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The Schema as a Solution to Some Persistent Problems in Motor Learning Theory

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I. Introduction

Over the past decades of research in motor behavior, there has been an increasing trend, as described by Pew (1974), away from a "task-oriented approach" toward a "process-oriented approach" to various problems in motor performance and learning. Earlier work focused primarily on the effect of various experimental variables on the performance of rather "global" motor responses (e.g., the effects of massed practice on the learning and performance of the pursuit rotor task), whereas recently there seems to be a shift in emphasis toward understanding the kinds of changes that occur in humans as they perform and learn. This recent concern has led to the creation of various models and theories that attempt to explain performance data through the postulation of various hypothetical mechanisms or processes. The work of Adams (1971), Anokhin (1969), Bernstein (translated in 1967), Konorski (1967), Laszlo and Bairstow (1971), Pew (1974), and Sokolov (1969) are representative of this kind of thinking about motor skills. This trend has been important because it has stimulated a great deal of research and thinking about motor behavior that was not present in earlier traditions, and the area has become very interesting because of the competition among the various explanations of motor performance. This paper is concerned with the various theoretical approaches to the learning of motor skills. Some of the persistent problems for theory are discussed, and the Schmidt (1975a) schema theory is summarized, showing how some of these problems can be handled with this approach. Finally, some pressing concerns for future research and theorizing are presented.

II. Limitations of Existing Theories

A. The Storage Problem

In open-loop theories (or models) of learning and performance, movement control is assumed to be regulated by a central program that determines all of the relevant spatial and temporal details of a motor act such as a baseball swing (e.g., Henry and Rogers, 1960; Lashley, 1917). While open-loop theorists do not explicitly say so, there is the implication that for every response a subject makes, there is a separate motor program that controls it. The number of such programs for motor responding must be very large indeed when we consider the number of speeds that the person can move, the number of starting positions and environmental states that can exist prior to the response, and the number of spatial patterns that the response can take. The number of such programs has been estimated for speech production by MacNeilage and MacNeilage (1973); considering only English and the possible accents and inflections, there are approximately 100,000 different phonemes (sounds), each presumably requiring a separate program for its production. This presents a difficult theoretical problem in explaining how the CNS can store this many programs. While it is true that the neurological networks are extremely complex, and it is also true that there is no good evidence that this many programs cannot be stored, the storage problem has led many motor behaviorists away from the one-to-one motor program idea because it represents a rather unparsimonious approach to understanding human responding.

Postulating closed-loop systems, with the roles of feedback, error detection, and error correction strongly emphasized, does not solve the problem. If it is true (as Adams says in this volume; see Chapter 4) that movements are controlled via feedback and the reduction of error, there must be a reference of correctness against which each of the movements must be compared. Again considering the number of possible movements, this implies that there must be as many references of correctness with which response-produced feedback is compared as there are movements, leading again to the storage problem.

B. The Novelty Problem

This problem is related to the storage problem discussed above, but the concern here is production of novel movements. During a game, the basketball player performs a shot from the floor that has a combination of starting body position, goal distance, and environmental situation (position of other players, etc.) that, strictly speaking, he has never experienced previously, and thus the movement can be considered "novel." Bartlett recognized the novelty problem (although he did not call it that) when he discussed the movements involved in tennis:

> When I make the stroke I do not, as a matter of fact, produce something absolutely new, and I never merely repeat something old [Bartlett, 1932, p. 202].

Thus, although a given tennis stroke might appear to be identical to other strokes made previously, it is always somewhat different because of the particular situation under which it is to be performed. At the same time, it is not totally novel, being strongly related to other, similar movements made previously. There is little evidence concerning such novel movements, and some critics would argue that learning a tennis stroke would involve the learning of a limited number of motor programs (open-loop theory) or a limited number of references of correctness (closed-loop theory) with the player choosing the proper program or reference depending upon the particular circumstances; thus the resulting movement would not be novel at all. However, investigations using cinematography for analysis of movement (e.g., Higgins and Spaeth, 1972) have shown that movements performed under apparently identical environmental conditions result in slightly different movement patterns, and that two apparently identical movements are not exactly alike in the pattern of output.

The theoretical problem that the novelty problem raises is that if performers can produce movements that have never been exactly performed previously, where do the references of correctness or motor programs come from? One cannot argue that they come from previous practice of the movement, because that particular movement has not been practiced before, and neither can one profitably argue that they are genetically determined. This presents a difficult problem that has not been considered in the development of theories of motor control.

C. The Detection of Errors

A third persistent problem that has faced theorists in motor control is how the individual can come to recognize his own errors and to produce corrections in subsequent responses. The most popular approach has been the adoption of closed-loop theory, in which response-produced feedback is compared against a reference of correctness to generate an error, and the error is the stimulus for subsequent corrections, a solution adopted by Adams (1971), Pew (1974), and Sokolov (1969). With the exception of Adams' (1971) position, however, in each of these theories the commands for action are generated first, and only then is the reference against which feedback is to be compared generated. The important point is that the reference of correctness is generated as a result of choosing the movement commands, and represents the expected feedback consequences of producing that movement. Thus, the only error that the performer can detect is that he failed to execute the program effectively, perhaps because there was "noise" in the system or because there were unpredicted variations in the state of the environment (e.g., wind on the tennis racket) that prevented the movement from being carried out as planned. While it is possible to imagine the subject making an error caused by "noise" in the motor system, there are no data that indicate to what extent these errors occur in skills, or even if they occur at all. Even if they do occur, we have no evidence that subjects can learn to recognize these errors.

More important, however, is the fact that these theories cannot explain how the subject detects and corrects a second, and more critical, type of error: an error in which the environmental goal is not met. Even if the movement actually chosen were perfectly executed, the movement could be grossly incorrect because the intended movement did not match the environmental demands. In other words, the subject can choose the wrong movement and execute it correctly (receiving no error information according to the theories mentioned above), and can still produce an error because the movement did not meet the environmental demands. The detection of the extent to which the environmental goal of the movement is met, in contrast to the detection of error in execution, is well supported by the evidence, as Schmidt and White (1972) and Schmidt and Wrisberg (1973) have shown that subjects are able to accurately estimate their performance scores after a movement has been completed.

Adams (1971) recognized this difficulty with the earlier positions, and his theory has the reference of correctness separate from the generation of the movement, so that the feedback from the movement can be compared against the feedback that "should" arise if the movement is, in fact, achieving the environmental goal. Since Adams has the reference of correctness tied to the environmental goal of the movement (e.g., the criterion location of the lever in positioning) rather than to the choice of the commands to produce the movement, the theory provides a means whereby the subject can detect the extent to which the environmental goal was achieved. The resulting error information can be used during a positioning movement to produce subsequent corrections so that the limb is guided to the correct location via the reduction or error. This feature of the Adams theory enables it to account for a great deal of learning data that could not be handled by the earlier theories, and is therefore a very strong aspect of its theoretical position.

III. A Possible Solution: The Schema Theory

The Schmidt (1974, 1975a) schema theory evolved from an attempt to take the strong parts of various theoretical positions, adding modifications and extensions so that the new theory would be able to deal with some of the problems raised in the previous sections, particularly the storage and novelty problems. A strong lead was provided by Adams' (1971) theory which has had a large influence on motor behavior because (1) the theory deals with the learning of motor skills, while most other theories deal with performance, (2) the theory is tied strongly to empirical data, and (3) Adams suggests experimental paradigms that enable the theory to be tested in the laboratory. The result of these features has been a great deal of research activity testing Adams' theory in the short time since its publication. But a number of problems appeared for the theory as a result of the research and thinking that it generated. These difficulties are discussed in detail in Schmidt (1975a) and are only summarized briefly here.

First, Adams' theory cannot deal with either the novelty problem or the storage problem because it assumes that for every movement there is a reference of correctness against which response-produced feedback is compared during the response. Second, there are logical difficulties associated with the prediction that, in slow positioning tasks, the subject should acquire a strong capacity to recognize his errors after the movement, and should be able to substitute this subjective information for knowledge of results (KR); this does not logically follow from the theory, nor are there data that support this contention. And third, Williams and Rodney (1975, unpublished) have presented evidence contrary to the prediction that in order to develop the reference of correctness (Adams' perceptual trace) the subject must have moved to the goal position previously (see Section IV,A,2 for a discussion of this study).

The schema theory postulates two separate states of memory, one for recall and one for recognition, as Adams' theory had done. The specific roles of recall and recognition memory depend slightly upon the type of task, but basically recall memory is the state responsible for the generation of impulses to the musculature that carry out movement (or movement corrections), while recognition memory is the state responsible for evaluation of response-produced feedback that makes possible the generation of error information about the movement.

It is also assumed that there are "generalized" motor programs formed in the central nervous system that contain stored muscle commands with all of the details necessary to carry out a movement. The program requires response specifications that determine how the program is to be carried out (e.g., rapidly, slowly, etc.). Given the response specifications, the program can be run off, with all of the details of the movement determined in advance.

The role of the program varies depending upon the duration of the movement. If the movement is rapid (i.e., with a movement time of less than 200 msec), the movement is carried out under the complete control of recall memory, in that the program determines all of the details of the movement in advance, and any event in the environment that signals that the present movement should be changed must await one reaction time before a new program can begin to become effective. Thus, in rapid movements, where the movement time is frequently less than one reaction time, the subject carries out the already programmed movement even though the environment might later indicate that this movement will be incorrect. Recognition memory operates after the movement is completed, providing expected sensory consequences against which the response-produced feedback stimuli are compared, with any resulting discrepancies indicating that an error has occurred.

With slower movements, such as linear positioning tasks, the movement is carried out using both recall and recognition. Here, the subject makes short programmed moves along the track, and after each one he compares the response-produced feedback against the expected sensory consequences. If the two do not match, a corrective movement is provided, the comparison is again made, and so on until the difference between the expected sensory consequences and the response-produced feedback is zero. Thus, the role of recall memory is to produce small, adjustive movement only, and the primary determinant of accuracy in the task is the comparison of expected and actual feedback. Hence, slow movements are dependent on recognition memory, even though the subject might be making adjustive responses with recall memory.

The theory also indicates how the response specifications and expected sensory consequences are generated. When the subject makes a movement, he stores a number of separate pieces of information. First, he stores the response specifications used for that movement. Second, he stores the initial conditions that existed when the movement was begun, including the individual's location in space, the relative positions of his limbs, and the state of the environment. Third, the subject stores the actual outcome of the movement, usually determined by the information presented by the experimenter in the form of KR, but sometimes resulting from the subject's own evaluation of the outcome of his movements (e.g., he saw the ball hit the target). And finally, he stores the sensory consequences of the movement, that is, the exteroceptive and proprioceptive consequences of making the response. Given these four sources of information, the theory assumes the development of a recall schema and a recognition schema that form the basis of the two states of memory.

A. The Schema Defined

The recall schema is the relationship, built up over past experience, between the actual outcome and the response specifications. When the subject makes a movement, he pairs the response specifications and the actual outcome on that particular trial. After a number of such attempts, there begins to form a relationship between two variables, and this relationship (the recall schema) is updated on each successive trial. After a great deal of experience the schema becomes well established. When the subject attempts to produce a novel movement he enters the schema with the desired outcome and the initial conditions, and the schema rule produces the response specifications for that movement. When the response specifications have been determined, the movement can be carried out by running the motor program.

The recognition schema operates in an analogous way, but the variables of concern are initial conditions, sensory consequences, and actual outcomes (KR). On each trial, the sensory consequences and actual outcome are paired, and are used to develop the relationship between sensory consequences and actual outcome (which is the recognition schema).[1] During an actual movement, the subject can specify the desired outcome and, through the recognition schema, can predict the expected sensory consequences of the movement. Then, after a rapid movement, the actual sensory consequences are compared with the expected sensory consequences, with any discrepancy indicating that an error has occurred in the movement. In this way the subject can have information about the correctness of his movements without having to be given KR. In the absence of KR, the error signaled by the recognition schema can be substituted for actual outcome information, and can allow the further updating of the recall schema; thus, the subject can learn without KR if the recognition schema is sufficiently well developed. Also, it should be noted that after a slow movement, where accuracy is controlled by recognition memory, the subject cannot generate error information about the success of his movement since he has stopped at that position for which his error signal was equal to zero; hence, there can be no

[1] In both the recognition and recall schemas, initial conditions are a third variable in the schema rule. Thus, it would be better to say that the recall schema is the relationship among responses specifications, actual outcomes, and initial conditions, and that the recognition schema is the relationship among sensory consequences, actual outcomes, and initial conditions.

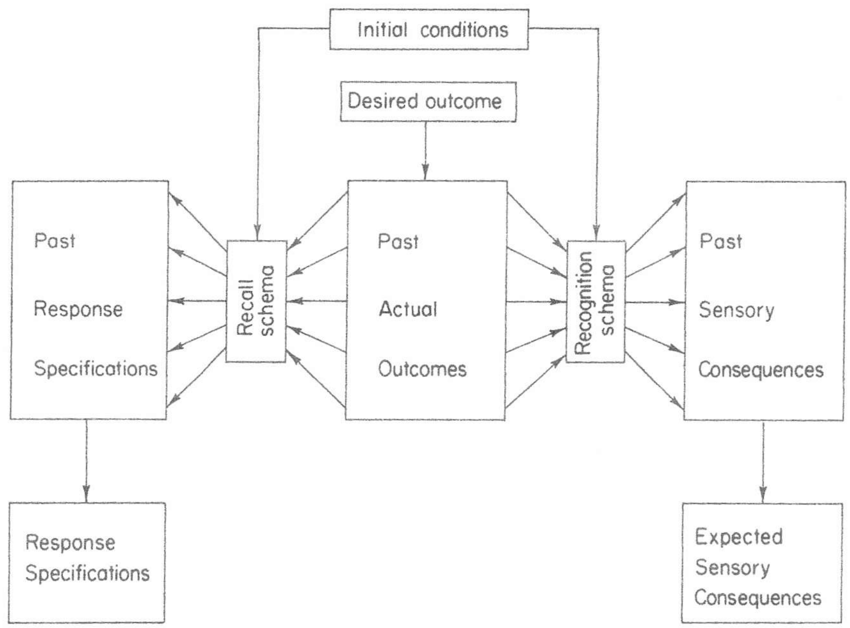

Figure 1 The recall and recognition schema in relation to various sources of information. (From Schmidt, 1975a.)

subjective reinforcement, and no learning without KR, in slow responses. The recall and recognition schemas are depicted in Figure 1; Figure 2 shows how the two schemas are thought to fit into the overall motor system, their interaction with feedback of various types, and the flow of information within a trial.

B. The Schema and Learning

It is important to define how the schemas are developed with practice. Since, for example, the recall schema is the relationship built up over trials between response specifications and actual outcomes (as modified by initial conditions), the strength of the schema is assumed to be a positive function of (a) the number of such pairs experienced (i.e., the number of prior trials) and (b) the variability of such prior experiences. Increased amount and variability in such experiences will lead to the development of an increasingly strong recall schema, so that when the subject is transferred to a novel situation governed by the schema, he will be able to determine more effectively the appropriate response specifications given the desired outcome and the initial conditions. In addition to improved performance on the first trials of the novel movement, the theory

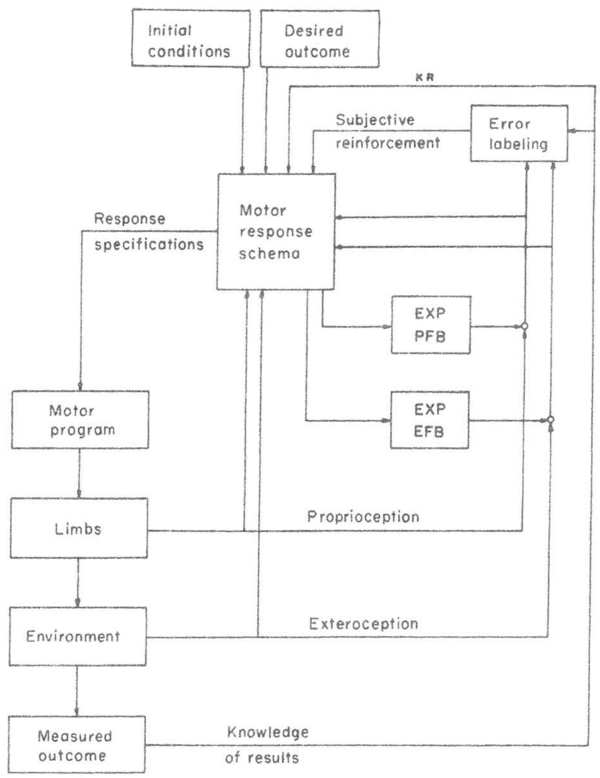

Figure 2 The motor response schema in relation to the events occurring within a trial; recall and recognition schemas are combined for clarity. (From Schmidt, 1975a.)

predicts increased rate of learning for the new task as a function of increased variability in previous movement experiences.

A similar argument holds for the recognition schema. Increased variability in practice leads to a stronger relationship between the actual outcome and the sensory consequences (as modified by the initial conditions). Then, when the recognition schema has been developed over practice, on a novel rapid movement the subject can generate the expected sensory consequences of that movement (even though he may never have performed it previously), and can compare the actual and expected sensory consequences to determine the extent of error on that trial; on a novel slow movement, the subject can move to the correct position through the comparison of response-produced feedback and the expected sensory consequences as generated by the recognition schema. Thus, increased variability in practice leads to increased sensitivity for estimating the outcome of the movement just made; if KR is not present in a fast movement, then the subject can inform himself about his errors via the recognition schema, and can make adjustments even without external error information.

C. The Schema and the Storage-Novelty Problems

The schema theory provides a solution to the storage problem for motor skills by postulating that the subject stores the relationship between actual outcomes, sensory consequences, and initial conditions for the recognition schema, and the relationship between actual outcomes, response specifications and initial conditions for the recall schema. These values that form the relationship are only stored briefly, however, and do not remain in memory except as they are needed to update the schema rules after the movement is completed. There is evidence from the pattern-recognition literature (e.g., Posner and Keele, 1970) that subjects store an abstraction of the set of patterns observed (the schema) as well as the individual patterns themselves, but the abstraction is retained more effectively over time than are the individual patterns, avoiding the theoretical problem of having all of the individual patterns being stored in permanent memory.

To produce a novel movement, the subject begins with the initial conditions and the desired outcome. Given these two sources of information, he "interpolates" between past outcomes (as modified by the initial conditions) to determine the response specifications that should be produced if the desired outcome is to be met. Thus, the subject can choose a completely novel set of response specifications that will result in a novel movement. Notice that there is no necessity for a specific motor program to be stored for each movement that the subject makes, and that the schema in conjunction with the generalized motor program can specify the response specifications for a large number of movements of this type.

A similar argument holds for recognition memory, but in this case the schema is the relationship between sensory consequences and actual outcomes, as modified by the initial conditions. When the subject makes a novel movement, having the desired outcome and initial conditions specified allows the schema to generate the expected sensory consequences of that movement, even though that movement may never have been made before. Then, if the movement is rapid (e.g., movement time less than 200 msec), the expected sensory consequences are compared with the actual sensory consequences to define an error, which can be substituted for KR to guide changes in the response on the next trial. If the movement is slow (e.g., a positioning response), then the difference between the actual and expected sensory consequences defines an error that can be responded to within the same movement, and the subject moves to that position he recognizes as correct (i.e., as having zero error). In either case, the recognition schema can satisfy the novelty and storage problems because (a) there is no necessity of storing the sensory consequences for every past movement, and (b) the subject can produce a novel slow movement by matching the actual sensory consequences with the expected consequences, or he can recognize the correctness of the novel fast movement through the difference between expected and actual sensory consequences after the movement.

D. The Schema and Error Detection

Error information in the schema theory is generated by a comparison between the expected sensory consequences (generated from the recognition schema) and the response-produced sensory information. Earlier theories use this type of comparison to generate an error, but the main distinction between these and the schema theory concerns how the expected sensory consequences are chosen. In the schema theory, the subject begins with the desired outcome (the environmental goal) for the movement. Then the response specifications and the expected sensory consequences are generated from separate schemas: recall and recognition, respectively. These states are separate because they are developed using different sources of information. Both the recall and recognition schemas use actual outcomes and initial conditions, but the recall schema is the relationship between these two variables and the response specifications, whereas the recognition schema is the relationship between these two variables and sensory consequences. Thus, specifying a desired outcome enables the generation of response specifications and expected sensory consequences semi-independently. The expected sensory consequences represent the best estimate of the nature of the response-produced feedback that would be produced if the goal is achieved, while the response specifications represent the best estimate of the response specifications that will have to be used in order that the goal be achieved.

IV. Some Key Concerns Facing the Schema Theory

While the schema theory can provide solutions to a number of the common problems facing earlier motor-learning theories, the notion has a few difficulties of its own. This section discusses some of the most important problems facing the schema theory, and presents some possible means whereby the problems can be solved. The most serious question surrounding the schema theory is the apparent lack of evidence supporting the existence of motor schemas, and it is to this issue that we turn next.

A. Evidence for the Motor Schema

The strength of the evidence for the schema notion is quite different for the two types of schemas (recognition and recall) presented in the theory. The evidence for the recognition schema is quite strong indeed, but the support for the recall schema is somewhat lacking.

1. Recall Schema Evidence

Speaking subjectively, it makes a great deal of sense to infer that something like a recall schema must exist if we are able to produce a movement of a given class that we have never produced before. This argument, together with the unattractiveness of the theories that imply the storage of one motor program or reference of correctness for each movement that the subject will ever produce, makes attracitve the argument for a system that conserves storage space and enables flexibility. Of course, this kind of reasoning does not provide sufficient justification or evidence for the schema notion, but there are a few experiments that suggest the existance of a recall schema.

One of the major predicitions of the recall schema ideas is that increased variability in practicing a number of variations of a movement class should result in increased transfer to a new, and as yet unpracticed, member of that same class. This idea has been tested several times (e.g., Crafts, 1927; Duncan, 1958), and the evidence is reasonably clear that this prediction from the schema theory has held in earlier work. For example, Duncan (1958) used a task in which there were 13 slots into which a lever could be positioned, and the subject's task was to move the lever to the appropriate slot when one of the 13 light stimuli came on. Duncan constructed the task so that 12 variations of it could be produced, and he varied the number of different tasks (either 1, 2, 5, or 10) that were presented in training trials, holding the absolute number of trials constant. The amount of transfer to two novel variations of the same task (not used in the training trials) was a positive function of both the amount and variability in training, providing evidence for the schema theory predictions.

While it might seem that this evidence could be interpreted as showing the development of a recall schema for the class of tasks in question, the task had substantial cognitive components, with the primary task for the subject being to learn which of the 13 responses went with the various stimuli; the actual movements of the lever seem quite trivial in contrast to these cognitive processes. The Duncan paper appears to show the existence of schemas for making decisions about light-slot pairings, which can be considered as a type of concept formation, but the important question here concerns the development of schemas that can provide the details necessary for the motor program to produce a novel set of motor commands, and the Duncan findings really do not provide such evidence. What was needed was an experiment using Duncan's basic design, but using a task in which it could not be argued that a cognitive concept only was being transferred, leaving the way clear for an interpretation in terms of a motor recall schema.

R.A. Schmidt and D. Shapiro (unpublished data, University of Southern California, 1974) conducted an experiment that used Duncan's (1958) method, but with a more "motor" task. The subject had to knock over four small barriers with the right hand in a predefined order, and the goal was to perform the task as rapidly as possible. The task could be varied by changing the locations of the barriers (but not their orders) to produce four different tasks, varying slightly in terms of the lengths of the movement segments and the angles between them. One group of subjects performed three of the tasks, 40 trials of each with KR after each trial, while a second group performed a single, randomly assigned task for 120 trials with KR. Thus the amount of practice on the task was constant, and variability in practice was the experimental variable. When subjects were transferred to the fourth task, the subjects with high variability in practice tended to perform the fourth task more rapidly, with differences increasing slightly as practice continued over the 40 task 4 trials; but these differences were quite small, and were not statistically reliable.

Data such as these do not, of course, disprove the existence of the schema, as the lack of significant advantage for the high-variability group might be explained by the fact that the task involved the dominant hand in ways that have been used in previous tasks throughout the subject's lifetime. Thus, the schemas for arm movements might have been well developed by the time the subjects entered the laboratory, rendering the added variability in laboratory activity relatively ineffective in generating further increases in schema strength. Also, it could be that the four variations were not sufficiently different, or were different in the "wrong" ways, for the development of added schema strength. These experiments should be attempted using more novel tasks, perhaps with younger children in whom such schemas would have more opportunity to be strengthened by laboratory activities.

Thus, while it is true that there is no strong experimental evidence that supports the existence of the recall schema notion, neither is there evidence against it. However, subjectively, we appear to be able to produce responses that we have not made before. If it is true that we can, then we need a notion like the schema to explain how these can be performed. The most important line of research that can be done in relation to the schema will therefore concern the verification of the existence of the recall schema.

2. Recognition Schema Evidence

In sharp contrast to the scanty evidence for the existence of the recall schema, there is considerable support for recognition schemas, although most of the evidence does not involve strictly motor tasks. The main point to be demonstrated in such experiments is that a subject can learn to recognize a stimulus that he has never experienced previously, and a number of experiments have shown that this can be done.

A good example of this type of demonstration is provided by Posner and Keele (1968, experiment III). They presented subjects a series of 9-dot patterns on a screen. There were three basic patterns termed "prototypes," and variations of the prototypes termed "distortions" were formed by randomly moving each of the 9 dots slightly. The experimenters presented 12 distortions (4 from each prototype) to subjects in a training session, and subjects learned with KR to classify the distortions into the correct category; the original prototypes were never presented in this session. In a transfer session, subjects received the 3 prototypes, 6 "old" distortions (2 from each prototype) from the training session, 12 "new" distortions (not previously shown), and 3 unrelated random patterns. Subjects were able to classify the prototypes (which they had not seen previously) nearly as accurately (14.9% errors) as the distortions that thay had seen previously (13.0% errors). The interpretation was that the presentation of the distortions in the training session enabled the subjects to develop a "concept" (or schema) concerning the 3 prototype dot patterns. Then, when the prototypes were presented, the subjects could recognize them even though they had not seen them previously. Similar findings have been shown by a number of other researchers as well (e.g., Attneave, 1957; Edmonds *et al.*, 1966; Posner and Keele, 1968, 1970).

The important point for the present purposes is that these experiments have provided evidence, with visually presented materials, for a recognition schema that enables the subject to recognize and classify stimuli that he has not experienced previously. One way of thinking about the mechanisms behind the Posner-Keele (1968, 1970) findings is that the subject developed the schemas for the various prototypes during practice with the distortions. When a "new" stimulus is presented, the subject compares the stimuli against the schema for the prototype; if a match is received, the subject indicates that the stimuli are a member of the category. In the Schmidt (1975a) schema theory, a similar sort of process is thought to occur, and the Posner-Keele studies provide evidence for it. When the subject determines the desired outcome, the recognition schema generates the expected sensory consequences. When the movement is fired off, the response-produced sensory consequences are compared with the expected sensory consequences, and any mismatch signals that an error has occurred.

A study by Williams and Rodney (1975) provides additional evidence for the recognition schema. Subjects attempted to learn the criterion position for a linear-positioning task in two ways. One group moved 16 times to a stop that defined the position. A second group moved to stops at each of 16 randomly ordered positions to either side of the criterion, with subjects being told that the correct location lies in the center of this range. Then on transfer trials, all subjects attempted to move to the criterion position on 20 trials without the aid of either the stop or KR. Performances of the two groups (absolute errors) were nearly identical on the first transfer trial, but with additional trials the group with variability in practice maintained performance, while the group that moved to the stop regressed significantly. The interpretation in terms of the schema theory is that subjects could generate the expected sensory consequences of being in the correct location without ever having been at that position, and they could then match the actual and expected sensory feedback to position the lever at the correct location. While the Williams-Rodney data provide support for the recognition-schema notion, they also provide strong contradictory evidence for the Adams (1971) position. Adams' theory clearly predicts that the perceptual trace (the reference of correctness) develops as a function of having experienced the feedback stimuli resulting from being at the correct location, and that without having been at the correct location, the perceptual trace could not develop.

In contrast to the situation with the recall schema, there is rather strong evidence for the recognition schema idea. The evidence with visually presented stimuli provides encouragement that similar findings can be produced with stimuli presented in other modalities—such as proprioceptive or auditory—as well as for stimuli that represent errors in responding. In addition, the Williams-Rodney (1975) experiment provides evidence for the recognition schema for slow movements. Additional work needs to be done with other stimuli, and with more rapid motor tasks.

B. Some Problems with the Motor Program Concept

The evidence that Lashley's (1917) patient, who was accidentally deprived of sensation from his lower limbs by a gunshot wound, could position his limb rather "normally" stimulated the first suggestion that movement could be controlled centrally, without the need for peripheral feedback. Later various workers found that the time to process peripheral information was on the order of 150 msec (e.g., Posner and Keele, 1968; Slater-Hammel, 1960), raising questions about how the subject could possibly use peripheral feedback for the control of limb movements when the loop times were so long. A particular problem for closed-loop theorists was the fact that a subject can begin with the hand at rest, initiate a movement via an abrupt acceleration, and then decelerate the hand so that it comes to rest on a target 10 cm away, all with a movement time of 100 msec or less. The problem is where the "decelerate" instructions come from. If we wish to argue that the subject uses feedback to inform himself of his progress in the movement, such that when the movement reaches, for example, the halfway point the "decelerate" instructions are issued, we are faced with the problem that the movement is completed 50 msec or so before the "decelerate" instructions can even begin to become effective. Clearly, the instructions to stop the movement have to be planned prior to the beginning of the movement.

One solution to this problem was the postulation of the notion of the motor program, usually expressed as a set of prestructured movement commands that contain all of the details of the movement, including which muscles are to contract, for how long, and with what force. Keele's (1968) definition of the motor program as a set of prestructured muscle commands that allows movement to be carried out "uninfluenced by peripheral feedback [p. 387]" is the best accepted statement of the idea today. Various theorists have used the motor program as a largely "default" argument to provide a solution to the apparent fact that feedback loops are too slow to provide control in rapid movements (see, e.g., Pew, 1974), without insisting on direct evidence of the existence of the motor program.

There is evidence for a kind of motor programming with subhuman species. For example, Wilson (1961) has shown that locusts with deafferented wing systems can provide wing movements closely resembling the movements during flight in the intact insect, suggesting the existence of a motor program for wing movements. However, these programs are probably innate, and they might not indicate a great deal about the existence of learned motor programs such as would be necessary for a human to throw a ball. Because of the scant evidence for the program notion, there has been renewed controversy lately about its viability (e.g., Adams, this volume, Chapter 4), with other possibilities being proposed (Jones, 1971, 1974).

One major objection to the program notion as stated earlier is that evidence is accumulating that feedback is present in almost all movements, and that the loop time for the feedback to become effective may be far shorter then the 150–200 msec that is traditionally used. Consider, for example, the experiment by Dewhurst (1967), who had subjects hold a small weight in the hand, with the elbow flexed at 90°, and monitored the EMG activity from the biceps. At a time unknown to the subject, the weight was suddenly either increased or decreased, resulting in a sudden displacement of the limb either downward or upward, respectively. Dewhurst showed that there was a change in the EMG pattern in approximately 30–50 msec, and that the limb began to reacquire its 90° position a short time thereafter. Similar findings have been produced with the chest musculature associated with breathing; when the resistance to the flow of air through a mouthpiece is suddenly increased, there is an increased EMG from the intercostal muscles within 30–80 msec (Sears and Newsom Davis, 1968). Findings such as these, not to mention the suggestion that loop times may be as rapid as 4–5 msec (Sussman, 1972) in the tongue, have been taken as evidence against the motor program notion that peripheral feedback is unnecessary in the control of movement.

The explanation for the corrections in the Dewhurst (1967) and Sears and Newsom Davis (1968) studies concerns the functioning of the muscle spindle system. There is good evidence (Granit, 1970) that the alpha efferent system (to the main body of the musculature) and the gamma efferent system (to the intrafusal muscle fibers of the muscle spindle) work in cooperation, and this concept is termed alpha-gamma coactivation. In the Dewhurst example, the argument is that the alpha and gamma systems are coactivated so they maintain the 90° position. The intrafusal fibers are "biased" so that if the position is altered by an external means, the spindles are changed in length, setting up a reflex change in the alpha activity (seen in the EMG patterns) for the biceps. These changes are quite rapid, and are known to have a loop time of approximately 30–50 msec, consistent with the findings in Dewhurst's (1967) experiment. In addition to such monosynaptic reflexes, there are higher-order reflexes as well (e.g., the "long-loop reflex") with somewhat longer times; these more "complex" reflexes, while being slower than the simple stretch reflex, are far faster than the usual 150-msec estimates of reaction time.

If alpha-gamma coactivation is used in the maintainance of posture, there is reason to believe that it is involved in the control of limb motion as well. For example, Smith (1969) showed that blockage of the gamma system with anesthetics impaired fine control in arm movements, and Frank (1975) has shown that the blockage of the stretch reflex via the cuff technique reduces fine control in finger movements even with vision presented.[2] In addition, Hubbard (1960) had subjects make oscillating elbow flexion movements at various speeds, and EMG records indicated that there were many alternating biceps and triceps contractions during a single movement (especially if the movements were very slow), with the time pattern of these contractions being consistent with the loop times for the spindle system. Evidence such as this suggests that the spindle, with alpha-gamma coactivation, may be strongly involved in the fine aspects of movement control.

The relevance of this evidence for the present argument about motor programs is that if central motor programs exist at all, it is clear that they must contain information not only to the main body of the musculature (i.e., the alpha efferent activity) but also the information to the intrafusal fibers of the muscle spindle (i.e., gamma efferent activity). In addition, reflex activity of the spindles appears to be present and active in most movements, and it therefore makes little sense to speak of the motor program as producing movements without involvement from peripheral feedback as Keele (1968) and others, including the writer (Schmidt, 1972; Schmidt and Russell, 1972), have done.

The problem for the motor program notion is not, therefore, whether or not feedback is active (because there is strong evidence that feedback is active), but rather it concerns what this feedback does in movement control. It is useful in this regard to define two kinds of errors whose corrections are based upon feedback. The first type of correction arises when something in the environment signals to the subject that the movement he has planned is not going to be

[2] These conclusions should be taken cautiously, however, because there was probably some decrement in alpha activity which could have reduced performance of the main musculature. However, since these tasks did not involve very much strength, an interpretation in terms of decrements in the gamma system seems reasonable.

correct. There are countless examples of this type of error, such as the ball changing course as the batter is swinging, seeing or feeling that one's limb is moving in the incorrect direction, and so on. There is very clear evidence that such stimuli, whether they result from the environment (ball-flight information) or whether they result from response-produced sources (seeing one's limb moving incorrectly), require one reaction time (about 150 msec at the least) for the subject to initiate a correction (e.g., Henry and Harrison, 1961; Keele and Posner, 1968; Slater-Hammel, 1960; see Schmidt, 1975b, for a discussion of this evidence). Thus, the movement that was planned carries itself out as if nothing had happened, and the movement is said to be programmed because the "originally intended" movement is carried out even though feedback might indicate that it is going to be incorrect. The generalization is that this type of error requires the subject to change the goal of the movement, such as swinging the bat in a different place, or moving the limb in a different direction.

The second type of error concerns situations in which sudden unexpected changed in the environment exert changes in the dynamics of the limb which, if uncorrected, will make the movement incorrect. For example, if in a tennis stroke an unexpected puff of wind slows the racket somewhat, the muscle-spindle system can exert a small correction to increase the output of the relevant musculature so that the "intended" swing is actually produced. Note that in this case the goal of the movement does not need to be changed (i.e., to swing at a given place and speed), but rather the spindle system needs to provide minor adjustments in the pattern of motor output for the given goal. These changes can be initiated very rapidly in sharp constrast to the 150-msec lags necessary to change the goal. Thus, this second type of error is in the execution of a movement, with the spindle system acting to ensure that the movement is carried out as "intended."

Those who argue, as Adams (Chapter 4 of this volume) has done, that feedback loop times can sometimes be very rapid—far more rapid than the 150-msec loop times usually accepted—are correct, but they fail to consider what kinds of corrections these sources of feedback are able to effect. If the implication is that the reflex activities of the spindle can effect a change in the goal of the movement within 30 msec or so, then there is surely no evidence that supports this point of view. Changes in the goal of the movement via peripheral feedback require far more time than can be explained by such reflex mechanisms.

It seems clear from the evidence presented in the previous paragraphs that a motor program that produces movement without the involvement of peripheral feedback probably does not exist in human behavior. The problem is not concerned so much with the idea of a program as centrally controlled movement as it is with the stated definition of it, and a change in the definition in order to retain the usefulness of the concept seems necessary. Neurological evidence indicates that both alpha and gamma efferent activity are sent to the musculature, and that they both "cooperate" so that fine reflex adjustments can occur to insure that the movement is carried out as planned. Thus the motor program provides all of the alpha and gamma details necessary for the limbs to reach a certain goal, and feedback is intimately involved in attaining that goal. If the goal needs to be changed because the environment has changed, then the program must run its course for one reaction time (150 msec or so) before a new goal can begin to be achieved. In this case, the reflex mechanisms are active in seeing to it that the old goal—the now "incorrect" goal—is faithfully achieved. This concept can be summarized by defining the motor program *as a set of prestructured alpha and gamma motor commands that, when activated, result in movement oriented toward a given goal, with these movements being unaffected by peripheral feedback indicating that the goal should be changed.*

Notice that there is nothing in this definition that deviates from the original analogy to the computer program. We can imagine that a computer program could have a feedback loop in it that prevents it from attempting to divide by zero, and if the feedback indicated that such a division was going to be attempted, the program could have an instruction that would print out an error message. But all of the instructions to the computer are still prepared in advance, and if the program is consistently reaching a wrong answer (an improper goal), the program cannot be rewritten until it has run its course and the wrong answers are seen.

In summary, the motor program notion, as redefined above, seems essential to account for the evidence indicating that when a movement toward a given goal has been initiated, the movement cannot be changed by feedback information indicating that the goal was inappropriate. Evidence that feedback loop times are far faster than one reaction time do not damage this position at all, as these feedback loops simply ensure that the limbs reach the original, predefined goal, even if that goal is inappropriate. The lack of direct support for the program notion is somewhat disturbing, but abandoning the notion would seem to leave us without an adequate explanation for the control of movements with movement times of less than 150 msec.

C. The Role of Efference Copy

The notion of an "efference copy" has created a great deal of interest recently, but considerable confusion surrounds the idea in part because the term has been used in a variety of ways. From the literature, there are at least three distinct meanings of the concept, and in this section these meanings will be presented so that the position of the schema theory in regard to efference copy will be more clear.

1. The von Holst Position

Von Helmholst (1925) reasoned that in order for accurate visual perception to occur it is essential that the visual system have information about the motor commands sent to the eye musculature. If this information were not present, the organism could not know whether the images that changed on the retina were the result of a moving eye in a stable environment or a stable eye in a moving environment. Later, von Holst (1954) proposed the idea that an efference copy of the instructions sent to the eye muscles was used as a "template" against which to compare and modify the incoming visual signals. If the efference copy indicated whether, or by how much and in what direction, the eye had been moved, the visual information from the retina could be interpreted unambiguously.

Workers in the area of motor control quickly adopted this idea as a potential rival for the motor program notion for movement control, and also to the more traditional feedback control models. The extension to motor control proposed that as the individual initiates the motor commands to the limbs, a copy of the command (the efference copy) is sent to a central storage location. Then, as the movement is being carried out, the incoming proprioceptive signals are compared against the commands that were issued, with any mismatch indicating that an error in responding had occurred. Jones (1971) has referred to this position as the "inflow model" because it depends upon the inflow of proprioceptive feedback to be compared against the efference-copy-based reference of correctness.

There are a number of problems with this formulation, although space limitations do not permit more than a brief mention of them here; see Schmidt (1975a) for a more thorough discussion of these issues. One problem is that the codes for the efference copy and the incoming proprioceptive feedback are in different "languages"; the efference copy is in the "language" of muscle commands, while the proprioceptive feedback is in the "language" of joint motion, skin pressure, and the like. Strictly, how could the two sources of information ever match, just as how could the same idea expressed in French and German ever literally match? It is far too simple to postulate that there is massive recoding throughout the CNS, and that the two sources of information become comparable after they have become recoded. This begs the issue, because now one must specify the theoretical operations underlying this recoding, indicating the hypothetical constructs, postulates, etc., that are required of any theory. Von Holst (1954) must have had something like recoding in mind when he postulated the idea, but not having the operations specified makes the idea untestable.

A second problem with the notion is that it can only indicate to the subject that the movement selected was (or was not) carried out correctly, and it cannot indicate to what extent the goal chosen for the movement was appropriate in meeting the environmental demands. The reason is that the reference of correctness is based upon the commands actually sent, and if the wrong program is chosen, the feedback might match the efference copy (after recoding, of course), and the subject would receive no error information. Thus, this problem concerns the fact that the reference of correctness is tied to the movement actually chosen, and is not related to the achievement of the environmental goal.

2. The Jones Position

Under this view, a copy of the information sent to the musculature is also sent to a storage location in the CNS where the efferent copy is "monitored" centrally, eliminating the delays inherent in the delivery of proprioception. The rationale for this "outflow model" (Jones, 1971) is that if I know where I have told my limbs to go, and I know that my limbs will carry out these orders faithfully, then I know where my limbs are at some time afterward. Thus, the subject is presumed to monitor the motor outflow (the efference copy) to the musculature, and knowing that the efference had reached a certain state provides information about where the limbs are at that point. Also, some writers use this notion (e.g., Angel *et al.*, 1971) to suggest that the subject, via monitoring his own motor outflow, can detect a movement error even before he makes the movement since there is no necessity of waiting until the movement has begun in order to generate feedback as with the previous model.

However, there are a number of problems with the "outflow" model of efference. First, the idea appeared to make a great deal of sense for the perception of the position of the eye (Festinger and Canon, 1965) because of the peculiar properties of the eye-movement system. For example, the eye operates under a nearly constant load, and being able to specify the final location of the eye given the commands provided to the extraocular muscles seemed possible because the loads on the eye are so predictable. However, with the limbs the problem is not so simple because we frequently cannot predict the loads that will be experienced; in such cases, a certain motor outflow may produce any number of final limb positions depending upon the particular loads on the limb. Thus, for perception, there seems to be more necessary (i.e., proprioception) in order that the individual know where his limbs are.

A second problem concerns how the efferent commands are monitored. Although Jones (1971) does not state this in so many words, there is the implication that the efference is monitored against some reference that defines the correct movement. For example, if I wish to move to a particular position, I arouse the reference of correctness (i.e., the reference involved in moving to that position), and then begin to move until the actual efference matches in some way the reference of correctness. When the subject receives the match, he "knows" that he has arrived and he stops moving. One difficulty is in defining how the reference of correctness is learned, and what the variables are that determine its strength; without such statements about the development of this part of the model, the idea remains largely untestable.

3. Efference as a Feedforward Process

A third notion about efference copy is related to the previous two, but is far more general in its statement. Basically, the idea is that when movement commands are sent out to the muscles, the commands are accompanied by other kinds of information that "prepares" the system for the upcoming motor act or for the receipt of sensory information (Teuber, 1964). One example has been mentioned earlier, that dealing with alpha-gamma coactivation. Here, the gamma efferent activity can be thought of a feedforward information that "biases" the muscle spindles in such a way that they can exert fine control over the path of the movement. Such feedforward processes occur throughout the motor system, and these are frequently referred to as efference copy or corollary discharge (Teuber, 1964). Of course, there is no necessity that the efference be a literal copy of the motor commands as with the two previous models, as the gamma efferent activity could take on a form quite different from the alpha activity.

One instance in the schema theory where this version of efference copy is used concerns the generation of the expected sensory consequences. Before the movement begins, the expected proprioception, audition, and vision are aroused and "fed forward" to be later compared with the incoming actual proprioception, audition, and vision in order to detect a movement error. Without this expected feedback state, the resulting feedback could not be interpreted. More basically, the feedforward information seems necessary in order to inform the subject that a program has been executed so that the subject can have information that the feedback that is produced resulted from the carrying out of a program (active movement) versus the movement of the limbs from the environment (passive movement).

There can be little argument with this version of efference because it is so general in its statement. There is strong evidence that such feedforward processes exist, and logical arguments such as are presented in earlier paragraphs indicate that this information is necessary in order that the subject perceive his environment correctly and in order that he detect his own errors in responding. The more precise specification of the generation of the expected sensory consequences in the Schmidt (1975a) schema theory, however, are still open to question, and there are methods available for testing these predictions. The main point here is that such feedforward processes are known to exist, and the postulation of a set of expected sensory consequences is in keeping with the current thinking in neurophysiology.

4. Efference Copy in the Schema Theory

Space in the present chapter does not permit the discussion of the evidence for and against the various efference copy positions, but the evidence is summarized in Schmidt (1975a). Briefly, though, the most important lines of evidence are the deafferentation studies with monkeys (e.g., Taub and Berman, 1968) and the evidence on the rapid correction of errors (e.g., Angel *et al.*, 1971; Megaw, 1972). The deafferentation work indicates that monkeys can learn a bulb-squeeze shock-avoidance response with total loss of feedback from the responding limb, and the implication was that since some form of feedback is needed for learning, it must have been the efference copy that supplied it. Adams (Chapter 4 of this volume) has correctly pointed out that other, nonproprioceptive sources of response information (e.g., vision of the apparatus movements correlated with the bulb-squeeze) might serve as the feedback used to learn the movement. Another possibility is that all that is necessary for learning is information about what motor command was issued (the response specifications in the schema theory) and information about the success of those specifications (the offset of the shock). Either of these explanations can handle the Taub-Berman (1968) findings very well without invoking the Jones (1971) notion of efference copy feedback loops.

The data on rapid error corrections indicate that subjects in two-choice reaction-time tasks sometimes move in the incorrect direction, but often correct their error with latencies (from the initial incorrect move to the beginning of the correction) of about 60 msec, far less than could be explained by peripheral feedback loops. One interpretation (e.g., Angel *et al.*, 1971) is that the subjects monitor their own efferent commands, and detect an error very early in the movement. An alternative explanation, however, is that the subjects anticipate the direction of the move on those error trials, and that the onset of the stimulus light (opposite to their expectations) is the signal which initiates the correction. If so, there is no necessity of postulating the internal monitoring of efference to explain the rapid corrections.

In short, there is no evidence for the first two efference copy models that cannot be handled easily by other explanations, and thus the schema theory position rejects these two views. The third view, that of efference as a series of feedforward mechanisms that "ready" the system for subsequent control, is widely supported by the evidence, and the schema theory is in keeping with this view. Thus, in the schema theory, efference copy has two roles. First, the feeding forward of the expected sensory consequences for later comparison with incoming feedback is fundamentally no different from feeding forward the gamma information to the spindles to alter the reflex influence of subsequent muscle length changes; in both cases errors can be detected, and corrections can be made, although the corrections based upon the expected sensory consequences are considerably slower than those associated with the spindle. Second, the arousal of the expected sensory consequences allows accurate perception of the incoming feedback, and allows the subject to discriminate between active and passive movements.

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