Motor Skill Learning: A Review of Trends and Theories

Natalie Krahe
Carroll College, Helena, MT

Follow this and additional works at: https://scholars.carroll.edu/psychology_theses

Recommended Citation
https://scholars.carroll.edu/psychology_theses/14

This Thesis is brought to you for free and open access by the Psychology at Carroll Scholars. It has been accepted for inclusion in Psychology Undergraduate Theses by an authorized administrator of Carroll Scholars. For more information, please contact tkratz@carroll.edu.

Natalie Krahe
Carroll College
This thesis for honors recognition has been approved for the Department of Psychology.

Director

Reader

Reader

Date

Date

Date
## Table of Contents

<table>
<thead>
<tr>
<th>Contents</th>
<th>Page Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Introduction</td>
<td>3-5</td>
</tr>
<tr>
<td>II. Historical Approaches</td>
<td>6-12</td>
</tr>
<tr>
<td>III. Theories of Motor Skill Learning</td>
<td>13-26</td>
</tr>
<tr>
<td>IV. Summary</td>
<td>27-31</td>
</tr>
<tr>
<td>V. References</td>
<td>32-34</td>
</tr>
</tbody>
</table>
Introduction

Think of a typical day. Waking up to the sound of the alarm a person may get up and stumble into the shower. Perhaps, after turning the alarm off they zap themselves awake with a walk or some form of exercise. Then again, maybe they simply sit sown with a cup of coffee and the morning paper. Whatever the case may be, most people eventually get themselves ready, have some breakfast, and head off to work. Throughout the course of the day, they are presented with different tasks and each of them completes them in one way or another. At the end of the day they drive, walk, or bike back to their homes where they concern themselves with the activities of the evening. They may fix dinner and go out to a movie or stay at home and relax with a book. At the end of the day however, they all crawl back into bed to get ready for yet another day.

There are a million different things that people can do within a day. These examples may be typical for some people and not for others. Whatever the case, one common theme remains constant for most people; it is the concept of movement. All people in today’s world are on the go and the movements of our bodies are what get us where we want to be. Movement is truly a critical aspect of life. Without it, we could not feed ourselves, we could not reproduce, and we could not survive. Life as most know it would cease to exist.

Unfortunately, it is not an easy task to understand movement. The enormous topic can be subdivided into different categories or forms. Some forms of movement can be regarded as primarily genetic (inherent) such as the control of our limbs or the ability of a baby to suckle (Schmidt, 1988). Other forms are termed reflex movements. Blinking of an eye or the scratch reflex in dogs are both good examples of this. They are
movements that tend to be stereotypical across members of the same species (Schmidt, 1988). Another form of movements can be thought of as learned, such as those involved in controlling an automobile, typing, or performing a complicated dance move. (Schmidt, 1988). These movements are often termed skills and for the purposes of this paper we will focus our attention here on motor skill learning (MSL).

In addressing motor skill learning, researchers have proposed various similar definitions. One of the most common definitions is based on the four distinct characteristics of MSL proposed by Schmidt (Shumway-Cook & Woollcott, 1995). First, learning is a process of acquiring the capability for producing skilled actions. Second, learning occurs as a direct result of practice or experience. Third, learning can not be observed directly, it must be inferred from the behavior changes seen. Finally, learning is assumed to produce relatively permanent changes in the capability for skilled behavior. The resulting definition given by Schumway-Cook & Woollcott (1995) is that, “motor learning is a set of processes associated with practice or experience leading to relatively permanent changes in the capability of responding” (pp. 24). It should be pointed out that the processes mentioned are thought to be complex central nervous system phenomena whereby sensory and motor information is organized and integrated (Winstein, 1991).

Many more general definitions have been proposed by others to describe motor learning. For example, one definition states that it is the increasing spatial and temporal accuracy of movements with practice. (Willingham, 1998). Another is that MSL is the formation of new or novel movement sequences to gain speed, precision, accuracy, and efficiency in a task (Leonard, 1998). Hasband and Freund (1993) state that motor
learning, “involves the acquisition of new skilled movements and refers to the ability of an individual to acquire the temporal and spatial characteristics of movement patterns so that their execution will be increasingly characterized by pre-programmed processes” (pp. 940).

All of these various definitions have been developed in accordance with specific hypotheses and theories that researchers have developed about MSL. Thus, the next logical step in understanding is to discuss the historical approaches that lead to the development of these hypotheses and theories. Not surprisingly, the history originates in the early development of the field of psychology where most motor behavior was being studied.
Historical Approaches

The study of MSL has not progressed in a direct and orderly fashion. In fact, the beliefs and theories of motor learning have changed frequently as a result of more structured research approaches, advances in technology, and environmental factors. These changes have not had that much of a negative effect on the field. Fortunately, many questions concerning MSL have been answered as a result. But, debate continues and researchers today still have questions about which theories to pursue and which to drop.

Prior to the 1900's, the general focus of research was on introspection. Data was gathered based on self-reports, unobservable feelings, and subjective findings (Schmidt, 1988). Skills were studied only because they were thought to provide access to the mind. With the turn of the century however, there was a shift to a more objective and systematic approach to the study of skills. They began to be studied because researchers wanted to know about the skills themselves (Schmidt, 1988). This shift encouraged researchers to design experiments that could be replicated, analyzed, and reviewed by many. The field of motor skill learning thus began.

The shift in research previously mentioned had a very large impact on the field of psychology, and it is here that the early research on MSL took place. As early as 1892, Cattell started examining force reproducibility. In 1899, Woodworth was studying rapid repetitive arm movements. He introduced two phases of control which he called the initial impulse and the current control phase (Glencross, 1993). Both of these concepts are still cited in current research. Thorndike, in 1914, was concerning himself with the underlying processes of skill learning and other behaviors that eventually lead to his
Law of Effect (Schmidt, 1988). It did not stop here, others were making further contributions such as those by Lashley. In 1917, he was delving into the mechanics of the brain for answers as to how we learn (Schultz & Schultz, 1992).

This early research had a functional behavioristic style that led to the first major approach to the study of MSL called the task approach. It was most prevalent from the early 1940’s to the late 1950’s. Research within this approach had a very global viewpoint and was concerned with complex skills (Schmidt, 1988). It was influenced primarily by the dominant stimulus-response orientation that was popular in the previously mentioned behavioristic psychology (Winstein, 1991). It focused mainly on the effects of variables on the performance of certain motor tasks trying to key in on “real world” skills (Schmidt, 1988).

This approach may have been partly due to the behavioristic research going on in the field of psychology, but it can also be attributed to environmental influences of the time. Our society was very work-orientated and this ethic changed the direction of MSL slightly. In the 1930’s we started placing a greater emphasis on industrial applications in the realm of skills research (Schmidt, 1988). This too may have pushed research to a more task orientated approach.

During this period there were two major influences that caused a boom in the research of MSL: World War II and the emergence of various theories of learning (Schmidt, 1988). WWII created a need for a selection process that could find the most suitable soldiers for various tasks. Work done by Arthur Melton (as cited in Glencross, 1993) was a direct result of this selection need. He created the Psycho-Motor Testing Program for the US Army Air Force. It was put into action in hopes of finding the most
suitable people for pilot training. When the war ended in 1945, the attitude in the US was that efforts in selection of military personnel should not be abandoned. The research continued with people such as Fleishman (as cited in Schmidt, 1988) who began to take note of individual differences and the positive effects of training. Researchers began to realize that training, not selection, was more important (Schmidt, 1988). Thus, much attention was paid to teaching and retention of motor skills.

The second boom came in the form of theories of learning. As research started to become more objective, people began to formulate written theories that provided strong directions for research and contributed hard data for future generations (Schmidt, 1975). Many of the first theories have since been proven incorrect or inadequate, but all of them have helped to push research forward. Such was the case with Hull’s theory of learning which was presented in a book called Principles of Behavior. It was a theoretical framework “so comprehensive as to include all behavior” (Schultz, & Schultz, 1992, pp343). Schmidt (1988) points out that it was a, “general learning theory-applying to animals and humans, to verbal and motor behavior-and tests of it were often done with motor tasks” (pp10). As tests of the theory continually challenged it, researchers eventually came to the conclusion that it was not adequate in describing the processes and variables associated with motor learning and performance (Schmidt, 1988).

The disillusionment with Hull’s Theory and the end of the post-war era brought about a decline in the number of psychologists doing research in the area of MSL. They began to turn their interests to other areas such as the learning of verbal skills (Schmidt, 1988). This lull in research lasted up until the mid 1960’s when a new approach to MSL began to take place called the information-processing approach or the
prescriptive-computational approach. The first attempts to propose such a model were actually started in the 1940's. Craik (as cited in Glencross, 1993) was an influential researcher that initiated this new avenue of research. Craik proposed that researchers, "look at the brain as a kind of computer in which information was received, processed, and then output to the environment in the form of overt actions of the limbs". He helped to forge the link between communication, cybernetics, and human behavior. Glencross made reference to another man by the name of Weiner who wrote *Cybernetics* (1948) in which he outlined an information-processing basis for human behavior. He proposed the formal study of self-regulation in biological as well as physical systems (Glencross, 1993). The result of work done by these and other men was a framework to follow in which information is abstracted and processed by the brain. This brought about an emphasis on cognitive science and cognitive psychology. In the 1960's, this approach finally began to emerge and research again began to pick up (Schmidt, 1988).

The information-processing approach takes the computational metaphor quite literally (Glencross, Whiting, & Abernethy, 1994). It functions in a top-down heirarchial manner in which a human receives, stores, retrieves, transmits, and monitors information so that they can perceive, think, and act (Glencross et. al., 1994). It is different from the task approach because it focuses more on the neural control of simple movements and takes into account internal, mental, and motor processes (Schmidt, 1988). This approach has the capacity to explain both closed-loop motor learning (feedback dominated) and opened-loop motor learning (program dominated). In addition, it encompasses schema-governed motor learning.
A closed-loop system can be described as a self-regulating system which has feedback, error detection, and error correction as its key elements (Mulder & Hulstyn, 1984). Schmidt (1975) sums this up by saying that most closed-loop systems have essential features in common, “a provision for the receipt of feedback, a reference of correctness to check the feedback against with any discrepancies resulting in an error, and subsequently, error correction” (pp. 226).

An opened-loop system is slightly different from a closed-loop system because the concept of feedback is not as important for the production of correct movements. According to opened-loop theorists, “control and coordination is possible because a central mechanism or program contains the information necessary to specify the temporal and quantitative aspects of the movement” (Mulder & Hulstyn, 1984, pp228). This concept suggests a separate motor program for every movement. In other words, for any movement you make, there is a program that is activated to help you perform the movement correctly. Thus, feedback is less needed because a program already exists to tell the subject how to move. However, this presents a problem in the domain of information storage. If a motor program for every separate movement is needed, the central nervous system would need to have an endless amount of storage space (Schmidt, 1975).

To alleviate this problem, another system was developed which proposed the existence of a schema or general motor program. Schmidt (1975) was the first to suggest such a theory through his research of MSL. He proposed that a schema contains a broad motor program that can govern a class or category of movements. Many different movements with similar muscle groups working exist under the same schema.
For example, there may be a single motor program for the various ways to jump: fast or slow, high or long, one leg or two legs.

These aforementioned proposals were simplistic in that they dealt with movement that was being derived from experimental subjects who had to perform in laboratory tests under various experimental limitations. This has become a point of criticism in recent literature and research. Mulder & Hulstyn (1984) point out that, “the developmental progress of the experimental laboratory seems to be towards less and less complex coordination based on more and more primitive stimuli” (pp. 233). What this means is that it is not sufficient to define motor learning as the ability to perform simple laboratory tasks. Movement research is broadening the perspective of the discipline to include the concept of action instead of movement (Mulder & Hulstyn, 1984). Many are now trying to emphasize the importance of studying “total meaningful goal-orientated actions instead of isolated simple movements” (Mulder & Hulstyn, 1984, pp. 233) because this provides a better picture of how events occur in unconstrained environments. Mulder & Hulstyn (1984) point out that movements are elements of a larger framework termed actions. “These elements are by no means independent entities which can be studied on their own; they can only be understood against the background of the action of which they are a part” (pp234). Thus, it is important to establish a connection between the environment and the action in order to grasp the entire concept.

This recent change of perspective has brought about another approach to the study of MSL termed the dynamic or emergent properties approach. It is a new approach that first became apparent in the 1980’s. Glencross et. al. (1994) point out that this approach is, “grounded in physics, synergetics, ecological psychology, and views
muscle dynamics and the self assembly of action via muscle collectives or coordinative
control” (pp. 42). It can be seen as heterarchial (vs. the hierarchial organization seen in
the information-processing approach) due to the fact that properties of movement emerge
as a consequence of underlying muscle group dynamics rather than as a result of higher
cognitively represented plans (Kelso [1981] as cited in Glencross et. al., 1994). In a
heterarchial system, the direction of control is not unidirectional (top-down) but is
distributed throughout among a number of structures (Mulder & Hulstyn, 1984). It is a
more democratic system in which there is not a central program commanding lower
levels (Mulder & Hulstyn, 1984). However, there does exist an executive system that
regulates the interactions between the lower level systems. Thus, one could say that the
lower structures control movements and the executive system controls the overall action
(Mulder & Hulstyn, 1984). The executive system helps to formulate an action plan based
on your perception of the events surrounding you and the action you want to perform.
Theories of Motor Skill Learning

**Miller, Galanter, & Pribram's TOTE Model (1960)**

**Description:**

This model elaborated on a proposal that was made in 1932 by Bartlett. Bartlett (as cited in Glencross, 1993) introduced the concept that a schema (a general motor program) is the key central to our understanding of human skill. This became the starting point for Miller et. al. although they talked in terms of a plan rather than a schema. They defined a plan as “any heirarchical process in the organism that can control the order in which a sequence of operations is to be performed” (Glencross, 1993). This plan attempted to address the content, instructions, and information contained within a movement as well as possible operational mechanisms used (Glencross, 1993). It followed the information-processing approach. One important advance it made with this approach was that it integrated both closed-loop and opened-loop systems into one model (Glencross et. al., 1994). They proposed that as skill became acquired, control changed from closed-loop to opened-loop where it operated automatically. In other words, feedback was used less as you became more efficient at performing a skill.

The operational mechanism they developed was the “TOTE” unit, an acronym for Test-Operate-Test-Exit. It is a feedback controlled servomechanism that can be used in motor skill acquisition (Glencross, 1993). In their book, *Plans and the Structure of Behavior*, Miller et.al. (as cited in Glencross, 1993) use a simple example with which to explain their model. They used the human skill of hammering a nail into a piece of wood. Using the TOTE unit, it can be explained as follows: Test --This is the current status of the nail and hammer. We cognitively determine whether the nail is projecting
up and that the hammer is lifted above the nail. Operate -- We hit the nail with the hammer. Test -- Is the nail still projecting up? This test-operate sequence will continue until the person is satisfied with the outcome. Exit -- The person abandons this specific plan. (Glencross, 1993). It should be pointed out here that the specific TOTE unit explained might be only one such unit within a more complex TOTE unit. They can be added upon one another similar to building blocks. These units are thus hierarchically organized within a hierarchical plan. This plan is monitored by a feedback test or evaluation that is continually changing (Glencross, 1993).

Contributions:

Miller, Galanter, and Pribram were most influential in cognitive psychology (Glencross, 1993). They helped to provide evidence of the synthesis of cognitive concepts into a coherent motor skill model.

Limitations:

Most theories of the neural basis (such as the TOTE Model) have a problem describing skilled movements that are run off very rapidly (Glencross, 1993). Typing and playing the piano are two good examples. Researchers point out that there is very little time for proprioceptive (or other) feedback to occur from one movement before another movement must take place with entirely new feedback.

One other area that this model is weak in explaining is the question of intentions (Glencross, 1993). Cognitive processes such as intentions and motivation play a major role in this model (within the context of the Test) and it is not clear as to how much it affects the resultant movement.
Fitts & Posner Stages of Motor Learning (1964)

Description:

Fitts and Posner were also influenced by the information-processing theory. The basis of their model was that all skills are basically the same and that a common set of principles can be used to describe them. They developed three stages of skill learning to encompass the whole range of skilled behavior (Glencross, 1993). It can be applied to all people as they go through the process of learning a new skill. The three phases were the early (cognitive) phase, the intermediate (associative) phase, and the late (autonomous) phase (Schmidt, 1988).

In the cognitive phase the learner is attempting to understand the task. Each person is experimenting with a variety of strategies to find the one that produces the best performance. This decision making phase of “what to do” requires a high level of cognitive processing, as some strategies are eliminated and others are kept (O’Sullivan & Schmitz, 1994). Improvement in performance during this time is large but it occurs unevenly as the learner defines the task, assesses their ability, chooses strategies, and performs the task (Glencross, 1993). Learning in this phase is dependent upon environmental stimuli and visual feedback.

The associative phase is characterized by skill refinement achieved through practice. The person has selected the best strategy for the task and uses it to enhance skill performance. Instead of thinking about “what to do” the learner now concentrates on “how to do it” (O’Sullivan & Schmitz, 1994). Performance during this phase is more consistent and fewer errors are made. In addition, the learner concentrates less on visual (external) feedback and relies more on proprioceptive (internal) feedback.
The autonomous phase is characterized by motor performance that, after considerable practice, is largely automatic. This stage is still not well understood but Glencross (1994) points out that it appears that larger and larger chunks of perception and action are produced and controlled without direct cognitive monitoring. Motor programs are so refined they can almost “run themselves” (O’Sullivan & Schmitz, 1994). Improvement in performance is slow during this phase and movements are virtually error free.

Although these stages are described in three very separate phases, Fitts and Posner (as cited in Glencross, 1993) made it clear that the division of each was not distinct but rather represented different aspects along a continuum.

Contribution:

This model has had significant influence on subsequent modeling and has provided a basic framework for the understanding of human skill (Glencross, 1993). It is still referred to by researchers today.

Limitations:

Fitts and Posner (as cited by O’Sullivan & Schmitz, 1994) did not elaborate on the final stage of learning in any detail. Thus, Schmidt (1988) points out that the principles governing MSL in this stage are largely unknown and much research is still needed. One other criticism researchers have made is that each stage is not described with precise operational definitions. Instead, it is described with descriptive evidence that is not easily reproduced (Glencross, 1993).
Adam’s Closed Loop Theory  (1971)

Description:

The most important aspect of this theory is that it is founded on the concept of closed-loop processes in motor control. Again, this means that sensory feedback from the moving limb is used for the ongoing production of skilled movement (Adams, 1971). Adams (1971) believed that all movements are made by comparing the ongoing feedback from the limbs during the motion to a reference of correctness, termed the perceptual trace, that is learned during practice. The perceptual trace represents the feedback qualities of the correct position and is based on the memory of past experiences. Over time (with practice), it becomes more and more precise (Schmidt, 1975). The whole learning process hinges on the quality of the perceptual trace (Glencross, 1993). Repetition and the knowledge of results of each movement (auditory or visual feedback of correctness from the environment) both serve to strengthen the perceptual trace.

Adams (1971) went even further than this and proposed a second key concept to his theory. He called it the memory trace and it was proposed so that error detection could occur. The memory trace is responsible for the actual production of the movement and for specifying the details or program of action (Adams, 1971). Then, for a comparison process to occur, a trace of the intended or correct action (perceptual trace) must be available and different from the memory that actually produced the movement (memory trace) (Adams, 1971). In summary, the memory trace initiates a movement and then the perceptual trace takes over to carry out the movement and detect error (Shumway-Cook & Woollacott, 1995).
Contributions:

Adam’s theory represented a major step forward for MSL because it was the first empirically based theory presented for researchers to evaluate (Schmidt, 1988). It has generated significant amounts of research and has provided an extended view of MSL.

Limitations:

It has been shown that animals and humans can make movements without the aid of sensory feedback (Shumway-Cook & Woollacott, 1995). For example, Taub and Berman (1976) were cited by Schmidt (1975) saying that organisms deprived of sensory feedback from the limbs (deafferentiation) can respond skillfully and can even learn new actions. This cancels out major implications of Adam’s theory.

A second limitation that has been suggested is that Adam’s theory does not have the capacity to explain rapid movements that occur in everyday activity (Shumway-Cook & Woollacott, 1995). Researchers suggest that this is due to the amount of time it takes for feedback to occur. It is too slow to account for rapid movements. Thus, this theory focuses almost entirely on slow positioning responses that are not typical of activities of daily living (Schmidt, 1975).

Schmidt’s Schema Theory of Discrete Motor Skill Learning (1975)

Description:

Schmidt developed his theory of MSL in response to the various limitations presented by Adam’s theory. The schema theory he presented did retain some of the more general features of Adam’s theory such as two memory states but elaborated on the concept of a schema with opened-loop dependency (Glencross, 1993).
Schmidt proposed that each person has a recall schema and a recognition schema and that these two schemas contain a generalized set of rules for a specific class of movements (Shumway-Cook & Woollacott, 1995). The recall schema functions similarly to the memory trace suggested by Adams and the recognition schema functions as the perceptual trace in evaluating a response. The difference however, is that the notion of the two memory states being schemas (vs. traces) allows them to explain how people learn movements they have never performed before.

Schmidt (1975) uses these two schemas to explain both slow and rapid human movement. After a movement is made with a generalized motor program, an individual stores four things: initial conditions that existed before the movement (body position, weight of an object), parameters (force, speed, and direction), knowledge of results, and sensory consequences of the movement (proprioception, vision) (Schmidt, 1975). These four sources of information are stored just long enough so that the learner can form two relationships among them (Schmidt, 1988).

The first relationship is the recall schema, which is concerned with movement production. It utilizes the initial conditions, the response parameters, and knowledge of results to create a general rule or motor program (Schmidt, 1975). This program is then used and updated whenever a learner makes a new movement. The correctness of their movement is determined by a second type of relationship that’s been formed termed the recognition schema. This is the result of combining initial conditions, knowledge of results, and sensory consequences (Schmidt, 1975). Once this relationship is formed it allows the generation of a set of expected sensory consequences that represent the “best” estimate of the correct movement (Schmidt, 1975). This is then used for future
movements to help decipher correctness. This is accomplished by comparing the actual sensory feedback from the limbs to the expected sensory consequences (Glencross, 1993).

**Contributions:**

This theory has been beneficial in explaining opened-loop movements that occur in the absence of sensory feedback as well as closed-loop movements that use feedback. Since this theory is founded on the concept of a schema, it is also able to encompass a wide spectrum of different movements that exist within the same motor program. This theory was the first to objectively explain these problems and has since been very useful for the field of MSL.

**Limitations:**

A major limitation to this theory is that it lacks specificity. There are very few recognizable mechanisms of the general schema that can be tested (Shumway-Cook & Woollacott, 1995). Thus, it is not clear how a learner forms their first general motor program or how this program itself interacts with other systems.

Research on the variability of practice is another area that challenges Schmidt’s schema theory. According to the predictions of a schema, varying the ways in which one practices should increase learning and strengthen the general motor program. However, research to test this notion has been mixed. Shumway-Cook & Woollacott (1995) point out that this may be due to the age of the subjects. Some subjects were adults and others were children. The children may have adapted to the variability more easily and the results were thus misconstrued. They suggest doing more structured experiments in the future.
Newell’s Theory of Learning as Exploration  (1980)

Description:

This is one of the newer models that have been developed and it moves into the realm of the emergent properties approach. While drawing on both open and closed loop systems, Newell brings ecological motor theories into account (Shumway-Cook & Woollacott, 1995). He proposes that motor learning is a process that increases the coordination between perception and action in a way consistent with the task and environmental constraints (Newell, 1991). What this means is that we search for optimal strategies to help us perform a task in the most efficient way given certain environmental constraints. Part of this search for optimal strategies involves finding the most appropriate perceptual cues and motor responses for the task. Thus, the perception and action systems can be considered to be incorporated into an optimal task solution (Shumway-Cook & Woollacott, 1995).

Critical to the search for an optimal solution is the exploration of the perceptual-motor workspace (Shumway-Cook & Woollacott, 1995). This allows a person to identify the critical perceptual variables in the environment that are essential to optimal task solutions. Newell believes that perceptual information has a number of roles in MSL (1991). In a prescriptive role, it relates to understanding the goal of the task and the movements to be learned. Another role is as feedback, both during and after the movement.

Newell’s approach can be summarized by using an example of reaching for a glass. Repeated practice with reaching for a variety of glasses that contain a variety of substances within them, results in learning of the appropriate movement dynamics for the
task of reaching. But in addition, a person learns to distinguish what characteristics of the task we need to know to organize our actions. For example, we take note of the size of the glass, how full it is, how slippery the surface is and so on. Various sensory cues also play a role and help us to create optimal motor strategies (Shumway-Cook & Woollacott, 1995). For example, if a perceptual cue suggests a very heavy glass, we grasp with more force. If the glass is full, we slow up our speed and change our trajectory so as not to spill.

**Contributions:**

This model has helped to forge a link between our environment and its effects on MSL. “It emphasizes skill as a reflection of a dynamic exploratory activity, involved in the creation of the perceptual-motor workspace, which leads to optimal strategies for performing a task” (Shumway-Cook & Woollacott, 1995).

**Limitations:**

This is a very new theory. Shumway-Cook & Woollacott (1995) point out that is has yet to be applied to specific examples of motor skill acquisition in any systematic way. As a result, it is an untested theory.

**A Neuropsychological Theory of Motor Skill Learning (1998)**

**Description:**

This theory proposes that MSL is a direct outgrowth of motor control processes (Willingham, 1998). The relationship between motor control (planning and execution of movement) and motor skill learning (increasing spatial and temporal accuracy of movement with practice) is the basis for the theory’s name: COBALT-Control Based Learning Theory (Willingham, 1998). This theory applies three principles of motor
control to motor skill learning. The neural separability principle proposes that different cognitive processes of motor control are served by anatomically distinct parts of the brain. The disparate representation principle proposes that these different cognitive components utilize different forms of representation. Finally, the dual mode principle proposes that motor acts can be executed either in a conscious, effortful mode or in an unconscious, automatic mode (Willingham, 1998).

The neural separability principle describes four neurally separable processes. The first is the strategic process. It is used in selecting goals to create change in the environment such as swinging a bat so that a baseball flies into left field. (Willingham, 1998). The goal is the product of processes outside of the motor system and is based in the dorsolateral frontal cortex (Willingham, 1998). The second process is the perceptual-motor integration process. It is used in selecting targets for movement. In our example, it is the specific location you want the bat to swing to. According to this theory, a target is defined as a spatial location to which an effector (i.e. the bat) moves (Halsband, Matsuzaka, & Tanji, 1994). It is moved to this location with the help of the posterior parietal cortex (PPC). The PPC develops representations that serve as targets for end points of movements (Crossman & Goodeve, 1983). It is assumed that the representations of the end points are what guides movement control. The PPC does not by itself support all visually guided movements however. It gets help from the premotor cortex (Halsband et. al., 1994). Halsband et. al. (1994) summarize their roles nicely by saying the PPC works to select individual spatial targets while the premotor cortex contributes to movements to these targets. The third process is called sequencing. Essentially, a sequence of targets are assembled as a result of this process. It functions
through a neural circuit invoking the supplementary motor area. Information from the supplementary motor cortex travels to the striatum, goes through two major output stations of the basal ganglia (substantia nigra & globus pallidus), to the ventral thalamus, and then back to the supplementary motor area (Willingham, 1998). The result is a sequence message of movement that is sent to the spinal cord where the dynamic process occurs. This process works in conjunction with the primary motor cortex to innervate muscles. The primary motor cortex codes movements in terms of space (Scott & Kalaska, 1997). It then projects to interneurons in the spinal cord, which project to motor neurons, which innervate muscles. (Willingham, 1998).

The second principle of COBALT is the disparate representation principle. It supports the notion of three separate representations in motor control. The first is allocentric space for goal selection in the strategic process (Willingham, 1998). Research shows that much of the planning of motor movements occurs in spatial coordinates that exist in multiple forms within the brain (Willingham, 1998). Two of the most known forms are allocentric representations (objects locations are coded relative to one another) and egocentric representations (locations are coded relative to some part of the body). COBALT uses this knowledge to point out the difference between perception and motor behavior within the strategic process (Willingham, 1998). It suggests that allocentric representations support perception and are at a conscious level (Jeannerod, 1994). The egocentric representations support motor behavior and are not open to awareness (Livingstone & Hubel, 1988).

The second representation for motor control is target selection in egocentric space. Willingham (1998) points out that egocentric space depends on a coordinate system that
is centered on some part of the body. They go on to say that there is considerable
evidence that an egocentric representation is used by neurons in many of the cortical
areas known to support motor control. Thus, COBALT concluded that coding in the
primary and secondary motor cortices (including premotor cortex & dorsal and ventral
aspects of the secondary motor area) is in terms of egocentric space (Willingham, 1998).

The final representation of motor control is muscle innervation. The very fact that
movement occurs through muscle activity indicates that the central nervous system codes
movements as a pattern of muscle activity. Thus, spinal motor neurons clearly use a
representation of muscle activity (Willingham, 1998).

The final principle of COBALT is the dual mode principle. This proposes that all
voluntary actions are initiated by a conscious environmental goal (Willingham, 1998).
COBALT proposes that using the conscious mode has three consequences. First, the
environmental goal is coded not in allocentric but egocentric space. Second, the learner
is aware of the sequence of egocentric targets. Third, making the movements is more
demanding of attention than it would be if executed in the unconscious mode.
(Willingham, 1998). Thus, the conscious mode is used when a new motor task is
presented and much attention is needed to perform it correctly. However, as time passes
the task gets easier with practice and control switches to an unconscious mode (Logan,
1985). It should be pointed out that it is possible to engage the conscious mode at any
time. Most of the time, however, the less difficult the task the more the unconscious
mode is utilized (Willingham, 1998).

So how does all of this apply to learning? Two mechanisms can answer this
question: tuning and selection. In tuning for efficiency the perceptual-motor integration,
sequencing, and dynamic processes work similar to a parallel-distributed processing network (Willingham, 1998). Learning occurs if and only if a movement is executed. Feedback concerning accuracy is crucial to the learning process. All changes in performance are therefore small and operate in the unconscious mode (Willingham, 1998).

The selection of goals and spatial targets occurs in the strategic process. This too is important for learning. This process selects for effective high-level goals once a task is mastered and can sequence more effective spatial targets to maximize performance. All of this occurs via the conscious mode and helps us to direct our actions to perfection (Willingham, 1998).

Contributions:

This is an important step for MSL because it ties specific biological areas to the processes involved when mastering movement. It gives a direction for future research and a new model for developing experiments.

Limitations:

It is a very new theory that is yet to be tested. Also, it only addresses the spatial aspect of learning and does not take into account the temporal (timing) aspects (Willingham, 1998). This is one area that researchers must delve into in the future.
Summary

The ideas contained within this paper were presented with the purpose of providing a general overview of where the study of motor learning started, how it has changed, and where it is going today. Many forms of movement exist. There are genetic or inherent movements, reflex movements, and learned movements (skills). In the context of this paper an emphasis was put on learned movements in order to better understand the concept of motor skill learning. The first step towards understanding is accomplished by defining the term motor skill learning. Various definitions have been given to explain precisely what MSL is, although they vary slightly the underlying meanings are the same.

Much of this paper dealt with the historical approaches that influenced the study of MSL. Prior to the 1900’s research relied heavily on introspection. However, with the turn of the century, there was a shift to a more objective and systematic approach to the study of skills. This shift had a major effect on the field of psychology and it is here that early research on MSL took place. Woodworth in 1899, Thorndike in 1914, and Lashley in 1917 were major researchers who participated in this new approach to research. It has since been termed the task approach and it was prevalent from the early 1940’s to the late 1950’s. This approach had a functional behavioristic style and applied a very global viewpoint to complex skills. The task approach was deeply rooted in the dominant stimulus-response orientation that was popular in early behavioristic psychology and it focused mainly on the effects of variables on the performance of certain motor tasks (Schmidt, 1988).
The information-processing approach or the prescriptive-computational approach was most popular in the 1960's and is an approach that takes the computational metaphor quite literally. Glencross et. al. (1994) explain it best by pointing out that it functions in a top-down hierarchial manner in which a human receives, stores, retrieves, transmits, and monitors information so that they can perceive, think, and act. With the help of researchers such as Craik, a link was formed between communication, cybernetics, and human behavior. An emphasis on cognitive science and cognitive psychology was established and a framework was developed in which information is abstracted and processed by the brain in order to produce movements. Concepts of closed-loop, open-loop, and schema-governed learning were also mentioned in the context of this approach.

The dynamic or emergent properties approach was developed in the 1980's largely in response to the over-simplification of movement that the information-processing approach had fallen into. Mulder & Hulstyn (1984) point out that this approach broadens the perspective of MSL to encompass the concept of action instead of movement. Many are now trying to emphasize the importance of studying "total meaningful goal-oriented actions instead of isolated simple movements" (Mulder & Hulstyn, 1984, pp. 233). This is thought to provide a better picture of how events occur in unconstrained environments. This approach can be seen as heterarchial in which the direction of the control of movement is not unidirectional (top-down) but is distributed among a number of structures (Mulder & Hulstyn, 1984). It uses an executive system to help formulate action plans based on your perception of the events surrounding you and the action you want to perform.
The TOTE Model, one of a number of theories of MSL, was developed by Miller, Galanter, & Pribram (1960). It followed the information-processing approach and made an important step forward by integrating both closed and opened-loop systems. The operational mechanism they developed was the TOTE unit, an acronym for Test-Operate-Test-Exit. It is a feedback controlled servomechanism that can be used in motor skill acquisition (Glencross, 1993).

Fitts & Posner’s Stages of Motor Learning proposed that all skills are basically the same and a common set of principles can be used to describe them. They proposed three phases of motor skill learning: early, intermediate, and late (Schmidt, 1988). The early phase is a decision making phase during which the learner is experimenting with a variety of strategies to find the one that produces the best results. The intermediate phase is characterized by skill refinement achieved through practice. The learner has selected the best strategy for the task and uses it to enhance skill performance. The autonomous phase is characterized by motor performance that after considerable practice is largely automatic.

Adam’s Closed Loop Theory proposed that sensory feedback from the moving limb is used for the ongoing production of skilled movements (Adams, 1971). Adams proposed the concepts of a perceptual trace (trace of the correct action) and a memory trace (responsible for the actual production of the movement) to help a person create skilled motions. Adams (1971) summarized this by saying the memory trace initiates a movement and then the perceptual trace takes over to carry out the movement and detect error.
Schmidt proposed in his schema theory that each person has a recall schema and a recognition schema and that these two schemas contain a generalized set of rules for a specific class of movements. The recall schema functions similar to the memory trace proposed by Adams and the recognition schema functions similar to the perceptual trace. By creating a relationship between these two schemas, a learner can perform new movements and decipher their level of correctness.

Newell’s Theory of Learning as Exploration draws on both closed and opened-loop systems in order to incorporate ecological motor theories into his proposal. Newell suggested that motor learning is a process that increases the coordination between perception and action in a way consistent with the task and environmental constraints (Newell, 1991). A learner searches for optimal strategies by incorporating the most appropriate perceptual cues and environmental constraints into their motor responses for the task (Newell, 1991).

Willingham (1998) refers to COBALT, an acronym that stands for Control Based Learning Theory, in his neuropsychological theory of MSL. This theory applies three principles of motor control to motor skill learning. The neural separability principle proposes that different cognitive processes of motor control are served by anatomically distinct parts of the brain. The disparate representation principle proposes that these different cognitive components utilize different forms of representation. Lastly, the dual mode principle proposes that motor acts can be executed either in a conscious effortful mode or in an unconscious automatic mode (Willingham, 1998). All of these principles can be applied to two mechanisms within motor learning: tuning and selection.
Despite it's long history, the study of MSL is still in it's infancy. The previously explained theories have made individual attempts to explain the phenomena of motor learning but various shortcomings still exist both within each theory and within the field of MSL itself.

A major concern is the lack of collaboration that exists between past and present research. The theories presented here have not developed out of a direct progression in which past theories were the foundation of newer theories. In fact, only a few select bits and pieces of information were carried forward and mentioned in new theories. Schmidt's schema theory is one example of this. The notions of recall and recognition schemas were developed in part from the work done by Adams on the perceptual and memory traces. Newell's theory of MSL as exploration is another example where information from various theories was combined. Newell expanded on notions of perception in order to incorporate ecological effects into the process of motor skill learning.

Researchers in the field who have presented novel theories unrelated to previous work have been fortunate thus far. Their theories, formulated in what appears to be an isolated manner, have allowed the field of MSL to progress. Willingham's theory is a good example of this. By delving into the biological structures and innate wiring of MSL, Willingham started a new direction within the field. However, by incorporating older theories, Willingham's COBALT theory might have been strengthened.

In the future, the most productive approach will be to develop a model that takes all perspectives (behavioral, ecological, and physiological) into consideration. This can be achieved by utilizing better communication within the field.
References


