in verbal learning—including the assumption that it is independent of motor recall memory (i.e., that memory associated with the response-production portion of the schema), even if some of the variables (e.g., KR and subjective reinforcement) are similar for the two memory states.

An important point should now be made about the nature of the expected sensory consequences generated before the movement. In order for the subject to be able to receive information about the correctness of the movement in relation to the desired outcome, he must be able to compare the actual feedback with the feedback expected if the movement achieved the environmental goal, and thus the expected sensory consequences must represent the feedback consequences of this correct movement. This is in contrast to a number of earlier theories (e.g., Anokhin, 1969; Bernstein, 1967; Pew, 1974; Sokolov, 1969) in which the expected sensory consequences are of the movement actually chosen; such expected sensory consequences can provide information about the extent to which that movement was carried out faithfully, but can provide no information about whether appropriate response specifications were selected. A major difference between these theories and the present one concerns the way in which these expected sensory consequences are chosen.

In the present theory, the subject begins the process by selecting a desired outcome and by noting the initial conditions at the time. The relationship between actual outcomes and sensory consequences (the recognition schema) allows the generation of a set of expected sensory consequences that represent the best estimate of the sensory consequences of the correct movement. Also, the relationship between actual outcomes and response specifications (the recall schema) permits the generation of the response specifications that are the best guess as to how to achieve the desired outcome. With this method of selection, even though the expected sensory consequences and response specifications are strongly associated, there is no necessity that they be isomorphic, as with the earlier theories, because the recall and recognition schemata are separate. While the two schemata do share the initial conditions and actual outcomes as variables, they are separate because the recall schema is the relationship between these variables and response specifications, whereas the recognition schema is the relationship between these two variables and sensory consequences. Further, it is possible that the subject may choose inappropriate response specifications on trial n, recognize his error, update his recall schema, and produce different specifications on trial $n + 1$, even if the initial conditions are identical; even though two sets of response specifications were generated on the two trials, the expected sensory consequences could have remained constant because the desired outcome did.

In the earlier theories, however, the subject first chose the particular movement pattern and then chose the expected sensory

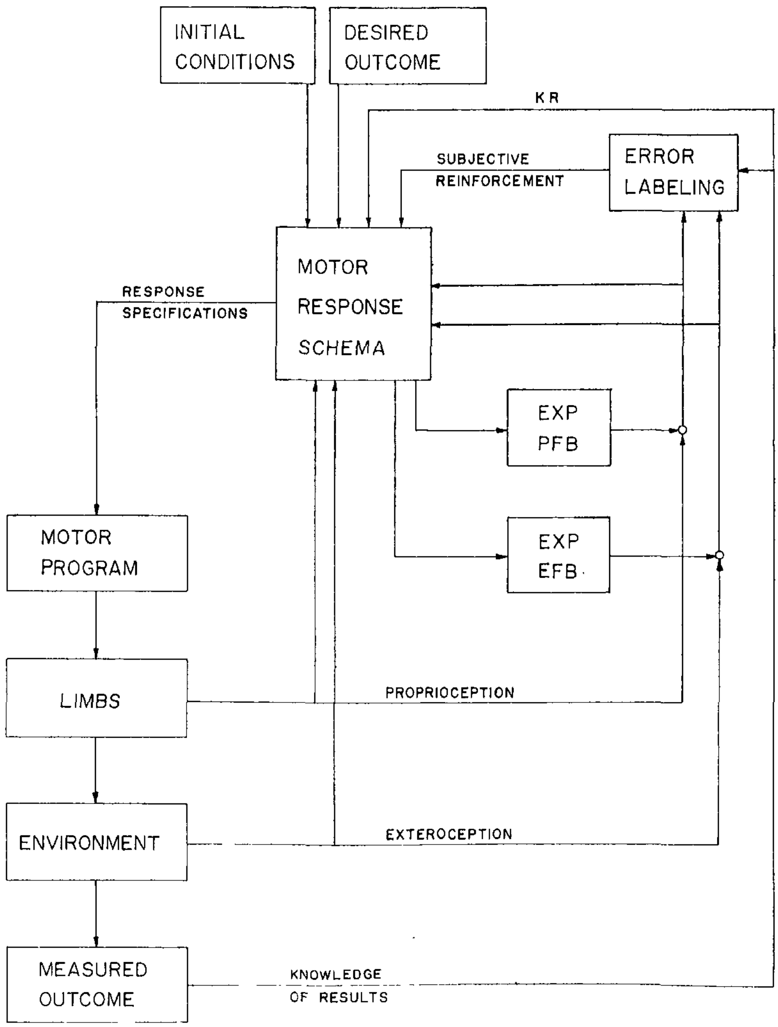

FIGURE 3. The motor response schema in relation to events occurring within a trial (recall and recognition schemata are combined for clarity). Abbreviations: KR = knowledge of results; EXP PFB = expected proprioceptive feedback; EXP EFB = expected exteroceptive feedback.

consequences associated with that response; here the expected consequences and response specifications are necessarily isomorphic because one was specified first and the other was chosen as a function of it. The limitation in this system is that if the recall schema is weak and the subject chooses inappropriate response specifications, the movewill be incorrect, but he will have no way of detecting his error, since the expected and actual sensory consequences, being of the movement chosen, necessarily match. Adams (1971) successfully avoided this problem in his theory by insisting that the perceptual trace (the expected sensory consequences) be developed through past experience with the correct movement.

The Labeling of Error Signals

The present theory proposes that the error signal generated by the comparison of actual and expected sensory consequences exists in two possible states: (a) the raw sensory signal that arises from the comparison of expected and actual consequences, and (b) this raw signal after it has been labeled and converted into a reportable form. This notion is certainly not new, as Bartlett in 1932 said,

> Perceptual processes, in fact, involve two different, but related functions: (a) that of the sensory pattern, which provides a physiological basis for perceiving; and (b) that of another factor which constructs the sensory pattern into something having a significance which goes beyond its immediate sensory character. (p. 188)

While this raw signal can be used by the subject, most notably in those situations where the subject makes a series of adjustments in order to reduce his error signal to zero in positioning tasks, it is the labeled error signal that plays a role in explaining learning. The labeled error signal is termed *subjective reinforcement* and can serve as a substitute for knowledge of results (KR), providing outcome information that can update the recall schema. Subjective reinforcement is less accurate than is the perfect KR, and so the subject will probably use KR to update the recall schema when KR is present, but when KR is not present, the subject can resort to the less accurate subjective reinforcement for his outcome information.

The error labeling system is proposed to be another schema, in this case a schema for labeling sensory signals. It is assumed that past sensory signals have been stored along with the actual sensory consequences (based on KR), and a schema rule is built up over time that relates the KR received to the signals received. When this schema is well established, it enables the subject to receive error signals from the expected–actual comparisons, and to attach a label to these signals according to the KR–sensory-signal relationship. Thus, in later practice, the subject can attach a label to a new sensory error signal that he has *not* experienced previously, and the result is subjective reinforcement. Of course, the essential ingredient for the error labeling system is KR, and without it subjects cannot develop the schema for labeling new errors.

Producing a Movement

Given the notions presented in the previous sections, it will be useful to describe how the schema operates in producing a motor response by explaining the steps in the movement in the order that they are thought to occur. Figure 3 shows the movement process, beginning with the specification of a desired outcome and subsequent determination of the initial conditions. From the relationship established in past responses between outcomes and response specifications, new specifications for the motor program are selected. Also, at the same time, the relationship between outcome and sensory consequences allows the selection of the expected proprioceptive feedback and exteroceptive feedback. When these processes have occurred, the movement can be initiated by running off the motor program.

Immediately following the initiation of the motor program, the impulses begin to flow out to the muscular system with all of the details of at least the first 200 msec of the movement specified. As the movement is carried out, sensory receptors in the body provide information about the movements occurring. For convenience only, these receptors are classed into two groups—proprioceptive feedback and exteroceptive feedback—although it should be recognized that this classification does not represent any meaningful differences in the way these feedback sources are assumed to operate. The feedback information is fed back to the expected proprioceptive and exteroceptive feedback states, respectively, and the discrepancy between these anticipated and actual states represents an error in responding. The raw error is fed back to the schema so that in positioning movements, for example, additional adjustments can be made to reduce the error to zero. This error is also fed to the error labeling system, where the subject assigns a reportable label to it, and this resulting subjective reinforcement is then fed back to the schema as subjective information.

The final source of error is the information that the experimenter or teacher provides for the subject after the movement, termed KR. It arises from the measured outcome of the response ("the ball missed the target by 20 cm to the left"), and is already in a form that is interpretable as a deviation from the desired outcome. The KR information, in addition to being fed back to the schema for updating the schema rules, is fed to the error labeling system to enable this system to improve its accuracy in labeling future error signals arising from the deviations of proprioceptive and exteroceptive feedback from their respective anticipated states.

Learning is possible by feeding back the essential error information to the schemata. The response specifications and initial conditions are stored when the movement is selected, and the actual proprioceptive and exteroceptive feedback are stored as the movement is progressing and as these sources of information are generated. Finally, the actual outcome is stored, based on KR when it is present, but based on subjective reinforcement if KR is not present. These sources of information can then be used to update the schema rules and provide revised estimates of the expected sensory consequences and response specifications on the next trial. The traces representing these sources of information are hypothesized to be relatively weak, so that rapid forgetting of them can be expected over time. However, the traces are assumed to be held in store sufficiently long so that they can be used to update the appropriate schemata. The schemata, on the other hand, are assumed to be stored far more permanently, although some forgetting of them over time could be expected.

SOME DISTINGUISHING FEATURES

This section concerns some of the important ways in which the present theory differs from earlier points of view. In this discussion, the ways in which the theory can deal with the problems and shortcomings of the other theories are discussed.

Applicability to Various Response Types

The present theory extends the notions of Adams' (1971) theory to response types other than linear positioning, and can handle the learning and performance of discrete tasks that are either open or closed (Poulton, 1957) and either rapid or slow. In addition, a type of discrete response not frequently discussed is one in which the performer continually strives to do "more of something," such as moving faster, jumping higher, or producing more force, and this type of task does not have accuracy, in the traditional sense at least, as a goal. Further, the theory has the capability of explaining novel movements that may not have been produced previously.

Open versus closed skills. Poulton (1957) defined open skills as those in which environmental and situational characteristics can change as the subject plans or performs his response, such as the response that would be required of a wrestler attempting a takedown. Closed skills, at the other extreme, are those in which the goal and environmental conditions are relatively constant. The important distinction between these two types of movement was recognized by Gentile (1972). Essentially, with closed skills the performer need only learn one movement that satisfies the goal, whereas with open skills, the environmental conditions are never constant, and the subject must plan his response to meet the anticipated situational demands of the enviroment. The question of the novel movement is particularly important for these open skills, since performers must make movements never before made if the environment is not exactly the same as for previous movements.

Theoretically, with closed skills the subject develops the schema rule so that he makes finer and finer predictions on the basis of the rule, and the expected sensory consequences are more and more accurate estimates of the consequences of that one movement. This is much the same as Adams has it (but the mechanisms are different, of course). The schema rule produces increasingly accurate estimates of response specifications and expected sensory consequences, and the movements become more and more accurate as a result. With open skills, however, the problem is similar, but it is complicated by the fact that the subject must be able to produce novel responses. He does this by again strengthening the schema rule between outcomes and response specifications and between outcomes and sensory consequences, as mediated by the initial conditions. When a new environmental condition arises, the subject can generate the response specifications and the expected sensory consequences on the basis of his perceptions about the state of the environment (and what that state will be when the movement is actually carried out).

The present point of view, contrary to Gentile (1972), does not see open and closed skills as being fundamentally different. Closed skills are those movements in which the subject does not have the problem of environmental uncertainty as he plans the movement. Open skills, however, can be regarded as closed skills with environmental uncertainty added. The problem for the performer in these open tasks is to determine what the environment will be like when the movement is finally executed, and to plan the movement accordingly. However, because of the reaction-time lags in the motor system, there comes a time in every open skill where the individual must execute the program associated with the best estimate of the changing environment, and at this point the movement becomes "closed" for the subject. That is, given his temporal limitations, he executes the movement and cannot change it for at least 200 msec, and it is exactly as if the environment were fixed in that state predicted by the subject when he planned the movement. If the subject was incorrect in his estimates of the environmental state, he would, of course, have produced a response that was inappropriate given the environment, and he would have to initiate corrections after the motor program had run its course (or on the next movement if the response was very short in time, e.g., 200 msec).

Rapid versus slow responses. The present theory extends Adams' (1971) theory dealing with slow, graded, linear positioning responses to movements that are too rapid to allow feedback to be used while the movement is in progress. Theoretically, these two types of responses are controlled and learned in very different ways.

In slow positioning movements, the schema rule determines the expected sensory consequences for the end of the movement specified by the desired outcome. Then the subject moves along the track and compares the response-produced feedback with the expected sensory consequences. He continues moving as long as his errors (the discrepancies between feedback and the expected consequences) are being reduced, and then finally homes in on the target location by reducing his error to zero. Even though the subject is moving actively and some (e.g., Marshall, 1972) have termed these movements "recall," the present position is that the subject is using feedback compared with a *recognition* state, and hence the subject is moving to that location that he *recognizes* as being correct. Such slow responses are dependent on recognition memory and the recognition portion of the schema rule.

What about error detection and the determination of subjective reinforcement after the movement? Clearly, since the subject has used the comparison between expected sensory consequences and response-produced feedback as the basis for determining the endpoint, he will have subjective reinforcement that is zero, reflecting the fact that he moved to that position for which the error signal was zero. He can, therefore, have no further estimate of his own error with respect to the target on that trial unless he receives KR. He cannot, therefore, continue to learn these movements without KR, because he requires KR and/or subjective reinforcement in order to strengthen the response-recognition schema. If the subject lacks this information, the schema remains stable, and the subject maintains his performance. If the level of practice is low, and the schema is not well developed, he may regress in performance after KR withdrawal because of inappropriate guesses about outcome being paired with the sensory consequences, to the detriment of the accuracy of the schema rule.

Now let us consider rapid responses. Since the time required for exteroceptive and proprioceptive feedback to circle the loop and result in subjective reinforcement is great, rapid movements (such as a task in which the subject learns to move 30 cm in exactly 150 msec) are completed before the subjective reinforcement can begin to have an effect. Even if it cannot act on that trial, however, the subjective reinforcement is present nevertheless, and still signals the extent to which the expected sensory consequences and response-produced feedback matched, and hence the subject has an estimate of his response correctness after the movement has been completed. This is fed back to the schema as actual outcome, and the rule between outcome and response specifications is strengthened. If KR is withdrawn, the subject has information about response correctness from subjective reinforcement based on proprioceptive and exteroceptive feedback, and performance can be maintained. If sufficient KR practice precedes KR withdrawal, the subject should be able to continue to learn without KR, since subjective reinforcement can provide a substitute for the actual outcome information that KR, when present, provided.

Tasks not requiring accuracy. Many tasks in daily life require one to attempt to do more of something, such as throw harder or jump higher. Theories such as Adams' have difficulty with response evaluation in such tasks, since the perceptual trace is the representation of the "central tendency" of past feedback states. While it is possible that the perceptual trace can provide information about the success of a new jump that is higher than any done previously, accuracy of the subjective reinforcement will be quite low, because the feedback from the new jump is so different from the average of the past attempts. However, in the present theory, the subject can generate expected sensory consequences for such responses on the basis of the recognition schema, and these are not tied to the central tendency of his past consequences. The result is a somewhat better estimate of the extent to which the subject achieved the goal when it lay outside of the range of responses previously executed.

Two Compartments of Memory

While there are two states of memory postulated, they should not be seen as totally independent, for they are hypothesized to develop using some of the same variables. The recall schema depends on the actual outcome (KR or subjective reinforcement), the initial conditions, and the response specifications, with the rule updated after each trial by an integration of this new information into the existing schema. By contrast, the recognition schema develops using the initial conditions, the sensory consequences, and actual outcome integrated into the existing recognition schema. Thus, while some of the variables are different, both schemata are clearly dependent on the actual outcome and the initial conditions, and both schemata will develop according to the experience the individual has had with these variables. On the other hand, they are separate in that the recall schema uses response specifications and the recognition schema uses obtained sensory consequences. The degradation of feedback when KR is present should have no effect on the recall schema, since KR is used as the estimate of actual outcome, but should have detrimental effects on the recognition schema.

As was pointed out earlier, Adams' (1971) theory has difficulty in explaining how one could continue to learn a positioning task after KR had been withdrawn, or even how one could simply maintain performance without KR. The problem was that if the subject ever made an error, the perceptual trace would be degraded somewhat, he would consequently make a greater error on the next trial, the trace would be further degraded, and so on until movement had become very inaccurate. For the slow movements, the schema notion cannot predict continued learning without KR since subjective reinforcement always indicates that the subject has moved to the correct location on each trial. The present theory can, however, predict that performance in slow tasks should be maintained, since in order to change the recognition schema the subject requires the pairing of actual outcome and the sensory consequences. Of the two he has only the sensory consequences after the movement, and hence no changes in the schema can occur. In the cases where KR is withdrawn after very few KR trials, decrements in performance might occur because of incorrect guesses about the actual outcome, with inappropriate updating of the schema resulting in the performance decrements commonly seen (e.g., Bilodeau, Bilodeau, & Schumsky, 1959).

In rapid movements, however, the KR-withdrawal effects are somewhat different. When enough practice with KR has been provided so that the subject has an accurate recognition schema, if KR is withdrawn the subject has the capability to store all that is necessary for continued recall schema development: the initial conditions, actual outcome (from subjective reinforcement), and response specifications. Hence, if the subject makes an error, it does not degrade the recall schema mechanism, but rather strengthens it, since in an error response actual outcome and response specifications will be lawfully related in the same way that they are in more nearly correct movements. The result is that the recall schema is at least maintained in strength, and is perhaps increased in strength, with KR withdrawal. Of course, the recognition schema remains stable because it requires the pairing of actual outcome and sensory consequences; in this case the actual outcome and sensory consequences are redundant, since the former was computed on the basis of the latter, and no updating can occur.

SOME SUPPORTING EVIDENCE

This section provides some experimental evidence that is taken as support for the various hypothetical processes assumed to occur in the performance and learning of discrete tasks. In addition, independent variables that are hypothesized to influence the various processes are mentioned, and experimental paradigms for subsequent tests of these ideas are suggested. Before turning to the evidence, however, a discussion is necessary concerning the dependent variables assumed to be indicative of the processes and states proposed.

Dependent Variables

Motor recall. Recently there has been considerable debate about which of many error scores should be used as measures of performance in tasks demanding accuracy. While the issue is certainly not new (e.g., Woodworth, 1938), Schutz and Roy (1973) have reopened the argument, advocating the use of constant error and variable error as measures of accuracy, arguing that absolute error should not be used because it is confounded with constant error and variable error. It is appealing to have measures that are independent within subjects such as constant error and variable error, allowing variable error to represent consistency and constant error to represent directional biases, but it can be argued that absolute error is to be preferred as a measure of performance. First, having two dependent measures in one experiment can allow opposite conclusions to be drawn about the processes that they are thought to estimate (e.g., Dobbins & Rarick, 1975), leading to equivocal findings. Second, absolute error has a solid history of use in psychology and motor behavior, probably because it is intuitively meaningful; it is the amount by which the subject was incorrect in his movement. Third, one can imagine the performance of an individual who is told that he will be financially rewarded for reducing his constant errors on a series of trials; he will probably move on trial n to cancel out a constant error made on trial $n - 1$, and will not attempt to achieve a correct movement. It seems that individuals try to reduce the amount by which they are incorrect in the task (i.e., the absolute error), and measuring constant error and variable error when the subjects are not aware of it could provide misleading data. For these reasons, the use of absolute error as a measure of recall-schema strength seems justifiable.

In some of the experiments cited in this article, variable error is used as a substitute for absolute error, and it can be argued from Schutz and Roy's (1973) analysis that the variable error and absolute error are probably measures of the same state or process, since the constant errors in such tasks are nearly zero. Finally, Henry (1974) advocates the use of the total variability of the subject's scores around the correct value as a measure of overall accuracy in responding, and this measure is probably highly associated with both absolute error and variable error under conditions where constant error is nearly zero.

Motor recognition. A number of researchers (e.g., Newell, 1974; Newell & Chew, 1974) have argued that the appropriate statistic for the estimation of recognition memory strength is the absolute value of the difference between the objective and subjective error, and that the within-subject correlation does not indicate the extent to which the subject is incorrect in his judgments, only that he is sensitive to the direction of his errors. They argue that he could be in error by a constant of 100 msec (i.e., his average guess might be 100 msec too large) and yet this fact would not be represented by a drop in the correlation. While they are correct on this point, there are a number of reasons that the correlation is to be preferred to the difference score.

First, there has been negative reaction to difference scores (e.g., Bereiter, 1963; Schmidt, 1972a), and the objective–subjective difference score is not free from undesirable effects, which include (a) an extreme correlation with the minuend, which in this case is the absolute error ($r = .80$ in Schmidt & White, 1972), (b) probable nonlinearity of relationship with the construct (in this case, the recognition-schema strength) that the difference score attempts to measure, and (c) statistical unreliability due to the summation of errors in measurement for the two components. A further difficulty for the present theory is the fact that the objective–subjective difference and the absolute error theoretically are measures of separate states of memory; however, the method of computation of these two statistics allows the inclusion of absolute error in both measures, leading to a strong correlation between these two scores, even to the point that the plots of these two scores over trials yields nearly identically shaped functions. In such cases, it would be possible to show that a given experimental variable influences both the recognition and recall measure identically because of a statistical artifact, leading to the erroneous conclusion that recall and recognition were not separate.

The objective–subjective correlation is to be preferred, because it is clearly sensitive to the direction of the subject's guesses. It also counters a strategy employed by some subjects whereby they guess the correct score (e.g., 200) on each trial of a 200-msec task. In such cases the correlation is zero, reflecting a total insensitivity to the size and direction of the error, whereas the difference score is minimized (especially if the constant error is zero for that subject), making him appear to be quite talented in predicting his score. As a measure of the strength of the recognition schema, therefore, the correlation statistic is to be preferred, but could be supplemented with the average objective–subjective difference to be certain that there were not large constant errors in guessing.

Support for the Schema Notion

The most important portion of the present theory is the schema, and this section deals with experimental and other evidence for it. The recall and recognition schemata will be considered separately.

Recall schema. Strictly speaking, very little published work supporting a schema for response production can be found. However, there are a number of studies suggestive of the schema's existence, and there is subjective-anecdotal evidence as well.

Anecdotal evidence for the schema is that subjects can produce sequences of movements that they have never performed before. A classic example concerns handwriting, in which a person's signature can be recognized as his regardless of the size of the actual marks produced; one can produce the same signature on a check or 10 times larger on a blackboard (Merton, 1972, p. 4). Of course, quite different musculature is used in these two signatures, with the movements confined to the fingers and perhaps the hand in small writing, and the entire arm in larger writing. The schema notion explains this by saying that the movements are all run off by a large motor program that needs to have certain specifications in order to produce a given movement sequence. When the specifications are that the movement should be small, rapid, and slanted slightly, the program can carry out these movements as planned. Of course, a motor program theory such as that of Henry (1960) cannot handle these findings, since it postulates that the movements are the result of a specific motor program, with a different program needed for each movement "style." The fact that individuals can do this seems to be evidence directly in conflict with such one-to-one program – movement-style ideas.

Pew (1974) adheres to the idea that the movement is programmed rather generally, and then the movement parameters are specified before the movement is initiated. In a study by Armstrong (Note 3) a sequence of lever movements was learned in a number of sessions. An important result was that the timing in the sequence appeared to be generalized, in that when the movement was done too rapidly the entire sequence was speeded up, keeping the temporal relationships among the various submovements approximately constant. The implication that Pew (1974) draws from these data is that timing is one of the response specifications that serves as a "parameter" of the motor program.[2] Also, Glencross (1973) found in handwheel cranking that the movements were very similar in terms of the timing of the onsets of force application even when resistance was added and the radius was changed; he labeled the phenomenon "gradation of effort." It is as if there was a program for cranking, and that changing the quality of cranking (i.e., less force, more speed, etc.) provided a situation in which the subject still used the program, but with a different set of specifications. While the present article does not attempt to deal with such continuous responses, these findings at least suggest that a schema-like process could exist in discrete movements as well.

However, the most impressive kind of evidence that could be generated in support of the schema is that subjects can produce movements of a given class that they had, strictly speaking, never performed previously; an example is the basketball player who shoots from various places on the floor with great accuracy. The notion is that the varied previous shooting experiences led to increased schema strength, providing a basis for generating novel movements of that same class. One important prediction is that increasing either the amount or the variability of such previous experiences lead to increased schema strength. These predictions suggest a test of the schema notion in terms of transfer of learning.

Experiments testing this idea have been conducted, and some of them are quite old (e.g., Crafts, cited in Ellis, 1965; Duncan, 1958). For example, Duncan used a task in which the subject had to position a lever into one of 13 slots depending upon which of 13 lights was illuminated, with the movements being done as quickly as possible. The task could be varied to produce 12 similar versions, and subjects received either 1, 2, 5, or 10 variations in a training session, with the total number of trials held constant. Duncan found that the amount of transfer to two novel variations of the task was a positive function of both the amount and variability of training, especially as the variability was increased from one to two tasks. While this study supports the predictions from the theory strongly, it could be argued that what was learned and transferred were cognitive–conceptual relationships related to which light went with which slot, and the findings may not tell a great deal about the existence of schemata for producing movement. To support the recall schema idea, a task should be used that involves primarily motor learning, with minimized cognitive aspects, so that transfer as a function of response variability could be attributed to the development of schemata that define the response specifications.

Schmidt and Shapiro (unpublished study, 1974) used Duncan's design with a task that could be considered more motor in nature than his light-slot task. The task involved moving the preferred arm and hand to knock over four small barriers in a predefined order, and minimized movement time was the subject's goal. The task was varied by

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[2] See also Brooks (1974), who found that timing appeared to be a parameter of alternating hand movements in monkeys.

changing the locations (but not the orders) of the barriers, so that four tasks with slightly different movement-segment lengths and intersegment angles were defined. One group performed three tasks (40 trials of each with KR) while a second group performed one task (120 trials with KR). When subjects were transferred to a fourth novel version of the task, there was some tendency for the group with high variability (three tasks) to perform more quickly than the group with low variability (one task), with these differences increasing somewhat over subsequent practice with KR, but the differences were small and did not reach statistical significance.

The failure of the Schmidt and Shapiro study to support the schema notion does not, of course, disprove it, as there are a number of alternative explanations. First, the task involved the preferred arm and hand with college-age subjects, and it is possible that schemata for movement production had already been developed throughout extensive previous movement experience with that limb. This suggests that future work along these lines should use limbs and movements that have not been used extensively, or should use younger subjects in whom the schemata have not been developed. Also, it is possible that the variations of the task did not produce movements that were sufficiently different, or produced movements that were different in the "wrong" ways.

Recognition schema. As was mentioned in a previous section, there is considerable evidence in the dot-pattern recognition studies for the existence of schemata. This evidence indicates that subjects not only can store the individual patterns seen, but also can store some abstraction of the patterns. This abstraction is the schema and consists of a set of rules for determining whether a given new pattern is or is not a member of the class of objects described by the schema rule. As strong as this evidence seems to be, there are two essential ways in which the experimental situation dealing with dot patterns differs from the motor recognition schema in the present theory.

First, the schema in the dot-pattern work represents the central tendency of the past sets of stimuli seen. This is different from the present situation in that the recognition memory for, say, a novel ball throw may not represent the central tendency of all balls previously thrown. To have it represent the central tendency would provide a recognition state that would not be associated with a new response, that might not be near the central movement pattern, and that would not provide recognition for novel movements. Rather, what the schema represents is the relationship among a number of sources of information stored on each trial, and in the motor recognition case, these are the actual outcome and the actual sensory consequences. Hence, the schema notion is extended from becoming the central tendency of a set of stimuli to the relationship between paired members of two sets of stimuli.

A second and less cautious extension of the recognition schema notion is to types of stimuli other than the visual patterns studied by Posner and Keele (1968, 1970) and others, and it is assumed that such abstracting processes can occur with auditory, tactile, and kinesthetic stimuli as well. There is some support for recognition schemata with kinesthetic stimuli in a report by Williams and Rodney (in press). As mentioned earlier, blindfolded subjects attempted to learn a criterion position along a trackway in two different ways. Group TO (target only) moved 16 times to a stop at the criterion position, whereas Group IR (interpolated random) moved to 16 randomly ordered stops that surrounded the criterion position; Group IR was instructed that the criterion position was in the center of the 16 positions presented. The critical transfer test (see Figure 1) showed Groups TO and IR performing with nearly equal absolute errors on the first block, but Group IR maintained performance over subsequent blocks, whereas Group TO regressed sharply in its performance.

The interpretation in terms of the schema theory is that the 16 practice positions performed by Group IR enabled subjects to develop a recognition schema for the locations along the trackway; the reduced variability for Group TO did not permit this schema development. Then, on the transfer trials, Group IR subjects could generate the expected sensory consequences associated with the criterion position (even though they had not experienced this position previously), and could then move so as to match the incoming proprioceptive feedback with the expected proprioceptive feedback. The recognition-schema strength was approximately maintained over the five blocks for Group IR, but for Group TO the traces associated with the criterion position apparently faded, resulting in less accurate responding for these subjects. The important point is that Group IR subjects could recognize the criterion position without having experienced it previously, and they could recognize it as effectively as Group TO subjects with experience at the criterion location. While the experiment does provide support for the schema theory, it is perhaps more important because it provides strong contrary evidence to the prediction from Adams' (1971) theory, which says that Group TO with practice at the criterion position should have greater accuracy (due to increased perceptual trace strength) and should maintain accuracy longer than Group IR. These findings provide considerable difficulty for Adams' position.

Separate States of Memory

There is considerable evidence in the verbal learning literature to indicate that there are two separate states of memory, one for recall in which subjects must produce the response term, and one for recognition in which subjects must only say whether the item has been seen before. (See Underwood, 1972, for a review of this issue.) The same view is presented in this article and is in general agreement with Adams (1971). Under this view, recall memory is the state that produces the movement, and recognition memory is the state that determines whether the subject can recognize that the movement was correct. While there is strong evidence for this view in verbal learning, what is the evidence for this contention in motor skills?

A research strategy. It was realized long ago in verbal behavior that recognition measures (in terms of number correct) were usually larger than were recall measures, but that this difference, in and of itself, did not necessarily mean that the processes underlying recognition and recall were different. If it could be shown that a given experimental variable influenced recognition in one way (e.g., increased it) and influenced recall in another way (e.g., decreased it), this would provide evidence that the two memory states follow different laws. If two systems have different laws, it makes little sense to maintain that they are the same system, and finding that some experimental variables (e.g., intentional versus incidental instructions) affect recall but not recognition has been used as support that recall and recognition are separate systems.

Motor recognition and recall. The recognition–recall issue had not been studied in motor skills until Adams (1971) proposed the independence of these states in his theory. Since the introduction of this theory, however, there have been a few attempts to show that certain variables influence recall and recognition differently in motor skills. One such attempt was made by Schmidt et al. (in press), who sought evidence for the independence of recall and recognition using KR delay as the main independent variable. In Experiment I, subjects learned to recognize lifted weights, a performance reasoned to be based on recognition memory. Increased KR delay (25 sec vs. 5 sec) caused a drop in the correlation between the actual weight and the subject's guess from .75 to .46, supporting the conclusion that KR delay is a variable in recognition memory. In Experiment II, the authors used a rapid ballistic task (as with Schmidt & White, 1972), attempting to show that KR delay was a factor in the recognition memory for the task (as it was with Experiment I) but was not a factor in the recall memory.

The task in Experiment II involved a paradigm wherein the subject was asked to learn to move a horizontal slide 30 cm (with follow-through permitted) in 200 msec. The subject made a response, the experimenter asked for his guess about his error (subjective error), and then the experimenter provided KR in terms of the actual (objective) error. The experimental variable was again

TABLE 1

RECALL AND RECOGNITION MEASURES AS A FUNCTION OF DELAY OF KNOWLEDGE OF RESULTS IN ACQUISITION

Measure	Delay interval 5 sec	25 sec
Variable error	18.6 msec	20.4 msec
Constant error[a]	+14.4 msec	+16.3 msec
Objective–subjective correlation	.92	.61
N	20	20

Note. From "Some Evidence for the Independence of Recall and Recognition in Motor Behavior" by R. A. Schmidt, R. Christenson, and P. Rogers, *Journal of Motor Behavior*, in press. Copyright 1975 by Journal Publishing Affiliates. Reprinted by permission.
[a] Positive values are overshoots.

the delay of KR. The rationale was that if KR is delayed and the proprioceptive feedback received from the movement fades with time, the actual consequences (based on KR) cannot be paired effectively with the faded sensory consequences, and hence the recognition schema will not develop efficiently. Recall, or the production of the movement, is dependent upon KR and the response specifications (which, it is assumed, do not fade with time as rapidly as the sensory consequences), and hence the theory would predict that the measure of response production would not be influenced by the delay of KR.

Subjects were given 50 trials, with KR provided either immediately (after 5 sec) or delayed for 25 sec, and then practiced 30 additional trials with no KR. The measure of recall in this task was the accuracy in terms of the 200-msec goal, and either constant error or variable error was the recall indicant here. Recognition concerns the extent to which the subject can detect his own errors, and the objective–subjective correlation was used as the indicant of recognition memory. The test of the strength of the recall memories was carried out on the no-KR trials in which the level of the independent variable (KR delay) was equated across groups, in keeping with the established paradigms for determining the learning versus performance status of various experimental variables (e.g., Schmidt, 1975).

The experiment supported the independence of recall and recognition when it was found that increasing KR delay had no significant effect on recall measures (constant error or variable error), but had significant detrimental effect on the recognition indicant, the objective–subjective correlation. As can be seen in Table 1, the 5-sec delay group displayed correlations of .92, whereas the 25-sec delay group showed a correlation of only .61, representing a significant drop in the error-detecting sensitivity of the long-delay group. Therefore, KR decay appears to be a variable that causes decrements in recognition, but leaves recall unaffected, and these findings are in the direction predicted by the theory.

If it is true that KR delay is a variable in the development of the recognition schema, then the learning of any task dependent on the recognition schema should be retarded as well. One such task is linear positioning, which, according to the theory, is dependent on the match between the expected sensory consequences (generated from the recognition schema) and the incoming proprioceptive feedback during the movement. The difficulty with all this is that there is ample evidence that linear positioning tasks are not affected by KR delay (see Bilodeau, 1966, for a review). One possibility is that the evidence on linear positioning has used procedures that prevented the matching of feedback and the expected sensory consequences because of the time constraints usually placed upon subjects, and one could assume that subjects may have switched to a strategy wherein they program the movements. In this case, the production of the movement would be dependent upon recall memory and the recall schema. Schmidt and Shea (unpublished study, 1974) tested this idea by insisting that subjects move very slowly and carefully, encouraging the subjects to "hunt around" for the correct location and preventing programmed movements by varying the starting location; but KR delay still had no effect on learning in this task. Newell [3] has pointed out that it is possible that KR delay does not affect the recognition schema, but

[3] The author wishes to thank Karl M. Newell for providing this suggestion in a personal written communication, October 1974.

rather affects the development of the error-labeling schema; if the subject could not label the errors effectively in the Schmidt et al. (in press) study, we may have incorrectly come to the conclusion that the recognition schema was impaired. More work will be needed to resolve this question.

Even if the Schmidt et al. (in press) study may be inconclusive concerning the recognition–recall distinction, there are other data that provide somewhat stronger evidence. The same basic strategy was used by Newell and Chew (1974) and Schmidt and Wrisberg (1973), but here the independent variable was the amount of response-produced feedback. In both studies, the presence of combined vision and audition was varied in the rapid, ballistic task (Schmidt & White, 1972), and they showed that vision and audition had no effect on response production in terms of absolute error. But in Schmidt and Wrisberg (1973), when KR was withdrawn, subjects with vision and audition regressed far less in performance than did subjects without these feedback sources present; the interpretation was that vision and audition enabled subjects to generate accurate subjective reinforcement via the comparison of the feedback with the expected sensory consequences from the recognition schema. Also, Newell and Chew (1974) showed that eliminating vision and audition in a transfer test increased the difference between the objective and subjective errors, a measure taken to be sensitive to the strength of the recognition schema.

The conclusion from this section is that variables have been isolated—the quality of feedback and perhaps KR delay—that influence the recognition memory for motor tasks but do not affect measures of the recall memory. This, plus the evidence from the verbal learning literature, provides support for the hypothesized separation of recall and recognition processes in motor skills.

Increased Error Detection With Practice

One of the main predictions of the theory is that error detection will increase with KR practice, and Schmidt and White (1972) and others since then (Newell, 1974; Newell & Chew, 1974; Schmidt & Wrisberg, 1973) have shown this quite clearly. In the Schmidt and White experiment, subjects were given 170 trials of the ballistic slide task, with a target movement time of 150 msec. Subjects provided subjective errors prior to the experimenter giving them their objective errors (i.e., KR). The correlation increased steadily over the course of practice, as can be seen in Figure 4, with the correlations being quite low (around .20) in initial practice and rising to around .90 in later practice. These data show clearly that subjects increased their sensitivity to the direction of their errors with practice, and support the notion that the schema for response recognition was increasing in strength.

Error Labeling System

What is the evidence for such a labeling system? Subjectively, it seems rather obvious that such a system must exist, since subjects clearly transfer information from the neurologically coded sensory input to words about the error, and they can do this rather well. Schmidt and White (1972) found objective–subjective correlations of .90, and subjects were able to guess their errors within 7 msec of the actual time moved on the average. Thus it seems clear that subjects can estimate their own errors quite well.

However, additional data arguing for a separate status of the two error signals (sensory errors versus subjective reinforcement) were presented by Newell and Boucher (1974). They asked blindfolded subjects to move a linear slide 20 times to a stop, then to estimate the movement distance verbally, and then to move to the designated position once without the aid of the stop. One group estimated the distance in millimeters and another group in inches, with all subjects having had more experience with the inches scale. The guesses in inches (transformed to millimeters) displayed nearly half the error of the guesses in millimeters, while the accuracy in moving to the target was not significantly different between groups. The interpretation is that the sensory signal arising from the comparison of actual and expected feedback was identical for the two

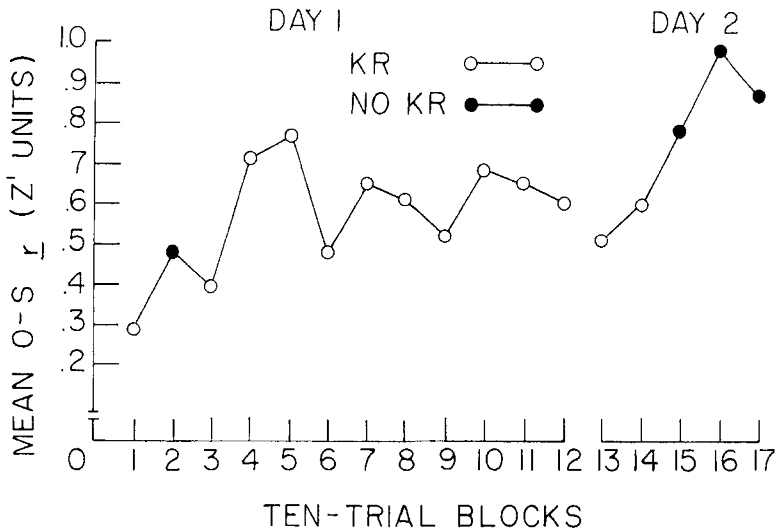

FIGURE 4. Mean objective-subjective (O-S) correlation as a function of practice. Abbreviation: KR = knowledge of results. (From "Evidence for an Error Detection Mechanism in Motor Skills: A Test of Adams' Closed-Loop Theory" by R. A. Schmidt and J. L. White, *Journal of Motor Behavior,* 1972, *4,* 143–153. Copyright 1972 by Journal Publishing Affiliates. Reprinted by permission.)

groups, but that the more efficient schema for labeling in terms of the inches scale resulted in a more accurate report of the distance. These data, then, provide some support for the idea that there exist two states of error: raw sensory signals and labeled subjective reinforcement.

Learning Without KR

The predictions of the present theory for no-KR learning differ considerably for rapid tasks (i.e., with movement time less than 200 msec) and slow positioning tasks. The categories of movement are discussed in turn.

Positioning tasks. The theory hypothesizes that the subject develops a recognition schema over the course of practice with KR, and that he uses the comparison of actual feedback and the expected sensory consequences generated on each trial as the mechanism by which he arrives at the correct location. The evidence is quite clear that without postresponse error information in the form of KR (and without presenting the correct movement on each trial), no learning can occur without KR; this conclusion is supported by a number of investigations (e.g., Bilodeau et al., 1959), and the evidence has been summarized by Bilodeau (1966). This is entirely consistent with the present theory, since the sensory consequences of the correct response are required to strengthen the recognition schema, and the subject has no way of learning the correct location without the guidance provided by KR.

Adams (1971) suggested that subjects could continue to learn these responses without KR after sufficient KR practice was provided, during which the perceptual trace (the expected sensory consequences in the present terms) was strengthened. The present theory does not predict this, and there are no data to suggest that such should be the case in linear positioning tasks. Theoretically, after the recognition schema is developed, withdrawing KR provides a basis for continuing to respond with the former level of accuracy, but any improvement, except by accident, is not possible. Subjects use the recognition memory to produce the movement, attempting to match their current feedback with the expected sensory consequences, but as discussed earlier, their subjective reinforcement indicates that they had moved to that position for which they received a match and for which the subjective reinforcement was necessarily zero. Hence, their subjective reinforcement is not capable of signaling their actual movement distance on that trial, and the substitution of subjective reinforcement for the withdrawn KR is ineffective. Hence, after the movement subjects have the actual sensory consequences to store for use in the updating of the recognition schema, but they do not have the other essential ingredient—the actual outcome. Therefore, no further development of the schema can occur, and learning does not continue after KR withdrawal. These predictions are upheld by a number of separate investigations reviewed by Adams (1971).

The reader should take cautiously the conclusion that if postresponse error information in the form of KR is not available in such tasks, learning cannot occur, for there are two studies that show clearly that learning *can* occur without KR under certain conditions. Solley (1956) used a motor-driven tilt-chair that the subject could operate by a two-way finger switch. The subject was firmly strapped to the chair and the head was immobilized with a bite-bar. He was powered to the vertical position, whereupon the experimenter said "vertical." Then the experimenter tipped the subject 30° to the left or right, and the subject attempted to replace himself in the vertical position with appropriate switch movements. When the subject had achieved what he thought was vertical, Solley "randomly" moved him about to disguise the relationship between vertical and the position to which he had actually moved, and then finally moved him to vertical again and again said "vertical." The subject was then tipped 30° and attempted to again replace himself in the vertical. Over the course of 30 such trials, the absolute errors in arriving at vertical decreased markedly and significantly, and this was achieved without ever providing direct error information. The crucial difference between this study and those referred to earlier is that the correct location was presented on every trial, and apparently this is

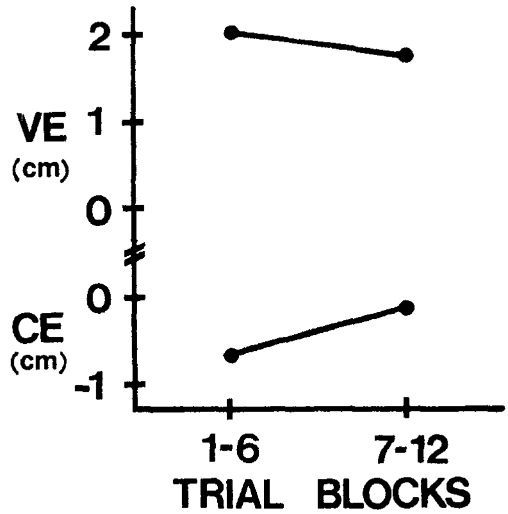

FIGURE 5. Mean constant and variable errors (CE and VE) as a function of practice. (From "A Note on Improved Motor Performance Without Knowledge of Results" by C. A. Wrisberg and R. A. Schmidt, *Journal of Motor Behavior,* in press. Copyright 1975 by Journal Publishing Affiliates. Reprinted by permission.)

all that is necessary to acquire the correct movement.

Wrisberg and Schmidt (in press) duplicated the Solley study with a linear positioning task. They presented the correct location on each trial by having the subject move to a stop, and then waited either 5 or 50 sec before having him attempt to move to this position without the stop. Subjects repeated this trial sequence of the correct movement plus an estimation 12 times to the same target, and KR was never provided as to the response correctness. The results of the study are shown in Figure 5, where the constant errors and variable errors are presented for two successive 6-trial blocks. Both constant error and absolute error (not graphed) decreased significantly with practice, with less undershooting as a function of trials; variable error decreased as well, but the differences just failed significance. These two studies provide evidence that subjects can learn slow positioning tasks without postresponse error information, provided that the correct location is provided on each trial. Adams and Dijkstra (1966) produced similar findings in linear positioning.

The present theory can handle these findings quite easily. When the subject is presented with the correct movement, he stores the sensory consequences along with the desired outcome, and the recognition schema begins to be developed. Then when he attempts to reproduce the movement without the stop, he moves to that position he recognizes as correct. On the next trial he receives the sensory consequences of the correct response again, further updates the schema, and reproduces the second trial with greater accuracy than the first. KR is not necessary to learn because subjects received the appropriately paired sensory consequences and desired outcome (the latter being a constant) on each trial, and this is all that is needed for development of the recognition schema.

Rapid movements. The predictions about learning without KR in rapid tasks are somewhat different from those in positioning tasks. Theoretically, the movement sequences are carried out totally open loop in the rapid tasks, with recall memory having a major role in movement production. Recognition memory and the resulting subjective reinforcement occur after the movement, since these feedback loops are considered quite slow. Therefore, in such tasks there is the capability of detecting one's errors after the movement so that corrections can occur on the subsequent movement.

Even so, however, considerable initial practice is needed in order to strengthen the recognition schema to the point that it can provide subjective reinforcement of sufficient accuracy to be of advantage to subjects in the absence of KR; hence, the theory cannot predict learning "from scratch" without KR, except perhaps in the situations where (a) the correct movement is presented in a way analogous to the method used in the Solley (1956) and Wrisberg and Schmidt (in press) studies, or (b) the task to be learned is a member of a highly practiced class of motor responses for which a strong schema has been previously developed. There is apparently no evidence concerning the former situation, but the latter possibility has some support from Henderson (1974), who showed (with experienced darts players) improved performance in dart throwing without any KR or other feedback information.

After sufficient practice with KR, the subject not only should be able to continue to perform effectively under KR-withdrawal conditions, but also should be able to continue to learn the movement. This prediction, however, has been quite difficult to support because of a number of methodological problems. In order that the task have strong recognition memory, it should presumably be simple enough that the recognition memory can be developed within the time constraints of the typical experiment. However, with such simple tasks, the improvement in performance is quite rapid, with nearly asymptotic conditions reached in very few trials (e.g., Schmidt & White, 1972; Schmidt & Wrisberg, 1973). If KR is now withdrawn, subjects have no room for improvement, because errors are already at an effective floor in the task. Thus, attempts to demonstrate continued learning without KR have been almost universally unsuccessful. An example is the Schmidt and White (1972) study in which KR was withdrawn after 150 trials in a 150-msec movement–time task; while there was some indication of a continuing downward trend in absolute errors, the effect was very small and was not statistically reliable.

However, an alternative approach has proven useful. Schmidt and McCracken (unpublished study, 1974) allowed subjects to perform 200 trials of rapid movement with a 200-msec movement–time criterion with KR on one day, and then brought subjects back 1 week later, providing 20 additional trials with no KR at any time. Through the forgetting that would occur over the 1-week interval, subjects could return to the task with elevated error, allowing some room for subsequent decreases, and thus the study investigated relearning without KR. The 20 trials on the no-KR period were grouped into blocks of 5 trials and are presented in Figure 6. The decrease in absolute error was significant, but there were no significant changes in either constant error or variable error. While these downward trends were significant, the error at the end of this period was considerably larger than it was at the end of initial KR practice, and whatever relearning took place was quite slow and rather incomplete. Nevertheless, these data do suggest that relearning can occur without KR when initial KR practice has been provided (although, strictly, a warm-up interpretation is possible), and they support the theoretical expectations about no-KR learning.

The interpretation is that the recognition and recall schemata were retained to some extent over the 1-week layoff, but that they both suffered considerable weakening. The error on the initial no-KR trial was quite large, suggesting that the choice of the response specification was degraded by forgetting. Even though the schemata had undergone forgetting, it appeared that sufficient subjective reinforcement was available to allow improvement over the next 19 trials. Further work needs to be done using more extensive practice with KR, and with more no-KR trials to determine if this prediction might hold more strongly if given the chance.

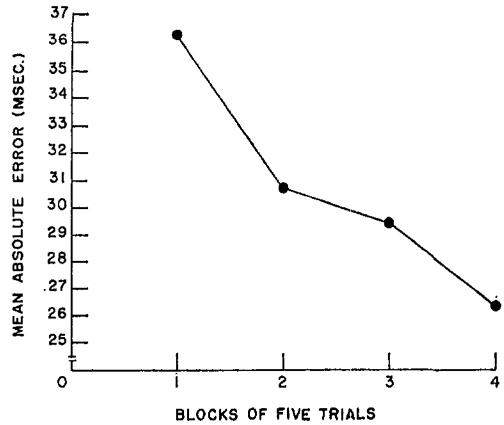

FIGURE 6. Mean absolute error in relearning without knowledge of results (from Schmidt & McCracken, unpublished study, 1974).

Response-Produced Feedback and Recognition

The present theory hypothesizes that the development of the recognition schema, and hence the capacity to detect errors either during (slow responses) or after (rapid responses) the movement, is dependent upon the pairing of the actual outcome (based on KR) with the sensory consequences of the movement. Attempts to manipulate proprioceptive feedback in motor tasks have been fraught with difficulty arising from either unknown effects of direct degradation of feedback, as in the "cuff technique" (Laszlo & Bairstow, 1971), or by the confounding effects of changing the dynamics of controls (e.g., Bahrick, 1957). If the manipulation of feedback can be argued to change the movement required of the subject, then one cannot be sure that degraded error detection after such treatments was due to the effects on the recognition schema or due to the fact that subjects had been attempting to learn a different task. Given these limitations, however, there are a few studies that link feedback and error detection.

Within the framework of Adams' (1971) theory, a number of authors attempted to show that error detection and error correction were enhanced by the enrichment of feedback and practice. Adams & Goetz (1973) showed that providing vision, audition, and increased force cues in linear positioning (as compared with no vision and audition and minimized force cues) increased accuracy in detecting and correcting errors. Practice was effective in increasing the recognition processes as well. Adams, Goetz, and Marshall (1972) have provided similar findings. The interpretation is that the recognition schema uses the proprioceptive information to form the rule, and that enhancing this information renders the rule more effective.

With more rapid movements, Schmidt & Wrisberg (1973) showed that eliminating vision and audition had no effect on performance when KR was present, but that when KR was withdrawn after 20 KR trials, the groups without vision and audition regressed in their performance to a greater extent than groups with these information channels present. The implication was that KR practice when vision and audition were present permitted the establishment of a recognition schema based on these channels, and that no-KR practice then allowed subjects the opportunity of using subjective reinforcement based on vision and audition; groups without vision and audition in KR practice regressed more because of less accurate subjective reinforcement. An interesting finding was that while earlier experience with vision and audition had strong effects on KR withdrawal performance after 20 trials, there were no such effects after 75 trials, suggesting that the channels of information used by the recognition schema may change somewhat as practice continues; vision and audition may have been important in earlier error-detection performance, and perhaps proprioception had become more important later. There is certainly more room for experimentation on this question.

Role of Efference Copy

An important line of thinking in motor skills research today is the notion of efference copy. There are a number of points of view about how it might operate and the issues are definitely not settled. The role of efference in the present theory, therefore, is somewhat unsettled also, and this section attempts to review some of the important issues and to explain the thinking that led to the present position taken on efference. Space does not permit a thorough treatment of this area, but for reviews consult Gyr (1972) or Jones (1974).

Evidence for Efference

The notion of efference copy began with the eye-movement work of Helmholtz (1925) and later Holst (1954). These writers argued that for accurate visual perception it was essential that the central nervous system have information about motor commands sent to the muscles that move the eye. Without this information, the visual images are ambiguous, in that the organism cannot know whether a shifting visual image means that the eye was moved in a stable environment or whether the eye was stationary in a moving environment. This finding led Holst (1954) to propose that an image of the motor commands (an efferent copy or corollary discharge) is "fed forward" to modify the incoming visual sensations to compensate for the fact that the eye was ordered to move. This contention has been strengthened recently by neurological evidence that such pathways exist (e.g., Chang, 1955; Li, 1958).

From this basic idea for visual perception, a number of other versions of the idea were created, and the application was made to the perception and production of movement. One major problem with the idea of efference for movement control is that the same term has been used to represent a number of very different ideas. There are at least three ways that the term has been used in the literature.

Efference as a feed-forward process. The most general, and perhaps most widely accepted, version of efference copy is that it consists of information that is fed forward before or during a movement that prepares the system in some way for the receipt of various response-produced feedback signals. The feeding forward of gamma efferent information to the spindles so that the movement is carried out as ordered, and the information fed forward so that accurate visual perception can occur are examples of this kind of idea. Generally speaking, such processes are thought to occur at a number of levels within the central nervous system. There is no necessity that the information fed forward be a literal copy of the motor commands sent to the musculature, as with the following two models.

The Holst idea. In the original statement of this model, a literal copy of the motor commands sent to the eye muscles is fed forward to modify the incoming visual information from the retina (Holst, 1954), enabling the accurate interpretation of the visual signals. The idea has been extended to movement control by assuming that an efferent copy of movement commands is compared against the inflow of proprioceptive feedback, with resulting mismatches representing an error in the movement. Jones (1974) has termed this idea the "inflow model" because it depends upon the inflow of proprioceptive feedback.

One problem with this inflow model is that the proprioceptive feedback and efference copy are in different "languages," with proprioceptive feedback coded in terms of the movements of joints, and efference coded in terms of the commands to the musculature. With the information in different codes, how, strictly speaking, could these two states ever match? A solution often heard is that massive recoding must exist throughout the nervous system, but this begs the question, as it does not provide testable assertions about how such recoding is accomplished.

A second problem, though, concerns the fact that such a mechanism cannot provide information to the subject about the extent to which he has achieved the environmental goal for the movement; it can only signal the extent to which the chosen movement was carried out as planned. As discussed earlier, this type of model cannot account for the evidence dealing with the detection of errors in movement (e.g., Schmidt & White, 1972) or the relearning without KR (Schmidt & McCracken, unpublished study, 1974).

The Jones idea. Largely because the inflow model depends on proprioception, Jones (1974) rejected this notion and argued in favor of what he terms the "outflow model" where a literal copy of the efferent commands is monitored centrally without comparison with proprioceptive feedback. According to the argument, knowing what the limbs were commanded to do (and knowing that the limbs will carry out these commands) is sufficient information to be able to determine where the limbs are after the movement. Hence, this version of efference has been used to explain the perception of limb locations in space. This basic idea, however, came from the eye-movement work where the loads on the eye musculature were nearly constant, permitting one to have information about the eye's location from knowledge of the efferent signals (e.g., Festinger & Canon, 1965). But the loads on the skeletal musculature are not nearly as predictable as they are in the eye, and it is difficult to imagine how limb location could be sensed solely from the record of the efferent commands.

In spite of the argument concerning the unpredictability of limb loading, some recent evidence has been interpreted in terms of an outflow model, because of the apparent difficulty of feedback models to account for the findings. These concern (a) the learning of movements in deafferented animals (e.g., Taub & Berman, 1968), and (b) the correction of movement errors in less than one reaction time (e.g., Angel, Garland, & Fischler, 1971).

Taub and Berman (1968) used monkeys that were deafferented from the head down in a shock-avoidance experiment. They prevented the animals from seeing their limbs by the use of a large collar extending outward from the neck, secured them into a chair-like structure, and taped a pneumatic bulb into the palm of one hand. When a shock was administered to a normally afferented portion of the head, the animals learned to turn off the shock by squeezing the bulb. The fact that the animals could learn a hand movement without any feedback from the periphery was surprising to many theorists, and the leading interpretation has been in terms of the outflow notion. According to the argument, (a) feedback is essential to learning, (b) there was no sensory feedback, (c) outflow or efference copy could provide information about the commands issued, (d) therefore, outflow was the mechanism that mediated learning.

The second line of evidence has used two-choice step-tracking tasks, in which the subject moved in one of two directions to a target as quickly as possible after a stimulus. Occasionally, the subject would make an error, in that he would initially move in the improper direction. When this happened, he was to reverse his direction as quickly as possible, and move back in the correct direction. Angel and his colleagues (Angel et al., 1971; Angel & Higgins, 1969; Higgins & Angel, 1970) and Megaw (1972) found that the latency of these corrections (the time from the first movement in the wrong direction until the subject began to correct his movement) was sometimes very short (from 60 to 90 msec), clearly less than one reaction time. Because feedback from the periphery is too slow to cause these corrections, it was reasoned that subjects detected their own errors before the movement was begun through monitoring of efference copy.

Efference Copy in the Schema Theory

The present theory sees efference copy as necessary to provide two kinds of information. First, the subject must know that he has executed a motor command so that the information he receives from the periphery can be interpreted as resulting from active rather than passive movement. Without being at all specific about the details, we assume the existence of some central mechanism that records that a motor program has been run off; no literal copy of the muscle commands is assumed to be stored. Second, the notion of efference as a feed-forward process is assumed in the present theory. Before the movement, the expected sensory consequences are generated from the recognition schema, and this information is fed forward so that the incoming response-produced exteroceptive feedback and proprioceptive feedback can be evaluated properly, resulting in the detection of error. In addition, the motor program output is thought to contain gamma efferent signals that are fed forward to the muscle spindles, preparing the local musculature for reflex-based corrections that ensure faithful execution of the program. Further involvements of efference copy are not proposed in the present theory. The evidence cited above apparently supporting the outflow model (i.e., learning with deafferentation and rapid error correction) can be handled with the present theoretical structure.

In the deafferentation studies, the monkeys had all that was necessary to learn the avoidance response without efference. When the shock came on, the animals began a series of random movements in an attempt to escape. Eventually, quite by accident, the animal squeezed the bulb and the shock ceased. According to the present theory, at this time the animal had stored both the response specifications (for the random movements ordered) and the actual outcome (the cessation of the shock). Which specification was associated with shock cessation was not clear, however, since many responses were being ordered at nearly the same time, but the schema rule notes the relationship between the various response specifications and the cessation of the shock. On the next shock trial, the many response specifications related to the desired outcome were executed, and eventually the hand squeeze occurred again, strengthening the relationship between the response specifications and the outcome. Hence, the animal could learn without direct feedback from the limb, because he had the essential ingredients on each trial to form the schema rule: the actual outcome and the response specifications. The logic presented here is similar to Guthrie's (1952) notion of stimulus–response contiguity. The notion of efference copy as a central feedback loop indicating the limb movements is not necessary to explain these findings.

The error correction studies can also be explained by the present theory without involving efference. In these studies, the reaction times for correct responses (the interval from stimulus until first movement) was greater than for incorrect responses, suggesting that subjects were anticipating on error trials. Theoretically, on an error trial the subject incorrectly guesses the direction of the upcoming movement and initiates response specifications in advance, with actual movement not beginning until after the stimulus. Before the program is initiated, the subject generates the expected sensory consequences, which include the expected (if the guess is correct) vision from the stimulus array. When the (unexpected) stimulus comes on, the incorrect program is already being run off when the subject receives a mismatch between the expected and actual sensory consequences. When the mismatch occurs, a visually based correction begins and the program for the correct movement is initiated. However, because the first (incorrect) program must run its course for one reaction time or longer, the beginnings of the incorrect movement occur before the correction. This explanation predicts that the time from the stimulus until the first movement in the correct direction should approximate one reaction time. These values were 367 msec (Angel & Higgins, 1969), 292 msec (Megaw, 1972), and 285 msec in a recent study by Gordon (1975), all of which are well within the normal range of reaction time.

Thus, the present theory uses efference copy as a mechanism that informs the subject that a motor program has been initiated, and represents various feed-forward processes. Feeding forward the expected proprioceptive and exteroceptive feedback is essential for the accurate detection of errors, and the generation of gamma efferent signals readies the musculature for subsequent action. There is no place in the theory, as presently stated, for efference copy as a mechanism that can allow the subject to determine errors in terms of reaching the desired goal, because the current evidence can be explained without resorting to such a notion.

POSSIBLE FUTURE DIRECTIONS

While the present theory can solve a number of problems with existing theoretical points of view and has strong empirical support in some areas, the evidence for it is weak or generally lacking in other areas. There are numerous directions in which one could move, including asking about individual differences in schema formation, how developmental influences are manifested, and how large a given schema might be in terms of the range of movements encompassed by it. But the answers to some essential questions should be sought first to determine whether the theoretical ideas presented here are worthy of further work. This section deals with some of these questions.

First, we need stronger evidence for motor recall and motor recognition schemata. We might take comfort that the schema notion seems acceptable enough for the visual pattern-recognition literature, but motor skills researchers have been embarrassed before by taking the work in verbal learning and applying it to motor behavior without a serious research effort to determine whether the application is reasonable. A number of methods of testing the schema notion for motor behavior have been mentioned, including evidence that transfer from a variety of experiences to a new instance of the same class is high, that increased variation in practice should increase transfer, and that responses presumed to be governed by the same motor program share in temporal and spatial organization (e.g., Glencross, 1973). The notion of the schema is clearly essential to the theory, and it seems logical that the credibility of this idea should be strongly tested initially.

It is possible that it will be difficult to demonstrate schema learning in adult subjects, and perhaps a more profitable population would be children. Many researchers adhere to the view that most of motor learning occurs in children and that adult learning is merely a recombination of the old habits; it would therefore make sense to study the acquisition of these new skills at the age when they develop most rapidly. Failing to demonstrate schema learning in adults does not necessarily mean that schemata do not exist, since the schemata for certain classes of highly practical activity (such as throwing) could have been developed years earlier.

Another important prediction made by the theory is the possibility of learning rapid tasks without KR after some initial KR practice. This has not been shown clearly so far, and additional work should be conducted with longer KR practice periods, with tasks in which complexity is higher than in the simple slide-movement tasks, and with more extended no-KR practice periods. In addition, the predictions about tasks in which accuracy is not a goal, as well as the predictions referring to open and closed tasks, need to be tested.

A final word concerns potential applicability. While the theory was certainly not developed for application to the teaching of motor skills, the predictions seem to have a great deal in common with the notion of movement education. While there are many branches of this idea, one of the important thrusts is that children should engage in activities stressing variety in movement patterns (e.g., jump over an object in as many ways as possible). Movement education people do not talk of schemata, of course, but one interpretation of their method is that it develops schemata in children. These schemata will then be useful in an open-skills situation where a jumping response is required. This area has been devoid of theory for a long time, and perhaps the present views can be of assistance.

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