Theoretical mechanisms and processes underlying motor skill acquisition
by Sharon Brooks Dorfman

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in PSYCHOLOGY
Montana State University

Abstract:
Recently, several theories (Adams, 1971; Schmidt, 1975; Keele, 1973) have been developed to explain the processes and mechanisms underlying the acquisition of motor behavior. Two separate constructs have emerged to describe the role of central process in the initiation and production of a response and the subsequent evaluation of the response. The current research attempted to test the constructs of motor program or memory trace (for response initiation and production), and perceptual trace or template (for response evaluation) using a perceptual-motor skill task. This task required the subject to time and anticipate an external stimulus event. The predictability of the stimulus and the amount of practice were the main variables manipulated. These variables should affect the development of a motor program and an internal template for response evaluation.

The study consisted of four experimental conditions: short practice, fixed target speed; long practice, fixed target speed; short practice, variable speed; and long practice, variable target speed. There were 10 females and 10 males in each of the four experimental groups.

The task required subjects to coordinate the interception of two dots on a cathode ray oscilloscope. The dots moved in a linear, but perpendicular pattern where the target dot moved in a vertical plane and the cursor dot (controlled by the subject) moved in a horizontal plane. The response measure was the Algebraic Error in milliseconds, or the difference in arrival times of the cursor and target dots.

The task consisted of two phases in which each subject performed a series of practice trials followed by 30 test trials.

During the practice trials the subject viewed the entire movement of the target dot. It should be noted that all feedback channels were available to all subjects in the practice session. However, during the test trials the subject only viewed the onset of target dot movement. The remainder of the path was masked from view.

Three statistically significant results were found. First, performance over test trials became more proficient. This result indicates that subjects were able to learn to predict the stimulus movement when it was masked out and initiate the appropriate response. Second, subjects in the long practice conditions performed better than those in the short practice conditions. Subjects in the long practice conditions abstracted the pertinent information concerning the nature of the criterion response and stimulus movement, which led to the development of an adequate response schema and internal model. And third, subjects in the fixed target speed conditions performed better than subjects in the variable target speed conditions. This result indicates that constant, predictable target speed during practice conditions enabled the subjects to develop a correct stimulus-response template which aided performance on the test trials.

One important contribution of this study is the extension of the constructs which in the past have been developed using simple tasks to a more complex task involving the timing and anticipation of external

stimulus events. More importantly, however, this study empirically supports the notion of separate mechanisms for the selection and initiation of a response through a motor program and a separate error detection and correction mechanism.

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UNDERLYING MOTOR SKILL ACQUISITION

by

SHARON BROOKS DORFMAN

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ABSTRACT

Recently, several theories (Adams, 1971; Schmidt, 1975; Keele, 1973) have been developed to explain the processes and mechanisms underlying the acquisition of motor behavior. Two separate constructs have emerged to describe the role of central process in the initiation and production of a response and the subsequent evaluation of the response. The current research attempted to test the constructs of motor program or memory trace (for response initiation and production), and perceptual trace or template (for response evaluation) using a perceptual-motor skill task. This task required the subject to time and anticipate an external stimulus event. The predictability of the stimulus and the amount of practice were the main variables manipulated. These variables should affect the development of a motor program and an internal template for response evaluation.

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One important contribution of this study is the extension of the constructs which in the past have been developed using simple tasks to a more complex task involving the timing and anticipation of external stimulus events. More importantly, however, this study empirically supports the notion of separate mechanisms for the selection and initiation of a response through a motor program and a separate error detection and correction mechanism.

CHAPTER 1

INTRODUCTION

Skilled motor behavior is a vital component of man's total behavioral repertoire, in that most events in daily life center around skilled movement. In fact, motor behavior is found in practically all activities ranging from gross body movement such as walking and running, to verbal behavior, and to the complex manipulation of tools and objects in man-machine systems. Recently, many researchers (e.g., Adams, 1971; Dorfman, 1972; Keele, 1968; Schmidt, 1968; among others) have studied human performance in an attempt to understand the characteristics and underlying mechanisms of perceptual-motor behavior. The present research represents an extension of this line of investigation. Specifically, it explores one critical process in skills; that of the development of an internal model or standard, and the error detection/correction mechanism which compares desired performance with actual performance.

In order to study the underlying processes and mechanisms of perceptual-motor skill behavior, it may be useful to identify and describe the distinguishing characteristics of skills. Skilled motor behavior consists of complex, highly organized series of movements. Although skilled behavior can be defined in various ways, certain characteristics seem to appear repeatedly in the definitions that have been offered. These identifying characteristics include anticipation, timing, receptor-effector feedback processes, and spatial-temporal patterning (Fitts, 1964). Other researchers stress learning and the goal-directed characteristic of skills. As an example, Whiting (1972) defines skilled behavior as follows:

> . . .complex, central and motor mechanisms which through the process of learning have come to be organised and co-ordinated in such a way as to achieve predetermined objectives with maximum certainty (p.269).

Fitts (1964) also places emphasis on the patterning and organization of the behavior process. The receptor-effector feedback processes must be highly organized both spatially and temporally in skilled responses. Thus, theoretical explanations of motor behavior should attempt to explain how the spatial and temporal organization (or patterning) is achieved.

The role of timing is a critical aspect of human motor performance. Timing is the process of initiating a response sequence at the best and most accurate moment, and coordinating muscular movements to insure precision and smoothness of response (Dorfman, 1972). According to Schmidt (1968), correct timing is observed in two main categories of performance. The first situation involves the movement of musculature in such a way that the resultant movement is well coordinated, such as the movement required in walking. The second situation involves responding simultaneously with some external event, such as hitting a baseball.

Obviously these categories are not mutually exclusive, as the first aspect of timing must be present in the second.

Proper timing in situations involving an external event obviously requires the anticipation of that future event. Anticipation is therefore the expectation or prediction of the occurrence of some future stimulus event. Thus, the predictability of the stimulus event is important for anticipation as well as timing (Dorfman, 1972). The process of anticipation occurs when a person has the opportunity to preview the forthcoming event, and can therefore prepare for the response (e.g., a car driver planning ahead for an approaching curve). Anticipation may also occur when a person is not able to view the stimulus in advance but instead can learn the identifying aspects of the stimulus. The predictability of the stimulus would be important in tasks requiring a series of responses with minimal preview. Anticipation may also involve effectors, as in the case of predicting various positions of the limbs as the movement sequence unfolds.

Although many characteristics of skilled behavior such as timing have been identified, the internal processes and mechanisms responsible for skilled motor performance are not nearly as well understood. A few of the important questions are the following: What nervous system processes as well as skeletal-musculature functions are responsible for performing and learning a movement? How can the movement be repeated and improved? What allows a movement to become automatic and less influenced by cognitive functions? How are correct movements maintained and incorrect movements corrected? Many models of skilled behavior have been developed to integrate the existing facts about movement processes, and to determine what mechanisms and processes must be operating to insure skilled performance.

Recently, several theories have been developed to explain the richness and complexity of skills, including Adams' (1971) closed-loop theory of motor learning, and both Keele's (1973) and Schmidt's (1975) models. The main characteristics of each of these conceptual models will be described in the following sections.

Adams (1971) notes three general aspects of motor learning that should be dealt with by any theory: 1) the interaction of both motor and non-motor response classes as response systems (cognitive and motor), 2) an adequate conceptualization of the nature and use of knowledge of results, and 3) the process of error detection and correction. Further, he distinguishes between open and closed-loop models of motor learning. The former are typified by Lashley's (1951) conceptualization of the central organization of response sequences, later called motor programs. In all open loop systems (such as the motor program concept), there is an input event, the system acts on the input, and the system generates an output. There is no feedback or mechanism for error regulation. In contrast to open loop systems, closed-loop systems include a feedback loop plus an error detection and correction mechanism, whereby discrepancies between the standard and the output are detected and corrected, if necessary, making the system self-regulating. An example of a closed-loop system is a household heating system in which the thermostat acts as a sensor for temperature discrepancies. The discrepancies between desired temperature (thermostat setting) and actual temperature are monitored, and the furnace is activated when the difference between actual and preferred temperatures is greater than some predetermined value. Adams (1971) prefers a closed-loop theory, emphasizing error detection and correction through feedback mechanisms.

Knowledge of results (information concerning the outcome of a response) is an important component of Adams' closed-loop theory of motor learning. In motor skill acquisition, knowledge of results can be used to modify a movement pattern to achieve more accurate performance. Two types of knowledge of results that can be given are: 1) qualitative, which is usually dichotomous in nature and lacks detail (e.g., too fast or too slow); and 2) quantitative, which is in the form of scaled numerical information (e.g., 50 milliseconds too fast). In this respect, knowledge of results mainly serves an informational role, permitting corrections that eventually will result in increased accuracy of response.

Adams (1971) describes two memory states which are critical to his theory: the memory trace and the perceptual trace. The memory trace is a mechanism that operates to select and initiate the response. The perceptual trace is a reference mechanism that is composed of memory representations of past movements. It acts as a matching device through which the memory of a recent movement can be compared to the memory of past movements. Adams' justification for the separate constructs of memory and perceptual traces lies in the distinction that response activation and evaluation require independent internal mechanisms.

The memory trace is an open loop construct since it operates without feedback. It is a type of motor program that selects and executes a response rather than controlling a longer sequence. In a single motor movement, recall and recongition are separate processes. Motor recall is based on the memory trace, and is the beginning of a movement. Response recognition is the awareness of whether or not the movement is correct, which comes about as a result of comparing the specific trace to the perceptual trace, the second memory state proposed by Adams (1971).

The perceptual trace is the stored representations of feedback (kinesthetic, visual, etc.) of all motor responses to a specific event. A distribution of traces is generated from a series of movements or trials in a motor task. That is, motor behavior on each trial establishes a trace, and the accumulation of traces form this distribution. Responses are attempted which approximate the specified correct response (i.e., those responses which closely resemble the required movement). The perceptual trace (i.e., the distribution of all feedback traces) is used by the individual as an internal reference mechanism for adjusting the next movement with the aid of the knowledge of results just received. Sources of feedback for the perceptual trace include proprioception, tactual, pressure, auditory, and visual information. As hypothesized, the strength of the internal reference mechanism increases as a positive function of experiencing feedback on each trial. Thus repetition of correct responses will increase the trace strength of the correct response, thereby decreasing the standard deviation of the distribution of traces for all responses.

According to Adams' (1971) theory, learning occurs when the person compares the knowledge of results just received on a trial to the perceptual trace (internal reference mechanism) in order to evaluate the response just produced. Then, on the next trial, the individual can adjust his or her movement in the direction of the correct movement response. Adams calls this early phase of learning the "verbal-motor stage", since corrections are made on the basis of verbal transformations of knowledge of results. The verbal-motor stage of acquisition ends when the perceptual trace is strong: that is, when error is within acceptable limits and the criterion response has been repeated a certain number of times. At this point, the perceptual trace can replace verbal knowledge of results as a relatively large amount of training has occurred. Learning should then be able to continue on the basis of internally stored information. For maintenance of the criterion at the advanced stage the person must be aware that the present movement is not discrepant with the internal reference. Knowledge of results then, is no longer needed because the person continues his or her movement until he or she "knows" it matches the perceptual trace.

In the early verbal-motor stage the distribution of perceptual traces has a large standard deviation. As learning passes into the motor stage, this distribution should have a smaller standard deviation; the dominant mode of correct responses is established, thus resulting in a criterion response resistant to forgetting.

According to this theory, the "motor stage" is the final stage of motor skill acquisition where external knowledge of results can be withheld without a decrement in performance. In the progression from the verbal-motor stage to the motor stage, conscious behavior processes eventually become less important.

Recent experiments testing this theory have used independent variables which are presumed to affect the development of the internal reference or error detection/correction mechanism and motor programs. Adams and Goetz (1973) employed a linear, self-paced task to study the role of practice and feedback in error detection and correction. They hypothesized that error detection and correction would improve as a function of both feedback and practice. To test this notion, subjects were required to move a slide along a track for a specified distance. In one experiment, four independent groups performed the error detection task under either minimal or augmented feedback conditions with either two or ten trials of practice. Since a basic assumption of Adams' (1971) theory is that a person is capable of detecting errors, error detection was measured by the percentage of correct responses in distinguishing between the criterion and error movements in a two-choice discrimination task. The results demonstrated that practice benefitted performance only when feedback was augmented. That is, when feedback channels were reduced (by blocking visual and auditory cues), practice had little effect on performance. Augmented feedback (all feedback channels available to the subject) produced better performance than minimal feedback. These findings support Adams' assumption that feedback and practice are important determinants of the internal reference.

In a second experiment, Adams and Goetz (1973) used the same design with correction rather than error detection as the primary task. The task involved reproducing a criterion movement after practicing a movement to a stop. The stop was then removed and the subject was required to move the slide to the length of the criterion movement. Amount of error, the difference between the criterion and reproduced movements, was the performance measurement. Results indicated that feedback was a significant variable for error correction, since groups receiving augmented feedback performed better than groups receiving minimal feedback. In this study practice alone was not a significant variable. However, when augmented feedback was available, practice enhanced performance. Adams and Goetz concluded that these studies verified the closed-loop theory of motor learning since the perceptual trace (internal reference) is a positive function of the amount of feedback and practice available, and practice improves performance only when adequate feedback channels are available.

Rather than using a self-paced movement as did Adams (1971) and Adams and Goetz (1973), Schmidt and White (1972) used a rapid ballistic movement (i.e., a movement with duration less than 200 milliseconds) for the task of moving a slide a specified distance along a track in a prescribed amount of time. In this type of movement, feedback from the response cannot be used to alter the movement, since the total response time is too short. Hence, the ballistic movement task was used in order to examine aspects of motor program movement (memory trace) without having the perceptual trace (internal reference mechanism) influence the ongoing motion. It was postulated that the ballistic movement is produced by the memory trace (motor program) alone since once the movement is initiated, it is too rapid to be concomitantly affected by feedback[1]. The strength of the trace was estimated by measuring objective error in movement time (the difference between the subject's movement time and criterion movement time). In this situation, the perceptual trace would have the role of evaluating the adequacy of the response just produced. The measure used to account for the strength of the perceptual trace was the extent of agreement between the subject's actual response time (objective time) and the subject's guess about his or her movement time after each trial (subjective time). Over trials the discrepancy between objective and subjective error decreased.

The results of the Schmidt and White (1972) study using both objective error and the difference between objective and subjective error demonstrated the development of an error detection mechanism. Also, when knowledge of results is withdrawn, performance is maintained and there is a small tendency for learning to occur without knowledge of results. This is consistent with Adams' (1971) theory whereby performance should be maintained after knowledge of results is withdrawn when a strong perceptual trace has been established.

Schmidt and Wrisberg (1973) also tested various aspects of Adams' closed-loop theory of motor learning. Considering Adams'

[1]Recent evidence (Evarts & Tanji, 1974) indicates that feedback can be used for fine, graded adjustment in preselected responses, but changing the response does, in fact, require more than 200 milliseconds.

prediction that the error detection mechanism depends on quality of sensory feedback received during learning, Schmidt and Wrisberg eliminated certain feedback channels (vision and audition) during learning. In using a ballistic movement for the task, elimination of feedback should not influence response production but should result in a weaker error detection mechanism. Also, when knowledge of results is withheld, the person "substitutes" his or her own error detection mechanism, since the ability to maintain performance should decrease as feedback channels are progressively eliminated.

The Schmidt and Wrisberg findings did not support Adams' (1971) prediction that the development of the error detection mechanism is dependent on the quality of feedback. Also, those results did not support the notion that withholding knowledge of results late in practice should result in maintained performance along with more proficient performance by groups with standard feedback. Some findings, however, were consistent with Adams' closed-loop theory of motor learning. First, diminished feedback in learning lowered the resistance to the effects produced by withholding knowledge of results. These data imply that the perceptual trace (error detection mechanism) is based on response produced feedback. Second, the strength of the error detection mechanism increased with practice. Thus the overall findings of Schmidt and Wrisberg (1973) offered only partial support for

Adams' (1971) theory.

Although Keele had not proposed an inclusive model of motor skill learning until recently (Keele & Summers, in press), his discussion of motor programs, templates, and internal models is germane to the present research. Keele (1973) in a similar vein as Adams, has also suggested that in movement (or motor) performance, the use of visual information as feedback for corrective movements serves a different role and generally becomes less important as a function of increased practice. As a motor skill is learned, movements become structured so that direct visual control is no longer important, and hence, other mechanisms gain movement control. That movement sequences do not always require feedback for execution is illustrated by research on animals (such as birds) showing no deterioration in performance as a result of the elimination of kinesthetic feedback (i.e., feedback from joint senses, tendon receptors, and cutaneous senses) and visual feedback (Nottebohm, 1970; Wilson, 1961). Keele (1973) and others (Schmidt, 1968; for example) conclude that the patterning of motor behavior must by represented in the brain or spinal cord in the form of a motor program. According to Keele (1968), a motor program is a hypothetical set of muscle commands that are established prior to the beginning of the movement sequence. These commands allow the sequence to be initiated and at times completed without relying on peripheral feedback. Keele (1973) further clarifies the notion of motor program as follows:

> As a motor program is executed, neural impulses are sent to the appropriate muscles in proper sequence, timing and force, as predetermined by the program, and the neural impulses are largely uninfluenced by the resultant feedback (p. 124).

Keele (1973) points out that one critical aspect in motor skill learning (i.e., at least skills having regular and predictable movements) is the construction of a motor program. This concept of a motor program that is uninfluenced by the feedback from the actual motor response is quite congruent with Adams' (1971) notion of a memory trace. In Keele's concept of the motor program, feedback is necessary in the activation, monitoring, adjusting, and also the learning of the motor program. In the learning of a motor program for skilled performance, extrinsic feedback (i.e., feedback from outside of the organism) seems critical (Keele, 1973). Here extrinsic feedback can be compared to the role of knowledge of results in establishing what Adams (1971) calls the perceptual trace. The main difference between Adams' conception of the memory trace (modest motor program) and Keele's motor program is that the memory trace does not control long sequences of behavior. Hence the term "modest" motor program.

Keele (1973) discusses the external versus internal models or standards to which motor performance can be compared during and after acquisition of the skill. He defines an internal model as a model of skilled performance which is stored in memory. This internal model is somewhat analogous to the perceptual trace proposed by Adams (1971). After the motor program is established, the movement sequence becomes less dependent on feedback for activation. The memory representation of the movement is then compared to the internal model (Keele, 1973). In Adams' terms, the motor response is compared to the reference mechanism (perceptual trace), and the person is aware of whether or not the movement is accurate. Thus, recent trends in the motor learning literature point to the establishment of two separate mechanisms for the production and evaluation of perceptual-motor responses.

Schmidt (1975) has proposed a schema theory for motor skill learning which incorporates Adams' (1971) theory, but is modified to account for theoretical inconsistencies and discrepant research findings in the original closed-loop theory. Borrowing from the verbal learning literature, Schmidt postulates a recall memory to evaluate response correctness. According to Schmidt, the schema is a hypothetical construct which refers to an abstraction of a set of stimuli related to movement production. Essentially, a schema is a set of rules, stored in memory, of critical aspects of a movement or class of movements. These critical aspects are stored in four types of informational memory constructs. The schema is then referred to for movement production and evaluation.

These four sources of information are as follows: 1) initial environmental and sensory conditions just prior to the movement, 2) response specifications (characteristics of the required response) for the motor program, 3) sensory consequences of the produced response, and 4) the outcome of the movement. When a number of movements have been made, the individual abstracts the pertinent information about the relationship of the four classes of information and thereby creates a response schema. A recall schema for response production is similar to Adams' (1971) notion of a memory trace. The difference here seems to be that Schmidt's theory allows the individual to execute a movement which may be new, but similar to past movements. In referring to the recall schema the individual may abstract the similarities and execute the novel movement.

Schmidt (1975) postulates a recognition schema for response recognition. This recognition schema contains stored information concerning the relationship between the past outcomes and past sensory consequences of similar responses. While the movement is occurring and after the movement has occurred, the person makes comparisons between the expected sensory consequences (i.e., those consequences which are stored from past movements and are thus expected on next movements) and the actual sensory information occurring during the movement. If the expected and the actual information are different, error information is fed back to the schema, thus providing information about the response outcome.

The recognition schema is similar to Adams' (1971) perceptual trace and Keele's (1973) internal reference mechanism. According to Schmidt (1975), the expected sensory consequences are dependent upon establishing a relationship between the response outcome on past trials (which is determined by knowledge of results and other reinforcement) and the sensory information (in the form of feedback) actually experienced. The strength of this recognition schema should increase as a function of knowledge of results received in initial practice and the feedback received on each trial.

The present research may be viewed as an outgrowth of the above implications of Adams' (1971), Keele's (1973), and Schmidt's (1975) explanations of the processes and mechanisms involved in motor performance. Specifically, the current study was designed to evaluate several hypothetical constructs postulated by Adams, Keele, and Schmidt. Research designed to test the above models (especially Adams, 1971) has not supported all aspects of the models unequivocally. The research does, however, seem to be an adequate representation of those processes involved in simple lever positioning tasks. It should be noted, however, that even though the research has so far been limited to those simple tasks, the models were developed to explain more complex skilled behavior.

The current research attempted to test the various constructs using a more complex task, specifically, a two-phased task requiring the timing and anticipation of an external stimulus. The predictability of the stimulus and the amount of practice were the variables manipulated in order to affect performance. The first phase consisted of a number of practice trials on an intercept task in which the subject was required to time the arrival of an external stimulus and make a response to that stimulus. In this phase, the subject would be expected to develop the capability for producing the proper movement response (memory trace, or motor program) and also some sort of internal standard for response evaluation (perceptual trace or internal reference mechanism). In the second phase (test trials) the subject's task remained essentially the same but features of the stimulus movement were degraded, requiring the use of a hypothesized motor schema developed in the practice trials. The task involved both the timing of responses and the anticipation of stimulus movement. If the hypothetical constructs of motor schema, motor program, and perceptual traces are valid, the amount of practice and the predictability of stimulus movement should greatly affect performance. The following specific hypotheses were posed:

(1) Performance over trials will become more proficient, as indicated by smaller error scores.

(2) Long practice conditions will be superior to short practice

conditions. Practice should contribute to the development of a strong internal reference mechanism.

(3) Fixed target speed will result in superior performance to variable target speed. This predicted finding would indicate the development of a strong internal reference for fixed speed conditions.

CHAPTER 2

METHOD

Subjects

Eighty student volunteers (40 females and 40 males) from Montana State University served as subjects and received extra credit for course work and/or $1.00 for participation. In addition, they could earn additional money on the basis of their performance. Hand preference of the subject was not critical since the equipment could accomodate either right or left handed persons. There were 20 subjects (10 females and 10 males) in each of the four conditions.

Task

A perceptual-motor skill task was used in which the objective was to coordinate the interception of two dots on a cathode ray oscilloscope screen by manipulating a slide control. The dots moved in a linear but perpendicular pattern: the target dot (TDOT) in a vertical plane and the cursor dot (CDOT), which the subject controlled, in a horizontal plane. The movement of the slide corresponded to the horizontal movement of the CDOT on the screen in the ratio of 3:1, respectively. Under some of the experimental conditions, the target moved at a constant rate which was varied systematically between 600 and 800 milliseconds (msec) in 50 msec increments. Other experimental conditions specified a fixed target rate of 700 msec.

The experimenter initiated an intercept trial by typing an appropriate key on the teletype after inquiring if the subject was ready for the next trial. A random delay of 1 to 3 seconds intervened between the activation of the key and the start of TDOT movement in order to minimize the timing cue afforded by the sound of the teletype key.

Apparatus

The apparatus used to implement this task consisted primarily of a perceptual-motor skill device and a mini-computer (Hewlett-Packard Computer series 211X; in this particular case, the 2116 was used). The system components included a time base generator, analog to digital converter, digital to analog converter, teletype, paper tape reader, and a cathode ray oscilloscope. Figure 1 shows the system design and arrangement of the apparatus in the experimental laboratory.

The combined apparatus monitored the movement of a handle (slide) 10.16 cm (4") high, which was mounted on a standard table. The slide could travel horizontally a distance of from 0 to 114.30 cm (0" to 45"), although in the present study the critical movement was 30.48 cm (12"). The starting position of the slide for right-handed subjects was a rubber stop on the right hand side of the track; handle movement proceeded from right to left. If a subject preferred his or her left hand, the apparatus was internally programmed on signal from the teletype to reverse the modality of the slide and the corresponding cathode ray oscillo-