Differing Perspectives in Motor Learning, Memory, and Control
D. Goodman, R.B. Wilberg, and I.M. Franks (Editors)

COORDINATION, CONTROL AND SKILL

K.M. Newell

Institute for Child Behavior and Development
University of Illinois at Urbana-Champaign
Champaign, Illinois
U.S.A.

In this chapter, I develop the interpretation of coordination, control and skill sketched by Kugler, Kelso and Turvey (1980, 1982). The orientation promoted here is primarily descriptive with the focus being the development of a framework for a useful operational distinction between the three terms. I believe one can draw on the interpretation of coordination, control and skill outlined by Kugler and colleagues without necessarily invoking the theoretical position advanced by this group, although it will become clear as this chapter unfolds, that I am sympathetic to this theoretical position.

The terms coordination, control and skill are routinely used interchangeably in both the lay and scientific literatures of human motor skills. For example, reference is often made to a performer in a given activity exhibiting fine control, showing good coordination and being highly skilled; yet the distinction between the terms coordination, control and skill is not apparent. Furthermore, perusal of the many academic texts on motor skill learning and motor control reveals a disparity of perspectives on the meaning and significance of these three concepts to the extent there are virtually as many definitions as sources. This inconsistency exists both within a given level of analysis of action (e.g., behavioral) and in a consideration between levels of analysis, such as behavioral and physiological. Thus, it is not surprising that different domain labels exist, although the traditional distinctions between domain labels are less apparent than they used to be. The experimental psychologist traditionally although not exclusively alludes to motor skills or motor learning, whereas the neurophysiologist typically refers to motor control.

Many aspects of the operational interpretation of coordination, control and skill that is developed here are not new, but a full statement teasing out the significance of the relationships between these terms has not been forthcoming to date. The operational distinctions advanced between coordination, control and skill also provide a basis to examine these same phenomena at different levels of analysis in the study of action. This seems particularly appropriate as the psychological orientations to action recognize and incorporate concepts and methods from behavioral physiology (cf., Gallistel, 1980).

To date, most behavioral definitions of skill reflect emergent properties of skilled behavior rather than relate directly to the organizational properties of the motor system in skilled performance. For example, Guthrie's (1935, p. 162) useful definition suggests "skill consists in the ability to bring about some predetermined results with maximum certainty, and the minimum outlay of energy, or time, or of time and energy." Similar characterizations of skill have been advanced by many scholars including; Knapp (1963), Johnson (1961) and Whiting (1975).

A view of skilled behavior tied more directly to concepts from motor control is long overdue and it is the focus of this chapter to bridge this gap. In addition, and by way of setting up the readers for the essence of the closing sections of the chapter, it is proposed that the operational framework outlined here, opens up new ways to reconsider old problems in motor skill learning. In particular, the influence of many traditional learning variables on the acquisition of skill will be reexamined.

The motor learning domain has become rather stagnant of late with little theoretical or empirical activity being undertaken. The last major theoretical statement on skill acquisition was the schema theory of motor learning (Schmidt, 1975), but operational interpretations of this theory have been confined to the impact of variability of practice on the scaling of an already established pattern of coordination. Although general interest in the related domains of perception and action is on the increase (cf., Michaels & Carello, 1981; Turvey, 1977), perusal of the motor learning literature of the last 5 years reveals very little work on the problem of skill learning per se. Hopefully, linking the traditional issues of skill learning with current views on coordination and control will stimulate new and exciting lines of scholarly enquiry.

Before moving on to the discussion of coordination, control and skill a disclaimer is in order. The skill framework advanced appears to be more directly relevant to discrete and serial tasks than to an assessment of continuous tasks. The isolated elements (discrete tasks) that form part of continuous activities such as driving a car, flying an aeroplane and playing videogames can certainly be related to the coordination, control and skill framework. However, continuous tasks usually involve some strategy which overrides the importance of any single example of coordination within the context of the activity. The framework proposed does not address directly the issue of strategy although clearly it is an important element of skilled performance.

COORDINATION, CONTROL AND SKILL (after Kugler et al., 1980)

The interpretation of coordination, control and skill offered by Kugler et al. (1980) owes a large debt to the thinking of the Russian physiologist Bernstein. Many of the ideas of

Bernstein were only available to the Western world as a consequence of the publication in 1967 of a collection of his previous writings under the title of "The co-ordination and regulation of movements". Turvey, Kugler and colleagues (e.g., Kelso, Holt, Rubin, Kugler, 1981; Kugler, 1983; Kugler et al., 1980; Turvey, 1977; Turvey, Shaw, & Mace, 1978; Turvey & Kugler, 1984) together with Greene (1972; 1982) have done much to promote and develop the ideas advanced by Bernstein on problems of coordination and action.

Bernstein (1967, p. 30) considered coordination to reflect an activity which guarantees that a movement has homogeneity, integration and structural unity. Specifically, "the coordination of a movement is the process of mastering redundant degrees of freedom of the moving organ, in other words, its conversion to a controllable system" (p. 127). In short, coordination is the organization of the control of the motor apparatus.

Kugler et al. (1980) have built on Bernstein's formulation and suggested a distinction between the terms coordination, control and skill. Briefly, this distinction is as follows:

Coordination is the function that constrains the potentially free variables into a behavioral unit. The basis of this function is a set of variables:

$$(A, B, C, \ldots. X, Y, Z)$$

These variables may be constrained into a coordination function:

$$f\ (A, B, C, \ldots. X, Y, Z)$$

Control is the process by which values are assigned to the variables in the function, i.e., parameterizing the function.

$$f\ (A_i, B_j, C_k, \ldots. X_r, Y_s, Z_t)$$

Skill requires that the optimal value be assigned to the controlled variables.

The variables in the coordination function may be categorized into essential and non essential variables. The essential variables determine the coordination function's topological qualities whereas the non essential variables produce changes in the scalar values of the function. The distinction between essential and non essential variables is not fixed because outside of a certain magnitude range the classification of the variables may change or even reverse. Thus in the Kugler et al. (1980, 1982) formulation the distinction between essential and non essential variables is a pragmatic distinction rather than a formal mathematical distinction.

The nature of the variables in this function is, of course, one of the fundamental unknowns in the theory of action. Probably every level of analysis from cells to limbs, and even the kinematics of limb trajectories, has at one time or another been postulated as providing an appropriate language for the coordination function (cf. Easton, 1972; Klapp, 1978; Schmidt, 1975; Selverston, 1980).

OPERATIONAL FRAMEWORK FOR COORDINATION, CONTROL AND SKILL

The distinctions advanced by Kugler and colleagues between the three terms, coordination, control and skill, are useful in theorizing about action although to date we are no closer to understanding the language of the coordination function. It is appropriate, however, to develop concepts about the behavioral unit (or activity) independent (for the present) of theoretical advances regarding the language of the coordination function. Indeed, activities may be understood behaviorally by an operationalization of the terms coordination, control and skill through insights from both the visual perception of biological motion (cf., Cutting & Proffitt, 1982; Johansson, von Hofsten, & Jansson, 1980) and efficiency (Sparrow, 1983) literatures.

Recent work in the visual perception of biological motion has implicated the priority of relative motion over absolute motion in identifying many types of events (Cutting & Proffitt, 1982; Johansson et al., 1980). Specifically, it appears that the topological properties of the relative motion of the body and limbs specify the perception of a given activity. In other words, the natural nominal categorization of activities is determined by the invariant characteristics of the relative motions of the body and limbs. Indeed, by elaboration, it may be proposed that each physical activity is defined behaviorally by a unique set of topological properties of relative motions.

Although limited data support this proposition, some evidence toward this view has been provided by Hoenkamp (1978). He conducted a simulation experiment in which adult observers labeled computer generated stick figures which mimicked various patterns of human locomotion. In the basis of the observer's perceptions, Hoenkamp claims that it is the ratio between the time that the lower leg takes to swing forward and its corresponding return motion that determines the labeling of human gait patterns such as walking, running, skating and limping.

Figure 1 shows the saw-tooth function of the lower limb relative motion that specifies the labeling of the gait action. Changes in the break point of the saw-tooth specify the gait pattern with ratios of .9, .6 and .4 reflecting running, walking and skating, respectively. Interestingly, observers rely on the relative motion of the gait pattern for labeling a style of locomotion regardless of the average transport velocity. Furthermore, this situation pertains irrespective of the maintenance of foot contact with the ground which is a constraint specified by track and field authorities for distinguishing race walking from running.

Todd (1983) has recently questioned some of Hoenkamp's (1978) assumptions regarding the distinctive characteristics of the simulated leg motion, but the hypothesis that activities are defined behaviorally by a unique set of topologies of relative motions remains a viable and testable proposition.

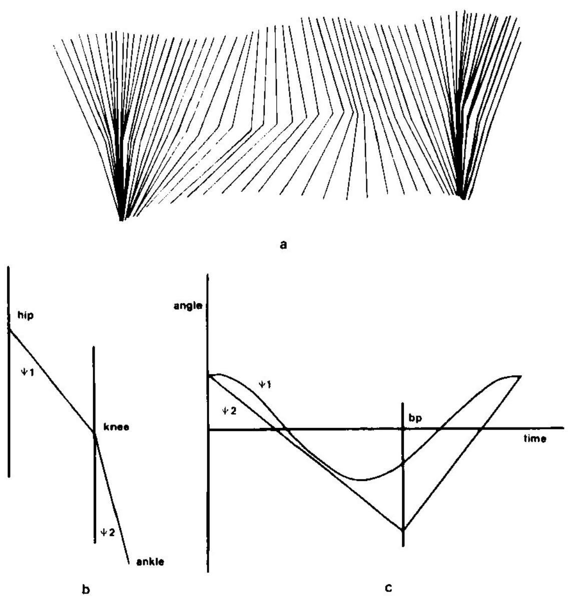

Figure 1. Schematic of leg movement during locomotion: a) recorded movement; b) convention for the measurement of the angles; c) variation in time of the angular displacement of the upper and lower leg during the limb cycle (adapted with permission from Hoenkamp, 1978, Journal of Human Movement Studies).

It is possible then to elaborate from the visual perception literature (Cutting & Proffitt, 1982; Johansson et al., 1980) and propose that coordination for a given activity may be operationalized by the topological characteristics of the relative motion, leaving control as the scaling or absolute level of a given relative motion. Shapiro, Zernicke, Gregor and Diestel (1981) provide a nice example of the scaling of a relative motion in their gait analysis of human walking and running at different velocities of locomotion (see Figure 2a). The relative motion of the angles of the thigh and knee in the sagittal plane was invariant in the face of increments in the velocity of locomotion. The fact that this topology was preserved over changes in gait pattern implies, consistent with Hoenkamp's (1978) emphasis of lower leg action, that the relative motion of the joints controlling the upper leg is not the unique topological characteristic distinguishing walking and running. Figure 2b, drawn from a study by Cavanaugh & Grieve (1973), depicts a similar scaling of upper leg motion in climbing stairs of different heights.

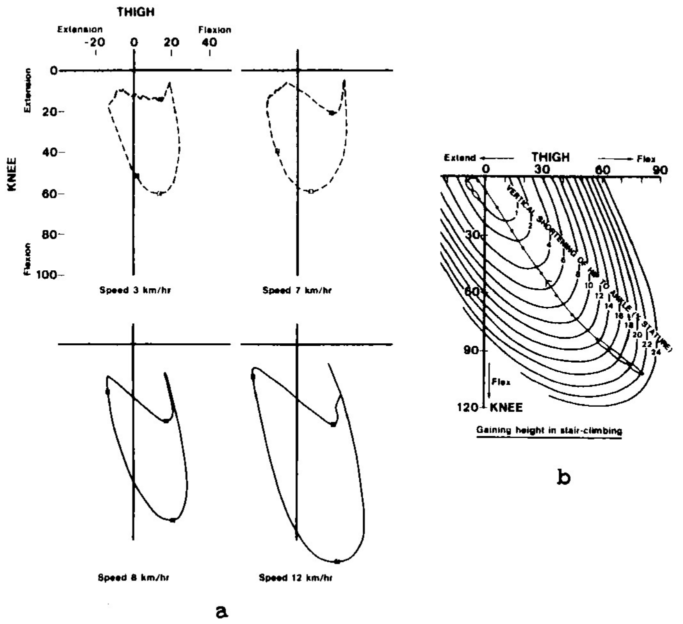

Figure 2. (a) Angle-angle diagram of knee-thigh relationship during the step cycle at 4 different speeds of locomotion (adapted with permission from Shapiro et al., 1981).
(b) Angle-angle diagram of knee-thigh relationship in climbing stairs of increasing height (adapted with permission from Cavanaugh & Grieve, 1973).

The examination of the topological characteristics of movement during action has largely been confined to cyclical activities such as locomotion (see also Chapman & Medhurst, 1981; Charteris, 1982; Grieve, 1969; Hershler & Milner, 1980a). However, topological properties of action emerge from the relative motions even during short duration discrete actions, although there are fewer examples of this in the literature. Figure 3 plots the relative motion of the left wrist and left elbow angle of baseball batters of different skill levels during the batting swing (drawn from McIntyre & Pfautsch, 1982). One can observe from this figure that the relative motion is invariant regardless of skill level of the hitter. What changes between ability groups in this study is the range of motion with the more skilled batters having a greater range of motion within the common topological structure.

In general, however, it is unlikely that common topological properties of the emergent kinematics will exist between performers with widely different skill levels, given Bernstein's observation that skill is the mastery of redundant degrees of freedom of the organism during action. This is particularly the case if one compares beginning performers attempting to learn the set of relative motions which define the appropriate pattern of coordination with highly advanced performers attempting to refine the scaling of the coordination function. Thus, whether topological shifts occur in the kinematics with practice will be largely dependent upon the stage of learning of the performer for the task at hand.

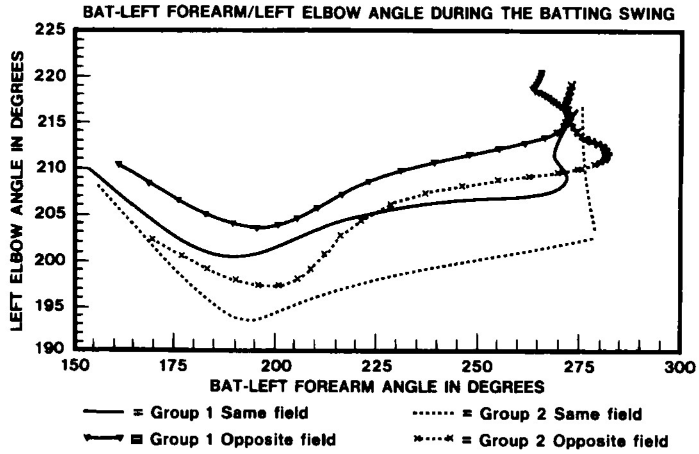

Figure 3. Angle-angle diagram of the elbow-forearm relationship during the baseball batting swing as a function of skill level and placement of baseball hit (adapted with permission from McIntyre & Pfautsch, 1982).

Topological characteristics of kinematics emerge regardless of whether the activity is cyclical or not. The limiting factor for the examination of the topology of relative motion of limb links is that the task requires the performer to constrain two or more biomechanical degrees of freedom (see Turvey et al., 1978 for an exposition of Bernstein's degrees of freedom problem). Only in such tasks can the topological characteristic of a relative motion remain invariant under transformations of scale. These biomechanical degrees of freedom may form a topological function within a biokinematic chain of links of a single limb such as an arm or leg and/or these properties may be apparent between limbs. One can, of course, also observe topological properties other than those of relative motion in the kinematics of single degree of freedom tasks.

The invariant relative movement characteristics are usually considered in 2-dimensional plots of limb position changes for a given activity. However, Beuter (1984) has utilized a 3-dimensional technique to examine the topological characteristics of three joint angles (hip, knee and ankle) during locomotion. These same techniques may be applied to higher order derivatives of a given position-time function so that, for example, the topological relationship of the relative velocity of two or more limb segments may be examined (e.g., Soechting & Lacquaniti, 1981). A review of the use of topological dynamics as a technique to prescribe and describe movement may be found in McGinnis & Newell (1982).

An important issue that remains to be resolved satisfactorily in topological analysis of movement is the method by which topological kinematic characteristics are formalized. In the preceeding examples, the researcher has relied on "eyeballing" to determine whether or not a topological characteristic was invariant in the face of transformations of scale (e.g., the discussion of the Shapiro et al. locomotion data). However, there have been attempts to provide formal mathematical solutions to the problem. Hershler & Milner (1980b) have proposed the dimensionless geometric solution of the ratio of the perimeter to the square root of the area of a given relative motion. In contrast, Whiting and Zernicke (1982) have outlined a correlational technique based upon pattern recognition procedures. While both of these techniques provide a formal basis to determine the similarity of relative motions, neither technique outlines a decision making criterion regarding nominal categorization of relative motions.

The measurement of kinematic topological properties is not a new problem in principle as it is an integral feature of the more general issue of categorical perception (e.g., Proffitt & Halwes, 1982). However, the examination of topological characteristics of motion represents a rather new problem for the movement domain. Traditionally, the movement domain has confined itself to the quantitative analysis of ratio movement scales (e.g., amplitude, velocity, etc), so that it has rarely had to address the qualitative problem of nominal categorization in movement analysis. At this point in time, it would seem that natural observation of the movement topologies is both viable (cf., Cutting & Proffitt, 1982; Johannson et al., 1980) and sufficient given the current level of theorizing regarding the coordination problem. The appropriate technique to utilize, however, may well depend upon the theoretical question at hand.

The majority of tasks utilized in the study of motor learning, require only the scaling of an already established coordination function (Newell, 1981). For example, linear slide tasks do not require subjects to acquire a new pattern of coordination. Similarly, the pursuit rotor, which was the primary task utilized in motor learning research in the 1940s and 1950s, merely requires the scaling of an already established configuration of relative motion. In short, the tasks typically employed to study motor learning by definition cannot address the problem of the acquisition of coordination.

The study of coordination has largely been confined to phylogenetic activities such as locomotion (e.g., Grillner, 1975) or other already established patterns of relative motion (e.g., Kelso, Southard, Goodman, 1979). It is only in the developmental literature (cf. Roberton, 1982) with the observation and charting of so-called motor stages that coordination has been studied with respect to the acquisition of skill. However, the motor development literature has failed, in the main, to address the coordination problem directly and descriptions of the developmental motor sequences have been confined to imprecise accounts of the movement kinematics. The preceding analysis of coordination, control and skill suggests that the identification of stages or steps by researchers charting the milestones of children's activity development is probably a reflection of the perception of a unique set of topological charateristics of relative motions (Kugler et al., 1982; Newell & Scully, 1984). A topological analysis of so-called developmental sequences might help clarify their significance to theoretical notions of the acquisition of coordination in action.

Thus, from a behavioral perspective, the relative motion and scaling characteristics of body and limb kinematics may define operationally the distinction between coordination and control, respectively. This distinction becomes very important in the acquisition of tasks requiring the constraint of more than a single biomechanical degree of freedom which is, of course, the situation in the majority of phylogenetic and ontogenetic activities.

The optimal parameterization of the coordination function, which reflects skill within the Kugler et al. (1980) framework, is somewhat more difficult to operationalize. This is in part due to the limited understanding of optimization criteria in physical activities and, the fact that measurement categories other than kinematics need to be invoked (Hatze, 1976, 1983). The measurement of certain biological systems during skill acquisition is essential to an understanding of optimization and efficiency in biological motion. Biological systems involved in energy conservation would appear to be prime candidates for a consideration of coordination beyond the confines of limb and body kinematics (Kugler et al., 1980, 1982). Indeed, one might elaborate from the behavioral definition of coordination to suggest that the optimal parameterization of the coordination function will also dictate a certain unique set of phase relationships between the cyclical characteristics of different biological systems, in addition to, the topological characteristics of the resultant kinematics.

Consistent with this proposition, Bramble and Carrier (1983) have demonstrated a coupling of the respiratory cycle and the gait pattern in efficient locomotion. This relationship changes with different task constraints, such as the speed of locomotion, and with the animal species under consideration. For example, quadrupeds have a tight 1:1 coupling between respiratory cycle and stride frequency whereas man can adopt a wider range of coupling ratios between these cyclical events. Few studies have examined the manner in which the phase relationships of certain biological systems and kinematics change with the acquisition of skill in a given activity.

The concept of efficiency is central to the optimal parameterization of the coordination function and may even be some a priori organizing principle of coordination and control, rather than its usual characterization as a post hoc reflection of skilled performance (cf., Sparrow, 1983). Efficiency is normally defined as the ratio of work done to energy expended and, as implied in Guthrie's (1935) behavioral analysis of skill, is reflected in work and energy related variables. Although indices of energy expenditure appear difficult to obtain in sedentary manipulative skills, the theoretical significance of the principles of optimization and energy expenditure should not be forgotten in consideration of any activity and set of task constraints (see also Nelson, 1983).

Obviously the nature of the task contributes to a determination of the optimization criteria. Typically, a performance criterion is either minimized or maximized. These criteria may be explicit in terms of the goal of the task or implicit due to the additional constraints of both the organism and environment.

In many activities, such as gymnastics and highboard diving, the task rules specify or constrain the pattern of coordination to be produced. In track and field, on the other hand, events have been contrived for which the optimal pattern of coordination for body and limbs given the task constraints has yet to be established (e.g., pole vault, see McGinnis, 1984). Tradition and local wisdom assume that phylogenetic activities such as walking reflect the optimal configuration of relative motions for the given task constraints, but optimization techniques and human ingenuity may reveal otherwise. Optimization criteria are derived from a thorough understanding of the interaction of constraints from the organism, environment and task; in principle, these constraints will determine the optimal coordination and control for a given individual in a given activity.

Numerous studies have used a minimal principle to model human gait (e.g., Beckett & Chang, 1968; Hardt, 1978). In many of these studies, work or some measure of muscular effort is minimized, and the optimal solution compared to empirical evidence to determine if the human body moves in an optimal manner. Sometimes performance is maximized, such as in the velocity of a golf swing (Lampsa, 1975) and the height of vertical jumping (Levine, Zajac, Zomlefer, & Belzer, 1980). Thus optimization is reflected in both minimization and maximization of a criterion.

Optimization procedures do not lead to a general solution, but rather to an individual specific optimal solution, based upon the individually tailored constraints included in the optimization model. To date, optimization modeling has been largely confined to a consideration of mechanical constraints. However, mechanical constraints are clearly not a sufficient criteria for optimization in biological systems, although they represent an important beginning to this effort. Principles of optimization need to be considered in determining the most appropriate pattern of coordination and subsequent scaling of the relative motion of body and limbs for the activity at hand.

It should be apparent from the above synopsis that the principle of optimization is central to motor skill acquisition, because it provides the necessary basis against which the process of learning and the impact of learning variables can be understood. By and large, the traditional learning theory approach to skill learning has failed to recognize the significance of optimization principles to human action. In effect, the learning theory orientation has been neutral with respect to biological constraints and their significance for human action (cf. Adams, 1971; Schmidt, 1975; Thorndike, 1927).

IMPLICATIONS OF THE SKILL FRAMEWORK FOR THE MOTOR LEARNING DOMAIN

The theoretical and operational relationships advanced among coordination, control and skill in action have many implications for the study of motor learning. I believe the perspective outlined above leads naturally to different operational approaches to the study of skill learning than those typically in vogue in the domain. In the remainder of this chapter, a number of issues in motor learning are examined from the perspective developed above on coordination, control and skill.

Stages of Learning

An important implication of the preceding analysis is that the concepts of coordination, control and skill reflect an embedded hierarchy. This implies that the early stage of motor learning primarily consists of acquiring the appropriate (optimal) topological characteristics of the body and limbs. Further practice leads to refined scaling of the relative motions with optimal scaling reflecting a skilled performance. Coordination does not precede control but rather coordination is the organization of control (Bernstein, 1967). However, the acquisition of the structural or behavioral unit requires the development of the appropriate set of relative motions.

It has already been argued that the task structure typically utilized in motor learning has eliminated the acquisition of coordination as a problem for study. Furthermore, and despite the domain label "skill learning," the phenomenon of skill has not been studied either, because a single 100 trial learning session is surely insufficient for a performer to approach optimal performance. Indeed, the cigar rolling study of Crossman (1959) suggests that factory worker's performance had not asymptoted even after 10 million trials spread over 7 years. There seems to be a renewed interest in expert behavior (cf., Anderson, 1981) and the skilled performer (e.g., Shaffer, 1980), but generally it would appear that the domain of motor skill learning has failed to study skilled performance.

Various accounts of the stages of motor learning have been advanced previously (e.g., Adams, 1971; Fitts, 1964; Gentile, 1972). These formulations all focus on the changes in so-called cognitive activity associated with the improvements in motor performance with practice over time. Although the Kugler et al. (1980) theoretical orientation to action is very different from the traditional cognitive lines of theorizing, the description of coordination, control and skill advanced is not inconsistent with these descriptions. A key difference worth emphasizing, however, is that the Kugler et al. framework explicitly addresses the problem of coordination and, therefore, is directly relevant to the emergent response dynamics. Previous accounts of the stages of learning have not addressed these issues.

Similarly, most previous accounts of skill learning have failed to consider sufficiently (even on the few occasions where it has been mentioned) the significance of biological constraints to action. One outgrowth of an appreciation of organismic constraints is the realization that even kinematic analysis is insufficient to understand fully the nature of coordination, control and skill in action (e.g., Bramble Carrier, 1983). While secondary task techniques have examined the degree of effort associated with performance and, even learning on occasions (e.g., Kahneman, 1973), an understanding of the role of various biological systems in action, such as the energy conservation systems, awaits examination.

Motor Tasks

It is evident that the narrow focus of study in the domain of motor skill learning has been in part a consequence of the motor tasks utilized. The general claim is that performance in tasks such as line drawing is easy to measure, and that the novelty of the task constraints ensures learning, in the sense that performance changes toward the task criterion will occur with practice. The legacy for this situation dates back at least to the early psychophysical examinations of movement (Fullerton & Cattell, 1892; Woodworth, 1899) and the beginnings of the S-R behavioristic approach to motor learning (e.g., Thorndike, 1927).

Clearly, the ease of operation and measurement should be important factors in selecting a task to examine any phenomenon in skill learning. However, it should be equally apparent that the task constraints dictate the nature of the emergent behavior. This concern is only partly reflected in the traditional issue of task specificity. Of more significance is the fact that task constraints are one source of constraint that dictates the optimal coordination and control function for a given action (Newell, 1984). Thus task constraints need to be carefully weighed in selecting a motor task to study motor learning. Greene (1971) has even suggested that we need to consider the development of a theory of tasks.

By definition, the single degree of freedom tasks used so often in motor learning have eliminated the problem of coordination from study. To examine this aspect of skill learning tasks need to be devised so that subjects cannot instantaneously exhibit the appropriate set of relative motions, either in terms of the kinematics or phase relationships of the cyclical biological processes. Indeed, it might be useful to operationalize task novelty by suggesting that a novel task is one in which the performer has not previously produced the appropriate set of topological characteristics of the relative motions.

The problem of the development of relative motions is particularly evident in young children because reflection will confirm that adults are rarely required to generate a set of relative motions that they have not produced previously. Changing task constraints for adults in everyday life primarily requires acquisition of the appropriate scaling of an already producable set of limb and body topological motion characteristics. Exceptions exist, of course, and the athletic and music domains often demand production of a novel set of relative motions by the performer. For example, pianists are sometimes required to produce 'apparent' incompatible rhythms on the key board with either hand. The creation of tasks with novel relative motions is clearly easier in consideration of kinematics than it is with respect to the coordination of the phase relationships of various biological systems in action.

ASSESSMENT OF MOTOR LEARNING AND THE IMPACT OF LEARNING VARIABLES

One of the major lines of enquiry in motor skill learning is the influence of various learning variables on the process of skill acquisition. This orientation stems from the early learning theory approach to motor learning (e.g., Judd, 1908; Thorndike, 1927) and has formed the backbone for much of the more current work in the area, despite the changes in theoretical orientation (e.g., Adams, 1971). The study of motor learning is a declining emphasis in motor learning to the extent that it is currently appropriate to ask whether there is still a place for learning in motor learning. By learning variables I am refering to that category of variables that shape the learning process; for example, augmented information feedback, demonstrations, and conditions of practice (cf., Newell, 1981). These variables, of course, not only influence learning as typically defined, but also the related processes of retention and transfer.

One of the major implications of the skill framework outlined is that the learning principles and laws formulated on the findings of traditional studies of motor learning may not be applicable to the acquisition of coordination in the initial stages of learning a multiple degree of freedom task, or to the more advanced stages of refining control in skilled performance. In the balance of this chapter I will illustrate this claim through a consideration of some traditional issues in motor learning. The significance of the discussion does not rest merely on the issue of task specificity for existing principles of learning but, in addition, the notion that a consideration of a broader range of task constraints may lead to the formulation of principles that cut across the stages of learning as reflected in the coordination, control and skill hierarchy.

Retention

The standard perspective on the long term retention of motor skills is that continuous skills are retained rather well, often better than verbal skills and certainly better than discrete motor skills (e.g., Adams, 1967). The reason why task type has an impact upon retention characteristics is still not understood even today. However, it is sobering to note that at the time of Adams' generalization much of the work in verbal learning rested on the examination of performance with nonsense syllables. By analogy, one might argue that the single degree of freedom movement task is the nonsense task of the motor domain.

The term nonsense is not used here lightly. Nonsense tasks (verbal or motor) are those that have little or no internal structure. In comprehension, structure (e.g., syntax) has a tremendous effect on retention so that nonsense syllables are poorly retained over time intervals without practice, unless structure is imposed on the material to be retained. It seems reasonable to propose that the same effects occur in the motor domain. Indeed, Kugler et al. (1980) have argued that unstructured motor tasks are those where no preferred kinematic trajectories exist because each potential configuration of limb position is neutral with respect to the stability of the system dynamics. The distinction between the retention characteristics of motor tasks has traditionally been based on a continuous vs discrete categorization, but a more useful categorization might be structured vs unstructured constraints.

Studies of retention have not been predicated on the coordination-control distinction. However, this framework seems to provide a promising way to reconsider the problem of retention of skill learning. Everyday observation suggests that the topological characteristics of action patterns are retained very well whereas the scaling characteristics of these relative motions require practice to regain the previous precision of control. The short term effects of warm-up decrement appear also to be limited to the scaling of the coordination function.

Transfer

Classically, transfer is the impact of performance on one task by performance on another task. Transfer effects are either proactive or retroactive (Adams, 1967) and can have negative, neutral or positive effects (Holding, 1976). Many instances of positive transfer have been demonstrated but very few cases of negative transfer have been recorded from laboratory studies although everyday experience suggests that performance on one task can be negatively affected by performance on another.

The failure to induce and/or recognize negative transfer is partly due to the indices used to record performance (cf., Holding, 1976). Another reason for this failure, which is apparent from the coordination-control distinction, is that most transfer studies have used tasks which require only changes in the scaling of a given relative motion. Negative transfer rarely, if ever, results under these conditions, while positive transfer seems linked to the similarity of the constraints of the two tasks. Intuition suggests that negative transfer is far more likely to emerge when the relative motion of the same joints is to be changed, particularly when the response is linked to a similar stimulus. Presumably in this situation a structured change is required in the coordinative action of muscles constrained to act as a unit around a joint(s).

An experiment by Summers (1975), which was originally designed to test notions about the role of timing in motor program theory, provides an example of negative transfer acruing from changes in the relative timing between tasks. In this experiment subjects learned to produce a rhythm with intervals of 500-100-500 ms or 500-500-100 ms between key presses. Once the rhythm had been learned, the subjects were asked to forget the learned timing sequence and depress the same keys as rapidly as possible. In the rapid transfer situation, the original rhythm remained to a considerable degree. In contrast, this rhythm was not evident in groups which had either constant or random intervals in original learning. Thus, Summers' study suggests negative transfer of the topological charateristics of motion, although a control group having no original practice was not available for comparison in the transfer test.

Augmented Information

Conveyance to the performer of any information that is not naturally available within the task constraints can be interpreted as augmented information. The term augmented information is usually linked to information feedback but the broader definition outlined above includes information that may be presented prior to action through verbal instructions or demonstrations, and during action through guided practice. Much of the work on knowledge of results (KR) has been confined to the line drawing task and its modern counterparts (cf., Adams, 1971; Newell, 1976). By contrast, a wider range of tasks has been used for the examination of observational learning through demonstrations.

A recent review of the augmented information literature (Newell, Morris, & Scully, in press) suggests that the impact of the various augmented information parameters is task dependent. However, the intuition of Fowler and Turvey (1978, p. 36) "that for the degrees of freedom necessitating control there must be at least as many degrees of constraint in the information supporting that control" appears a sound guiding principle for research on augmented information. Thus, goal oriented KR has proved so potent in KR learning studies because typically the task constraints require only a single degree of freedom action. In this situation, discrete goal KR provides all the necessary information for the single degree of freedom requiring constraint. However, in multiple degree of freedom tasks, information feedback of the response dynamics in the form of kinematic and/or kinetic parameters is required to augment goal KR if skilled performance is to be attained (Newell & Walter, 1981; Newell & McGinnis, in press; Newell et al., in press).

In general, it would seem that the application of augmented information should work within the coordination, control and skill framework outlined. This should hold whether the augmented information is given prior, during or after action and irrespective of the medium utilized to convey the information. If the initial stages of learning require attainment of the appropriate relative motion then information about these topological characteristics needs to be conveyed to the performer. It follows that augmented information appropriate for the refined scaling of the coordination pattern should complement the constraints of the task. In summary, the linking of learning variables such as augmented information to a motor control framework seems important to determine what information needs to be conveyed to the performer (see Newell et al., in press, for an elaboration of this position).

CONCLUDING REMARKS

The preceding discussion of the triumvariate of concepts of coordination, control, and skill has been primarily descriptive. In principle this descriptive framework could be applied to any of the data generated by traditional or current theories of motor learning. However, the theoretical position advanced by Kugler et al. (1980, 1982) is clearly distinct from previous theories of motor learning. The utilization of the operational distinctions advanced here may well open the significance of coordinative structure theory for the learning of motor skills.

The descriptive framework for coordination, control, and skill that I have elaborated from a behavioral perspective in this chapter, reveals many limitations to the traditional orientation to motor skill learning. Perhaps the most telling criticism is that the field of motor skills has been oriented primarily to the study of non optimal control. This limitation has been due, in part, to the operational focus on what are, in effect, single degree of freedom tasks such as the key press and linear positioning. Criticism of this narrow approach to tasks is not new. However, the link to concepts of coordination and control which I have offered here will hopefully provide a firm basis to understand a functional limitation of those tasks from the perspective of understanding the organization of the motor system and the embedded hierarchy of coordination, control and skill.

AUTHOR NOTES

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