MOTOR SKILL ACQUISITION

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INTRODUCTION

Motor skills are usually distinguished from perceptual skills, cognitive skills, communicative skills, and other skill categories; but clearly these traditional distinctions have been made as a matter of heuristic convenience. As a consequence, skill categories reflect primarily differences in scholarly emphasis rather than mutually exclusive avenues of scholarly enquiry. The term
motor skills usually refers to those skills in which both the movement and the outcome of action are emphasized.

In this chapter I review certain of the major theoretical issues that have guided the study of motor skill acquisition during the previous 20 years or so. Noble (1968) provided the last related review in this series. An encompassing overview of a century of motor skill acquisition research is that of Adams (1987).

Traditionally, the study of motor skill acquisition is viewed as distinct from the study of the related subdomains of motor control and motor development. Motor learning originated as a branch of experimental psychology and was labeled accordingly to distinguish it from what used to be called verbal learning. The term motor control originated in physiology and was taken to represent the neurophysiology of the motor system. A behavioral focus within the study of motor control was initiated with the influential edited book of Stelmach (1976), which examined the processes that support the control of movement. Motor control has since become the predominant theoretical interest of researchers with a behavioral interest in motor skills. Furthermore, with physiology increasingly using macrolevel behavioral experimental strategies and psychology increasingly using more microlevel experimental strategies, it is becoming difficult to draw a line between the physiology and psychology of motor control—an issue Woodworth (1899) thought was irrelevant to the study of movement. In contrast, motor development has always been viewed as distinct from motor learning and motor control because it examined children’s motor skills and placed special importance on the study of phylogenetic movement patterns.

In this review I adhere to the traditional domain distinctions and focus on adult motor skill learning. This decision is made at some conceptual cost, however, because it is becoming increasingly clear that the three subdomains of study—motor learning, motor control, and motor development—hold considerable common theoretical ground (see Wade & Whiting 1986). The linkage among these heretofore distinct areas of movement research has been stimulated by contemporary theoretical developments regarding perception and action.

The motor skill acquisition domain also falls on the boundaries of instructional theory, especially with respect to the role that a change agent (such as a teacher, instructor, or coach) may play in facilitating the acquisition of skill. This area of study is sometimes called training, particularly in engineering psychology or human factors research. The contemporary study of motor skill acquisition has tended to deemphasize the role of instructional concepts, implicitly focusing instead on self-generated motor performance enhancement within a variety of contextual and task constraints.

The basic actions of posture, locomotion, and manipulation (and their
variations) allow the learner to engage in a variety of motor skills defined by a wide range of task constraints (e.g. those found in athletic, musical, industrial, military, self-help, and vocational contexts). Differences in task constraints have promoted the establishment of separate study domains in both theory and practice. Certain activities, such as those found in sport, tend to emphasize the natural whole-body actions of posture and locomotion, whereas other activities, such as those found in military man-machine contexts, tend to emphasize the manipulative activities of the hands, sometimes with the direct minimization (or even elimination) of the role of movement in the task. Models and theories of motor skill acquisition have tended, as a consequence, to be task and hence context specific. One theme of this review is that a general understanding of task constraints is necessary for the development of broad theoretical perspectives on the acquisition of motor skills.

Like many domains of study in psychology, motor skill acquisition has been influenced, albeit somewhat indirectly, by the information processing framework of the 1950s and 1960s and the subsequent development of general cognitive perspectives on action. Accordingly, I review the major contributions of these theoretical perspectives to some key issues in motor skill acquisition. These issues include: the applicability of a general law to motor skill acquisition; the question of what is learned as reflected in the acquisition of representations of action; and the role of information in motor skill learning. A more recent theoretical influence in motor skill learning research has been the ecological theory of perception and action. Once more relevant to the study of motor control, this theory now also applies to issues in motor learning.

Currently, there is no prevailing theoretical view of motor skill acquisition; indeed, there has not been one since Hull’s theory fell from favor during the 1950s. This chapter, therefore reflects the theoretical eclecticism of the last 20 years, but it also indicates significant issues that a general theory of motor skill acquisition must address.

A GENERAL LAW OF MOTOR LEARNING

Investigators of motor skill acquisition have continued to eschew all-incompassing theories of learning. However, the principle that skill learning is continuous has remained an important (although often implicit) general proposition. The established continuous functions created from the learning curves for perceptual-motor skills have been reexamined and compared with the learning functions for a range of cognitive skills. As a consequence of this synthesis, A. Newell & Rosenbloom (1981) have proposed that the power law function is a general law of learning. A contrasting perspective holds that the
power law is simply a special case of the general nonlinear integro-differential form of learning (Shaw & Alley 1985).

Motor Learning as a Power Law

It has been known since at least the study of Snoddy (1926) that performance time, when considered as the task criterion in perceptual-motor skills, tends to decrease with practice as a function of a power law. This finding has been replicated in a number of motor performance tasks. The most well-known example of the power law function for performance time is Crossman’s (1959) between-subject demonstration of the reduction in the operator’s cycle-time in making 10,000,000 cigars over a 7-year period.

A. Newell & Rosenbloom (1981) have discerned the power law function for practice effects in skills beyond those usually classified as perceptual-motor. Indeed, they showed that the general power law fits the practice data much better than exponential functions for a range of cognitive tasks in which performance time is the critical dependent variable. They explained the power law description of learning across tasks with a chunking model of information processing in skill learning, based in part upon Miller’s (1956) classic account of information capacity limitations.

The generality of the power law for practice over a range of performance tasks leads naturally to the proposal that it is a universal law of learning not limited to a particular behavioral subdomain; but several limitations of the power law interpretation must be addressed. First, the power law function is typically demonstrated in tasks where time is the dependent variable. There is little evidence of a power law for other motor performance variables. Second, a power law cannot accommodate practice effects where the task dependent variable is on an ordinal scale, such as producing a given set of relative motions. In this situation, the qualitative properties of the coordination mode may change from trial to trial, leading to discontinuous changes over practice time in performance measures. Third, even if performance changes on one variable (even the task criterion variable) as a power law, parallel qualitative changes may occur on other dimensions of performance.

These potential limitations of power law interpretations for both motor skill acquisition and learning in general have not been examined directly owing to (a) the narrow range of task constraints currently used to examine motor performance; (b) the fact that multiple dependent variables are rarely measured in motor learning studies; and (c) the fact that long-term practice studies are now rarely conducted, even in the motor skills domain. In spite of these reservations, the power law function for learning has gained a considerable foothold as the most robust and best-known feature of motor learning (Logan 1988; Salioni 1989). Indeed, Logan (1988) has remarked that any theory of motor skill acquisition that does not accommodate the power law function for learning can be rejected immediately.
The Power Law—A Special Case of Motor Learning?

A different approach is to view the power law for practice effects in perceptual-motor skills as a special case of learning. That is, in spite of the apparent generality of the power law for practice effects across tasks, studies have still only examined tasks in a narrow segment of the potential state space of learning. In this view, learning is discontinuous or nonlinear, and the constraints of the experimental tasks chosen for study have allowed only the linear portions of that state space to be reflected in the emergent motor performance. Thus, narrow task selection may have served to confirm the a priori theory of a continuous state space for learning that has been exemplified, for example, in information processing models of performance. In the same way, narrow theorizing may have confirmed the a priori selection of highly constrained perceptual-motor and cognitive laboratory tasks for examination. Theory construction and task selection in motor learning have been mutually supporting but limiting endeavors (Newell 1989; Newell et al 1989).

The traditional associative theories of learning (Guthrie, Hull, Thorndike), upon which early motor learning theories were predominantly based, causally specified cumulative continuous changes in behavior. The strength of the representation of movement, such as an S-R bond, was seen to change in a continuous fashion. The more recent motor learning theories of Adams (1971) and Schmidt (1975) have implicitly reiterated this position by accepting the gradual build-up, over practice, of the strength of their respective memory constructs for movement control. Thus the prevailing theoretical bias, together with the accompanying limitation of research tools that emphasize linear analysis techniques (Greeno 1974), has helped sustain continuity as the null hypothesis of the laws of learning.

Shaw & Alley (1985) have outlined, from an ecological perspective on perception and action, a discontinuous or nonlinear approach to considering the laws of learning. They treat perception and action as dual entities in the mathematical sense that the values assumed by the function for perception constrain the course of values assumed by the function for action, and vice versa. Learning is the lawful operation that increases the coordination between the perception and action functions. This proposition treats learning as a functional rather than a function because the learning-to-learn source of variance that coordinates the perception and action dual is a function of functions. Shaw & Alley draw on the field of hereditary mechanics to provide a physical analogy to model the dissipative nature of the learning functional and propose that it will prove to be nonlinear. Within this broader nonlinear view of the laws of learning, the continuous changes in motor performance are considered a special case.

The continuity-discontinuity controversy surrounding the laws of learning can only be examined empirically through consideration of a broader set of
task constraints than have been manipulated in traditional and contemporary motor learning studies. The tests to date of the laws of learning have been biased toward confirming the continuity hypothesis as a consequence of the few tasks selected (usually single-degree-of-freedom tasks, such as linear positioning) and the limited amount of practice conducted over a single session (often no more than 100 trials). These task and practice limitations typically require the subject to learn only the scaling of movement amplitude, movement time, or force output in an already established coordination mode (Newell 1985). Rarely studied are the qualitative shifts in the movement dynamics that occur early in the exploratory phase of practice, or the qualitative changes that occur late in practice as a function of the flexible and adaptive qualities of the skilled performer.

Examinations of Shaw & Alley’s (1985) proposal of nonlinear integro-differential learning functions for motor skill acquisition require an enriched perceptual-motor environment rather than an impoverished one. An enriched perceptual environment, following Gibson (1966, 1979), has several informational invariants available that could be utilized to organize a stable coordination mode. In the same way, an enriched action environment, following Kugler & Turvey (1987), has several coordination modes that may suffice to provide stable solutions to the task constraints. The mapping of the perceptual informational invariants to the movement kinetic invariants reflects the learning or search through the perceptual-motor workspace.

Shaw & Alley’s (1985) proposal emphasizes motor skill acquisition as the learning of the laws that map the dynamics of perception and action, rather than the memory intensive rule-based procedures that reflect what have been loosely called the laws of learning. No direct tests of the Shaw & Alley hypothesis have been conducted, although qualitative changes in the movement dynamics as a function of practice have recently been demonstrated in learning to write (Newell & van Emmerick 1989), throw darts (McDonald et al 1989), juggle (Beek 1989), and ride a ski-simulator (van Emmerick et al 1989). The examination of tasks with a richer perceptual-motor environment than provided by the traditional single-degree-of-freedom tasks (such as linear positioning) is likely to open the door to a more ecologically relevant description and explanation of motor skill acquisition.

As a contrast to Logan’s (1988) statement about the primacy of the power law, I suggest that a theory that cannot explain the qualitative discontinuous changes in movement dynamics with practice will lack generality. The experimental strategy of examining the discontinuities of practice effects will also afford an understanding of their continuities. Current evidence suggests that the reverse theoretical and empirical strategy, which has dominated the motor skill acquisition field for the last 100 years, has failed to offer general accounts of the laws of learning.
WHAT IS LEARNED WITH PRACTICE

A fundamental assumption of traditional and most contemporary theories of motor skill acquisition is that learning is a consequence of the acquisition of more appropriate representations of action. That is, the improved performance over time is due to the acquisition of prescriptions for action that specify the movement dynamics in relation to the task demands. In general, theoretical propositions about the representation of action have shifted over the last two decades from a one-to-one to a one-to-many relation between what is represented and the movement sequence that is produced.

One-To-One Recall-Recognition Processes

A major influence on the motor skill acquisition domain was Adam’s (1971) closed-loop theory of motor learning, which proposed a two-state representational scheme for the learning of self-paced positioning movements. One memory state was the memory trace, whose role was to select and initiate the movement. The strength of the memory trace was seen as a function of stimulus-response contiguity; it grew as a function of practice trials. The second memory state was the perceptual trace which was the image of the correctness of the desired movement; it was based upon prior experience of the sensory consequences (both exteroceptive and proprioceptive) of action. Each movement created a set of associated sensory consequences, and the distribution of these sensory consequences from practice trials formed a modal perceptual trace or memory reference for matching the task demands at hand. In single-degree-of-freedom positioning movements the memory trace had a limited role (what Adams called a modest motor program), and the skill in the task in essence resulted from the formation of an appropriate perceptual trace to evaluate the on-going sensory consequences of movement.

Adam’s proposal of two independent memory states for movement initiation and movement evaluation was based primarily on two considerations. First was the logical argument that error nulling closed-loop procedures could not occur if a single mechanism both initiated and evaluated the movement. This was because the sensory consequences of the on-going movement would always be compared against a representation of itself. Second, evidence in the verbal learning domain that recall and recognition could be independently manipulated by certain learning variables supported the proposition that these processes were based on independent memory states. The theory thus proposed dual one-to-one memory processes for the recall and recognition of movement.

Adam’s theory stimulated a number of empirical studies of the two-state memory proposal for motor learning in positioning tasks (Adams & Goetz
1973; Adams et al 1972). Other investigators branched out from the confines of slow positioning movements and examined the recall and recognition processes that support rapid short-duration movements, because such movements allowed a cleaner operational distinction between movement initiation and evaluation processes (Newell 1974; Schmidt & White 1972). These experiments demonstrated that the development of movement recognition processes over practice trials with knowledge of results (KR) paralleled those that had traditionally been found for movement recall processes.

A direct test of the two-state recall and recognition memory proposal for movement was conducted by Newell & Chew (1974). After sufficient practice with KR to develop the movement recall and recognition processes, withdrawal of visual and auditory feedback of the movement produced an immediate decrement in movement recognition but not in recall. This differential effect of the feedback variables on recall and recognition processes was taken as evidence for a two-state memory system for movement control.

The concept of independent recall and recognition processes for movement control was preserved in Schmidt’s (1975) schema theory of motor learning (see below). The direct empirical examination of the dual-state memory concept for motor learning did not, however, receive subsequent empirical attention. The general influence of the Adams’s (1971) theory of motor skill learning faded rapidly with the arrival of schema theory, in part because Adams’s theoretical contributions were largely encapsulated within the schema theory. Furthermore, theoretical emphasis in motor control switched from closed-loop to open-loop processes (Keele & Summers 1976; Schmidt 1976) where the role of recognition in both motor control and motor learning was downplayed.

The beginnings of the ecological approach to perception and action were introduced via a challenge both to the two-state concept and to representation accounts of action in general. Turvey (1974) proposed that the problems facing perception theorists and action theorists were very similar. Consequently, similar principles were needed for their solution that would probably prove indigenous to neither. Fowler & Turvey (1978) subsequently outlined a new approach to motor skill acquisition that was based on the emerging ecological perspective on movement coordination and control (Turvey 1977; Turvey et al 1978). A key principle of this perspective was that coordination is a relation defined over the organism and the environment, and that control is the exclusive prerogative of neither. This idea provided a major challenge to prescriptive theories that viewed motor skill learning as the accumulation of more appropriate representations of action, even if these representations were of the one-to-many variety, such as proposed by schema theories.
Schema Representation of Action

Schmidt’s (1975) theory of motor learning retained the independent recall and recognition mechanisms for movement advocated by Adams (1971) but gave them a generalized (one-to-many) memory construct through the concept of the schema. The schema is seen as a rule that represents the relations between variables rather than the absolute instantiations of the variables themselves. The schema is an old concept in psychology and neurology (e.g. Bartlett 1932; Head 1920) but its links to movement were indirect until Schmidt (1975) merged the intuitions of Pew (1974) on schema and motor learning with the two-state closed-loop theory of Adams (1971).

Two primary theoretical problems motivated the proposal for generalized memory states in motor learning (Pew 1974; Schmidt 1975). First was the storage problem; how many representations of motor programs and closed-loop references could the CNS store? Although this concern was used in support of the schema concept, there was no evidence on this issue. Second was the novelty problem; how could a given motor program in a one-to-one memory framework generate new movement configurations? The schema concept finessed these two theoretical problems. Generalizable schema rules reduced the representation demands on the memory system and provided the necessary principles to accommodate new aspects of movement dynamics.

In Schmidt’s (1975) theory the relative contributions of the recall and recognition schemata to movement output varied with the task constraints, but the recall schema clearly played a stronger role in determining movement output than in Adams’s (1971) theory. The strengths of the recall and recognition schemata were postulated to be built up over practice trials and feedback. The recall schema was based upon the past experience of the relations between the actual outcome and the response specifications. The recognition schema was based on the relations between the initial conditions for action, the movement-produced sensory consequences, and the actual outcomes (KR). The generalized rule allowed the production of so-called new movements within the class of movements for which the schema was established. A major limitation to examining the schema concept in terms of the acquisition, transfer, and retention of motor skill was that no principles were established about what represented a class of movements.

Schmidt (1975) proposed that the schemata rules became more representative of the movement class if a range of movement conditions were experienced in practice. This principle gave rise to the hypothesis that retention and transfer would be facilitated by variable practice in acquisition, because under these conditions the schema rule was both more impervious to decay and more generative in execution. The concept of variability was not limited here to the natural variability that a subject produces in movement dynamics over repeated attempts to attain the same criterion but, in addition, included
the variability that accrues from structured practice under a range of task conditions.

The evidence for the benefits of variable practice has largely come from single-degree-of-freedom positioning or timing tasks in which variations in the amplitude or movement-time task constraints were made in both training (usually KR acquisition trials) and transfer (often no-KR trials). For example, Newell & Shapiro (1976) showed that variable practice in a timing task facilitated transfer to a criterion movement time that was outside the range of the initial movement-time practice conditions. McCracken & Stelmach (1977) also found transfer benefits in a timing task from variable practice over a range of amplitudes in producing the criterion movement time. Other similarly designed studies have reported either weak trends for the benefits of variable practice in transfer (e.g. Wrisberg & Ragsdale 1979) or no effects at all (e.g. Zelaznik 1977).

The early evidence for the benefits of variable practice on the transfer of motor skill was not strong (Newell 1981). Some schema studies also tended to confound the manipulation of variability of practice with differences in the similarity between acquisition and transfer task criteria. This is a significant problem because similarity of task stimulus-response conditions is the cornerstone of most traditional accounts of motor skill transfer (Holding 1976). Shapiro & Schmidt (1982) have suggested that the evidence for the benefits of variable practice is stronger in young children than in adults. Certainly a number of motor learning studies in children have demonstrated the facilitative effects of variable practice on subsequent transfer performance (e.g. Kelso & Norman 1978; Moxley 1979), but no study has conducted a direct test of the interaction of age and variable practice.

It appears that the structure of the variable practice schedule is very important in determining the resultant benefits in transfer (Lee et al 1985; Lee 1988). Random practice at a range of task criteria affords better transfer than blocked practice over the same range of practice conditions. Lee (1988) has given a transfer-appropriate processing interpretation to these and related transfer findings. He posits that learning is optimal when the processing activities promoted by the practice conditions are similar to the processing activities required by the transfer test. This view shifts transfer away from the similarity of task stimulus-response properties to similarity of information processing activities—an interpretation concordant with recent attentional theories (not reviewed here) of the acquisition of skill (Schneider & Fisk 1983; Schneider & Shiffrin 1977; Shiffrin & Schneider 1977).

The process of schema formation is poorly understood. Schmidt (1975) and Keele & Summers (1976) assumed that the schema rule was based on the invariant relations of the movement dynamics, which were independent of the specific muscle groups involved. These invariant characteristics of a move-
ment sequence may not, however, require representation. Indeed, the demonstration of movement invariances in a range of tasks may be a reflection of emergent properties of some other level of organization of the motor system.

Motor learning needs to be reconsidered within a broader framework of how the learner solves the motor problem. This has been a general proposition of cognitive approaches to skill acquisition, but the topic has not been examined systematically from this point of view. The change in performance with practice needs to be examined on an individual-subject basis over individual practice trials. The analysis-of-variance approach to examining performance on blocks of trials does not sufficiently inform about the change in behavior. There have been few studies of the between-trial performance in discrete movement tasks.

Another schema view of action was outlined by Rumelhart & Ortony (1977), an extension of their schema theory for comprehension and knowledge representation. By virtue of its attempt to accommodate the transfer between subactions or classes of movement, Rumelhart & Ortony's theory provided the basis of a view of knowledge and action broader than that offered by Schmidt (1975). On the other hand, its strong roots in the comprehension domain led to its isolation from the motor skill acquisition community, and the theory failed to attract empirical or theoretical attention. A similar fate befell other schema-like cognitive theories either directly or indirectly concerned with motor skill acquisition (Anderson 1976, 1982; Arbib 1980; Norman & Rumelhart 1975; Rumelhart & Norman 1982). It remains to be seen in what way the connectionist approach to cognition will influence the study of human motor skill acquisition.

Problems with Prescriptive Accounts of Motor Learning

The theoretical perspectives on motor learning reviewed above are all prescriptive in the sense of having representational schemes at some level of analysis that prescribe the movement sequence in relation to the task constraints. Learning is viewed as the acquisition of prescriptions for action that will more appropriately satisfy the realization of the task goal. The fundamental differences among the preceding accounts of motor skill acquisition lie in the nature of the representations they posit, which are seen as reflections of what is learned with practice.

Prescriptive approaches to motor skill learning have been challenged on a number of different grounds over the last two decades. The primary challenge came from the emerging ecological approach to perception and action (Fowler & Turvey 1978; Kugler et al 1980; Kugler & Turvey 1987; Turvey & Kugler 1984). Central concerns have been the appropriateness of rule-based accounts of action and the logical difficulties of mapping symbols and dynamics in a principled fashion (Carello et al 1984). Advocates of the ecological
position seek the solution in the mapping of perception and action with minimal resort to intelligent operations. Where representation is invoked, it is to be fashioned from law-based dynamic accounts of perception and action rather than from a discrete nonholonomic (non-integrable) symbol system logically separate from the dynamics. This central concern with prescriptive theories of motor skill learning gives rise to a number of subsidiary problems.

Schema theories of motor learning cannot account for the acquisition of new coordination modes or movement forms. As Kugler et al (1980) noted, it is logically difficult for rule-based schema theory to account for the instantaneous production of quadruped-like locomotion by centipedes after all but two pairs of their legs are amputated. Expressed another way, where does the centipede’s instantaneous representation of a quadrupedal gait originate? In principle, the schema rule can only accommodate the new scaling of an established coordination mode, and even here, the logic for generalizability of the changing movement dynamics is questionable.

Prescriptive theories of motor learning also have trouble handling logically the compensations to perturbations of an ongoing movement sequence. How does a template-reference-of-correctness concept account for the instantaneous, anatomically distant-in-time-and-space, and functionally specific compensations evident, for example, in sudden and novel perturbations to the jaw in ongoing speech production (Kelso et al 1984)? Expressed another way, where does the closed-loop representation of correctness arise that enables compensation during novel and unexpected perturbation?

The challenge of the ecological position to extant prescriptive accounts of motor skill learning has undoubtedly weakened the influence of information-processing and cognitive accounts of motor skill acquisition in the 1980s. On the other hand, Adams’s (1971) theory was limited by design to a very narrow set of task constraints, and this narrowness was fundamentally the cause of its demise. The potential generality to motor skill acquisition of the Schmidt (1975) schema theory was considerably broader but it only stimulated empirical activity on the variability of practice issue. Thus, the Adams and Schmidt theories were already a waning influence in the motor skill acquisition domain by the time the challenge to the prescriptive views arrived.

**Motor Skill Acquisition as a Search Strategy**

Bernstein’s (1967) insights into coordination strongly influenced the development of the ecological approach to action. Bernstein (1967:127) viewed “the coordination of movement as the process of masterering redundant degrees of freedom of the moving organ, in other words its conversion to a controllable system.” The process of practice was characterized as the search for the optimal motor solutions to the problem at hand. It is important to note that practicing was seen as repeating the solving of the motor problem rather than repeating a particular solution to the problem.
Consistent with the Bernstein proposals, Fowler & Turvey (1978) interpreted skill acquisition as the search for the optimization of the coordination and control function of several variables. Search strategies reflect the way the perceptual-motor workspace is explored to “solve” the motor problem (Newell et al. 1989b). The perceptual-motor workspace is the interface between the relatively high-energy movement-kinetic field and the relatively low-energy information-kinematic flow field—an interface that arises from the complementary influences of the perception-action cycle (Kugler & Turvey 1987; Shaw & Alley 1985). Learning is the coordination of the perceptual environment with the action environment in a way consistent with the task constraints.

In this perspective, Gibson’s (1966, 1979) insights about the informational properties that organize the perceptual environment are extended to the complementary action environment. The dynamic organization of the perceptual-motor workspace can be examined through defining the layout of the gradient and singular properties of the perceptual-motor fieldlike spaces that support the macrolevel coordination pattern. The search through this workspace can be analyzed via established search and optimization procedures from biology (Gelfand & Tsetlin 1962) and physical systems.

The significance of this orientation for motor skill acquisition is that it promises to provide a principled way to accommodate the adaptive nature of the dynamics of movement control without resort to the computation-intensive procedures advanced by the prescriptive accounts of skill learning reviewed above. The theoretical and experimental challenge becomes one of identifying critical perceptual and kinetic variables that are being exploited to channel the search for the appropriate mapping of information and movement kinetics in the perceptual-motor workspace. The promise is that there are relatively global macrolevel variables of few degrees of freedom that organize the many microlevel degrees of freedom harnessed in support of action.

A central hypothesis of the search strategy approach (Newell et al. 1989b) to motor skill acquisition is that the learning, retention, and transfer of skill in different tasks is dependent on the similarity among the corresponding searches through the equilibrium regions of the perceptual-motor workspace, and relatively independent of the specific effector and manipulanda utilized. The role of search strategies in motor skill acquisition, both in tasks where the perceptual-motor workspace can be specified a priori (Krisnik & Shik 1964) and in the more natural tasks where the workspace can only be modeled post hoc, is currently being examined.

INFORMATION AND MOTOR SKILL ACQUISITION

Information facilitates the changes in motor performance that reflect learning. Different types of information are used in motor skill acquisition, and there
have been a number of theoretical interpretations of the role of information. This section is organized around three themes: information as a prescription; information as feedback; and information to channel the search through the perceptual-motor workspace.

**Information as a Prescription**

The prescriptive accounts of motor skill learning hold that information strengthens the development of the respective memory constructs for action. The development of task-relevant prescriptions for action can be strengthened through the presentation of prior-to-movement information that specifies the to-be-produced outcome and movement dynamics. Instructions or demonstrations convey this prescriptive information (Newell 1981; Newell et al 1985a). Recent empirical work has focused on the role of demonstrations in motor skill learning.

The general evidence in support of the facilitating effect of demonstrations in motor skill acquisition is not strong. This is in part because experiments have tended to use tasks already familiar to the learner. In effect, the information conveyed via the demonstration is often redundant to the learner’s task-relevant knowledge.

Bandura’s (1977, 1986) social learning theory has stimulated a systematic set of empirical studies on the role of demonstrations in motor skill learning. The theory offers a generative schema-like account of motor learning in which the spatial and temporal elements of the movement are symbolically coded through perceptual cues. The coding of the perceptual cues allows the development of the reference against which movement may be successively modified by appropriate feedback, and used for covert rehearsal techniques. Thus, in this view feedback information is only useful in learning when the appropriate movement reference has been developed.

Carroll & Bandura (1982, 1985, 1987) have examined aspects of these theoretical ideas in a series of experiments that required subjects to learn separate arm and hand postures with specific movements between postures as a function of different modeling and visual control conditions. The results have shown that visual feedback is not useful in the early trials of learning the postural sequences, but it facilitates learning subsequently in the practice sequence; delayed visual monitoring of the just-produced movement does not affect the acquisition process; and the stronger the movement representation (as determined by independent procedures) the more accurate are the subsequent recognition and reproduction of the action patterns. The use of a task that requires the production of a novel movement coordination sequence was instrumental in revealing these systematic effects of observational learning. However, early in practice, learners may not always be able to produce the new coordination mode demonstrated by the model (Martens et al 1976).
Movement related demonstrations can be made to the learner via sensory systems other than the visual system. Newell (1976a) and Zelaznik et al (1978) have shown that auditory demonstrations of the sound associated with rapid movements can effectively convey information about the task movement dynamics. Indeed, in these auditory demonstration protocols, subjects reduced their timing error over a series of practice trials in the absence of KR.

Demonstrations can also provide information about procedural aspects of the task demands that are not directly related to the movement dynamics. In a recent study of different types of augmented information in learning a video-game task, Newell et al (1989a) found that the demonstration of game procedural information was more effective in improving game performance over a 10-hr training period than information and specific practice on the isolated components of the movement dynamics. This finding reveals another way task properties mediate the nature of the appropriate information to support motor skill acquisition.

A major challenge for the motor skill acquisition domain is to understand the nature of the information conveyed in a demonstration. Bandura's (1977, 1986) social learning model fails to address this issue and, in effect, holds that all aspects of the movement dynamics are in some way coded in a memory construct. Schmidt's (1975) schema theory proposed that the relative motion invariances are stored in memory, but no perceptual recognition tests of this hypothesis have been conducted. A perceptual orientation to demonstrations that attempts to understand what information for action is conveyed by a model offers a new approach to this problem (Newell 1985; Scully & Newell 1986).

Information as Feedback

Information feedback is available to the learner both during the ongoing movement sequence (concurrent feedback) and on completion of the movement sequence (terminal feedback). In either case, information can be provided about the outcome of the movement (KR) and/or some aspect of the ongoing movement dynamics (sometimes called knowledge of performance). Information feedback can also be naturally available through the inherent properties of the task constraints, or it can be supplemented via augmented information (i.e. information not normally available from engagement in the task). The distinction between natural and augmented information feedback is not absolute and is inevitably task dependent. The working assumption of the feedback literature has been that the natural and augmented types of information feedback operate on the same principles, but no direct tests of this intuition have been conducted.

CONCURRENT INFORMATION FEEDBACK  There is a long tradition of studying the influence of concurrent information feedback on motor skill learning
(Annett 1969; Armstrong 1970). Many studies have demonstrated the facilitative effect of concurrent information feedback on motor performance. The contribution of information from the different sensory systems, whether it is inherent in the task or augmented, varies with the particular task constraints. The positive influence of augmented concurrent information feedback on motor performance is often negated once the supplementary information feedback is removed.

The Adams (1971) and Schmidt (1975) theories of motor skill acquisition incorporated concurrent information feedback into closed-loop accounts of motor learning. In both of these theoretical formulations the ongoing sensory consequences to movement were used in a closed-loop error detection and correction framework. The more information available from sensory channels the stronger and more representative was the development of the respective recognition memory state, which led to a better performance during both KR acquisition trials and when KR was withdrawn.

Adams et al (1972) proposed that the development of the perceptual trace for movement recognition allowed the movement to be executed accurately through concurrent information feedback without external informational support in the form of KR. The perceptual trace provided the evaluation of the movement internally—a process that Adams (1971) called subjective reinforcement. Adams et al (1972) provided evidence for this proposition by showing that positioning movements were more accurate, and that the learner was more able to evaluate the correctness of the movement, when all the sensory channels were available.

The question of what information is available from different sensory systems during movement was never addressed in the closed-loop accounts of movement control. This limitation, together with the increased emphasis given to centralist accounts of motor control during the 1970s and 1980s, contributed to the decline in the study of augmented concurrent information feedback. Concurrent information feedback can clearly have a potent impact on performance according to the task constraints and the nature of the information provided.

TERMINAL INFORMATION FEEDBACK The presentation of information on completion of the movement sequence has traditionally proved to have a very strong influence on motor skill acquisition (Adams 1971; Bilodeau 1966; Newell 1976b). KR of the outcome of the action has continued to be studied during the past 20 years, but there has also been a new emphasis on information about the dynamics of the just-completed movement.

Adams’s (1971) closed-loop theory of motor learning gave a strong role to KR as information in strengthening the two-state memory process. Both the recall and recognition states were postulated to be strengthened over KR
practice trials. Schmidt's (1975) schema theory proposed similar learning principles in regard to the necessity and contiguity of KR in motor learning. The informational interpretation of KR was examined by studies that provided direct tests of the processing of KR during motor learning.

Rogers (1974) examined the idea that different precision levels of KR should have differential effects on learning according to the minimal amount of time allowed the learner for processing the information during the post-KR interval. The findings from a micrometer positioning task showed that increased precision of KR up to some point facilitated learning, beyond which decrements in performance occurred. The most beneficial level of KR precision could be changed by varying the duration of the time for information processing during the post-KR interval. Thus higher levels of KR precision could be used effectively with more time for information processing. Similar manipulations have also shown that older children can more effectively utilize more precise levels of KR precision (Newell & Kennedy 1978).

Single-degree-of-freedom positioning or timing tasks do not require much time to process the relevant KR provided. For example, Barclay & Newell (1980) showed that children of 10 years of age only used about 1.5 sec in a self-paced post-KR interval of a timing task study. This finding demonstrates that the manipulations of the post-KR interval have generally been too long to induce information processing effects (Boucher 1974; Magill 1973).

The information processing hypothesis has also been tested by imposing secondary task activity during either the KR-delay interval or the post-KR interval. The basic rationale for this manipulation was that a competing secondary task restricts the capacity remaining for processing the KR. Boucher (1974) showed that reading 4- and 5-syllable words during the post-KR interval produced a detrimental effect in learning a positioning task. In contrast, Magill (1973) failed to find interference effects as a consequence of inserting counting backwards by 3s during the post-KR interval of an angular positioning task. Marteniuk (1986) showed that the influence information processing activity during the KR-delay interval depended on the relative difficulty of the task and the secondary activity. Thus, the findings in support of the information processing idea that the subject actively operates on the KR information are suggestive rather than decisive, and are strongly influenced by task properties.

The general interpretation of KR studies has been challenged by Salmoni et al (1984), who argue that learning effects for KR can only be inferred if the performance difference from practice with KR is sustained during a subsequent no-KR test phase, such as on a retention test. They have picked up on an earlier finding by Lavery (1962), who showed that while absolute frequency rather than relative frequency of KR presentation was the variable that determined performance level when KR was available, the reverse effect was
apparent when performance was subsequently examined over a series of no-KR trials. Using a number of experimental protocols, Schmidt and colleagues (Schmidt et al 1989; Wulf & Schmidt 1989) have provided evidence that the presentation of KR on every trial may not be the most effective KR schedule if performance is to be subsequently evaluated under no-KR conditions.

This proposal for the benefits of relative versus absolute KR effect probably only holds once the learner has produced a performance that is in the ballpark of the task goal. In other words, the intermittent schedule is more appropriate to the maintenance of performance than to the acquisition of new performance states. Furthermore, performance under no-KR conditions is only one possible scenario for transfer and retention tests and therefore should not be taken as the single measure of motor learning. The findings of Schmidt and colleagues clearly suggest some modification to the traditional interpretation of the frequency effects of KR. However, they do not require the formation of new laws of KR as proposed by Salmoni et al (1984).

KR is very effective in single-degree-of-freedom tasks or tasks where the scaling of a given coordination pattern is all that is required to satisfy the task constraints. The usefulness of KR to a learner in acquiring whole body actions, or in tasks where the learner needs to establish a stable coordination mode for the task at hand, has been increasingly questioned over the last 20 years (Fowler & Turvey 1978; Gentile 1972; Newell & Waiter 1981). In this situation the learner requires knowledge of performance, or information about the dynamics of the just-produced movement, in addition to KR of the outcome of the action.

Fowler & Turvey (1978) suggested that the information required in the feedback must contain as many degrees of constraint as there are degrees of freedom in the action to be coordinated. This proposal attempts to explain why the single degree of constraint provided by KR is sufficient in single-degree-of-freedom positioning or timing tasks. Newell & McGinnis (1985) suggested a framework by which to determine what information is required by a learner in a given task situation. This framework requires an understanding of the sources of constraint upon action, particularly the role of task constraints (Newell 1986). A number of experimental demonstrations of how task constraints determine the nature of information feedback required by the learner have been provided. It has also been shown that in many task conditions, the use of kinematic and kinetic information feedback facilitates motor learning and performance beyond those reached by means of the presentation of KR alone (Newell & Carlton 1987; Newell et al 1985b; Newell et al 1983, 1987).

The experimental study of kinematic and kinetic information feedback has been limited to one and two-degree-of-freedom task constraints. The
generalization of this framework to whole body multiple-degree-of-freedom tasks requires an increased understanding of the nature of what is being regulated in the coordination mode. Furthermore, it needs to be understood that both KR and knowledge of the just-produced dynamics are information feedback and only tell the learner what has happened in regard to the movement dynamics and the outcome. These forms of information feedback do not directly inform the learner about what and how the action should be changed on the next trial. This limitation upon information feedback is particularly evident when a change in the qualitative properties of the coordination mode is required. In this situation a different form of informational support for motor learning is required and is discussed in the next section.

**Information to Channel the Search**

Information in the ecological approach to perception and action is interpreted as the means via which the learner channels the mapping of information and movement dynamics in the perceptual-motor workspace in a way consistent with the task demands (Kugler & Turvey 1987). After Gibson (1966, 1979), it is assumed that the invariant properties of the environment act as information to guide the exploratory activity of the learner. These informational properties are qualitative in nature and attune the learner to the layout of the perceptual-motor workspace. One important aspect of perceptual learning is the continued differentiation by the learner of the properties of the perceptual-motor workspace. The natural learner-generated search of the perceptual-motor workspace can be supplemented with various forms of augmented information, as described previously, to facilitate the search strategy.

The idea of a natural search through the workspace by the learner is consistent with the traditional concept of discovery learning. The evidence suggests, however, that self-discovery does not always enable the learner to locate a task-appropriate mapping of information and dynamics in the perceptual-motor workspace. Furthermore, even on the occasions where self-discovery affords attainment of the task goal, the process of learning or the search behavior can be very inefficient.

Information can be used, therefore, to channel the search through the perceptual-motor workspace to locate a task-relevant solution to the coordination function. This theoretical framework involves a three-component consideration of augmented information and skill learning (Newell 1990). The first component is understanding the nature of the perceptual-motor workspace in terms of the attractor equilibrium and gradient regions. The second component is understanding the natural search strategies used by learners to explore the space. The third component is the application of augmented
information to facilitate the search. These three components are interdependent. This orientation provides a new look at the strengths and weaknesses of traditional prescriptive and feedback accounts of augmented information techniques.

Demonstrations provide some information about the nature of the desired equilibrium set of the perceptual-motor workspace, but they do not inform the learner how to navigate through the space to arrive at the task-relevant solution. In static analogy consider the problems of a traveler being given a map marked only with her current location and final destination. Furthermore, demonstrations do not accommodate the individual nature of the layout of the perceptual-motor workspace.

Information feedback, such as knowledge of results, only informs the learner of performance error in relation to the task criterion. This can be very effective when the perceptual-motor workspace supporting that activity is linear—a condition well approximated in the traditional laboratory tasks that produce the power law for learning. However, feedback cannot provide direct information about how one might search the nonlinear portions of the workspace to produce the qualitative changes necessary to realize new coordination modes.

It has been suggested that a new class of augmented information is required to promote systematic qualitative changes in the coordination mode (Newell et al. 1985a; Newell, in press). This information category was labeled transition information. In effect, this information acts as another source of constraint on action in anticipation of producing a qualitative change in the coordination mode. This kind of information should prove valuable in the early stages of acquisition where the learner is attempting to find a new stable equilibrium region in the perceptual-motor workspace.

Instructors of physical activities often provide this information through instructions. The beginning golfer, for example, may be told “Keep your elbow in.” The instructor does not intend the learner to keep the elbow in to this degree after she has attained the desired coordination configuration. Rather, this informational constraint acts as a control parameter to change the configuration of the coordination mode. Thus the nature of the information required by the learner seems to depend on the stage of learning. This interaction has not been examined.

Perceptual-motor skills in context have rich sources of information available, but the traditional operational strategy in motor skill acquisition experiments has been to strip away from the learner the support of this information and construct impoverished environments in which skill learning is to take place. This experimental strategy has burdened the learner by providing the constraints to learning. The result has been an emphasis on cognitive operations. The emphasis of the ecological approach to information and motor
learning is intimately tied to understanding the natural dynamics of the perceptual-motor workspace.

CONCLUDING REMARKS

The information processing and cognitive frameworks have had considerable impact on concepts of motor skill acquisition domain over the last two decades. In many respects, however, this influence has been indirect. The information processing approach has been concerned primarily with performance, not learning. It has emphasized the processes that support performance. Only the attentional accounts of skill learning (not reviewed here) have treated issues of direct relevance to the changes that occur with practice.

The information processing approach has also given little or no emphasis to the question of what information is processed in motor skill acquisition. The focus has been on the how of information processing, with no direct examination of the informational support required from the learner. The schema view of motor learning promised a new way to examine the role of information in skill learning but failed to stimulate any empirical activity on this important topic. The revival of interest in learning from a cognitive perspective during the 1980s has largely been oriented to so-called cognitive tasks.

The strong influence of task constraints on motor skill learning is a key point to emerge from the foregoing synthesis. It is usually accepted that skill is specific. This conclusion may arise from the fact that even small changes in the experimental task constraints can lead to large changes in the performance of the learner. The ecological approach to perception and action has offered the beginnings of a new way to consider task analysis: in terms of the perceptual-motor workspace.

The traditional approaches to motor skill acquisition have failed to capture many of the dynamic qualities of the stages of motor skill acquisition exhibited by novice and expert performers. Skill is a reflection of a dynamic exploratory activity, not the stereotypic reproduction of a static representation of action. Current views of skill learning, such as those embedded in a power law view, have failed to capture the richness of the essence of skill and the fullness of the constraints that shape it. The effort to understand the ecologically relevant aspects of task constraints, in relation to the dynamic interface of information and movement, opens the door to a more general theory of motor skill acquisition.

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