TOWARD A DYNAMICAL ACCOUNT OF MOTOR MEMORY AND CONTROL*

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1. INTRODUCTION

Recent approaches to problems of complex, coordinated movement have emphasized that motor control arises from the task-specific dynamic system defined in a given actor-environment context. We suspect that motor learning and motor memory phenomena are likewise grounded in movement dynamics. Hence, a reformulation of certain memory and learning problems with reference to dynamic principles is undertaken here as a necessary first step. In the following sections we will: a) offer a constructively critical overview of several assumptions evident in current work on motor memory; b) attempt to sketch out a generalized type of dynamics that might lead to a unified approach to problems in sensorimotor control, learning, and memory; and c) offer a brief and speculative reformulation of questions relating to short term motor memory phenomena.

2. MOTOR MEMORY AND CONTROL: CRITICAL REMARKS ON SOME QUESTIONABLE ASSUMPTIONS

Considerable empirical advances have been made in the areas of motor memory and control in the last decade, yet we perceive some undercurrents among our colleagues to the effect that progress has become stunted, particularly in the memory field. This may be a general trend, arising from the realization that much more attention needs to be paid in the first place to the information being detected and used in the functional context of sensorimotor tasks, before we can ascertain anything about the nature of memory processes themselves. Even the standard metaphors of the memory theorist--such as storage and retrieval--have been seriously questioned (e.g., Estes, 1980). To be sure, something changes as animals behave adaptively with respect to their environments, and that something allows new performances to

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occur and old ones to be improved upon. But what changes? And why does such change persist?

Convention has it that what changes is some thing or accumulation of things in the animal itself—an assumption that may be only partially correct. This assumption has been sufficiently enticing, however, to lead the biochemist and the neuroscientist to seek structural changes in so-called "simple" organisms as a function of various conditioning regimes (cf. Kandel, 1976; Thompson, 1976). The physiochemical basis of the "engram" is a hotly pursued topic of research that is laden with hidden assumptions, a primary one being that engrams exist to begin with. One can readily see some of the problems here; even in species with low numbers of neurons, it has not been possible to relate neuronal patterns to behavior isomorphically (cf. Selverston, 1980).

"Context" continues to plague and puzzle us. Even the ethological concept of "fixed action pattern" as a behavioral counterpart to a unique set of neural events is under heavy fire at the moment in studies using the very organisms that Lorenz used to establish the idea. Bellman (1979), for example, has shown that the lizard (sceloporus) does not resolve competition between two behaviors (e.g., aggression and eating) by choosing one and suppressing others. Rather, the lizard's response to conflict is rich and varied. In what she calls "merging" (to contrast with a single type of competition resolution), elements of both behaviors are seen, as reflected posturally in limb configurations, temporally in the movements themselves, and spatially in overall orientation. These observations suggest strongly that fixed units of behavior are not selected as a whole in immutable form. The consequences are obvious for a theory of engrams that are isomorphically related to specific behavioral patterns.2

In the realm of psychology, few find it appealing to propose individual memorial counterparts for every possible behavioral variation. All nevertheless assume that something is stored, that information is somehow accumulated, that skills and habits are things that are acquired. In this style of thought, representations exist under a number of various guises—templates, perceptual traces, internal models, schemas, generalized motor programs, and the like. Our intent here is not to commence a diatribe against representationalism (but see Fodor & Pylyshyn, 1981; Turvey, Shaw, Reed, & Mace, 1981, for a lively debate). Rather, we would like to raise some questions about certain assumptions that seem implicit in current approaches to motor memory and control in order to suggest alternative styles of inquiry to those that presently predominate.

Often the way we ask questions determines what solutions we expect. Perhaps asking the question differently or changing its focus will allow, if not new insights, then at least an elaboration of perspectives that can be differentiated. We think that it can be argued justifiably that current approaches to memory and control are dominated by certain singular themes (or styles of inquiry) that most have agreed on. Differences in perspective are nested within the same style of inquiry; they may be more a product of the manipulations that people perform in their experiments than any fundamental difference in outlook. If correct, this intuition suggests a reason for our stymied progress. Rather than variations on a theme, perhaps we need contrasting themes (cf. Kelso, 1981; Kugler, Kelso, & Turvey, 1982). One of the aims of this paper, following recent theoretical and empirical work on
complex, functionally defined coordinated activities, is to promote dynamical principles on which to ground an understanding of motor memory and control. We will attempt to sketch out a generalized type of abstractly defined dynamics that may provide a departure point toward solving certain long-standing problems in the memory and control area. But, since our role here is to provoke and perturb, let us first do some consciousness-raising on the status of what we perceive to be the status quo.

2.1. Assumption 1: Skill Development as the Accumulation or Construction of Cognitive Representations

The acquisition of skill is difficult to understand, according to Assumption 1, without assuming that practice allows us to store a large number of movement patterns, or, more correctly some say, the perceived consequences of our actions. Whether we abstract out the key features of how the movements were produced and call it a schema or generalized motor program is not really the issue. The issue is the universal agreement that we accumulate, abstract, or construct something that is stored centrally as a memory or knowledge structure. For example, a common view of skills such as boxing that demand fast reactions of the performer is that people:

"...use cues in the situation to tell what will probably happen next: They anticipate. This constitutes a cognitive skill. (Italics ours) Redundancy inherent in the situation is stored in memory. The skilled person has quick access to that knowledge structure that allows prediction and anticipation." (Keele, 1982, p. 157)

And, further analogizing from research on cognitive skills such as chess, Keele (1982) offers the idea that skill depends "...largely on extended practice involving thousands of hours. In that time people accumulate a 'vocabulary' of thousands of patterns (or situations) that they can recognize, and they build an extensive repertoire of strategies and responses to deal with those patterns" (p. 159).

To be fair to Keele, these ideas are advanced as "quite speculative" and hypothetical. However, they are not at all unusual in the area of motor skills. Most would offer little argument and there is certainly a growing consensus that motor skills have a heavy cognitive component (at least initially), and that action sequences are centrally represented even in the highly skilled. But it might be a mistake to place skilled behavior in the cognitive domain—at least perceptual—motor ones like boxing. And it might be a mistake to assume that the brain or mind contains remnants of our experiences—cognitive and otherwise. An alternative to this accumulative or constructive view of skill acquisition is one that does not appeal to cognitive operations to make sense of incoming stimuli, but that rather suggests that the information being picked up becomes more and more precise and subtle as skill develops. This view argues that the skilled performer becomes attuned to increasingly subtle perceptual information as a function of experience (cf. Gibson, 1966, 1979). The contrasting perspectives afforded by the accumulation/construction versus attunement approaches represent entirely different theoretical accounts for the simple fact that experience changes the animal (Michaels & Carse, 1981). According to the latter alternative we do
not become skilled by increasing the number or complexity of memories (or knowledge structures) in the animal's brain; rather, we discover and become sensitive to, i.e., resonate to (cf. Gibson, 1966, 1979, and commentaries by Macé, Runeson, and Grossberg on Ullman, 1980) increasingly complex and differentiated information structures realized by events defined over the actor and environment. In Runeson's (1977) terms, we become increasingly smarter special purpose devices,3 attuned to complex information that is always available for detection in terms that are unique and specific to the acts that animals perform. Prediction and anticipation are consequences of this characterization, i.e., information is specific to what can be done (prediction) and when it can be done (anticipation). Our ability to use such information is exquisite. Two examples will illustrate these points.

Todd (1981) has considered the outfielder's problem of trying to catch a fly ball in terms of the visual information currently available that specifies whether the ball will land behind or in front of the fielder's present position. Todd identified several sources of such "predictive" information and demonstrated, using animated computer displays, that subjects could detect and use such information in perceptual judgments. In fact, it appeared that subjects were sensitive to information specified in the following relation between optic and physical variables, in which optic variables refer to the projection of the physical event onto a two dimensional planar surface:

$$-\frac{AY}{2R} > \frac{VY' \times VR'}{(R')^2}$$

(1)

where

- $AY =$ physical vertical acceleration of gravity,
- $R =$ physical diameter of ball,
- $VY' =$ optic vertical ball velocity,
- $WR' =$ optic ball dilation velocity,
- $R' =$ optic ball diameter.

When equation (1) is satisfied, the ball will land in front of the observer. Note that the visual information specifying final landing point relative to the observer is available throughout the ball's trajectory. In other words, the information available at a given point in time is "predictive" in that it specifies a task-relevant spatial relationship that will occur subsequent to that point in time. Note that for this relation to be useful, the observer must be sensitive to (and presumably must discover) the critical ratio, $AY/2R$, between the acceleration due to gravity and ball size. Presumably, the observer's sensorimotor system is posturally familiar with the gravity vector; however, information specifying the ball size and hence the critical ratio obviously depends on the specific ball-skill context (i.e., baseball, softball, basketball, etc.).

The second example of intrinsically predictive visual information is due to Lee (1976), who identified the optic invariant specifying the time-to-contact of an object approaching an observer (or vice versa) at a constant velocity along the line of sight. This information is specified by:
where \( Vr' \) = rate of dilation of the retinal image of the object. When the observer is driving a car and approaching a stationary obstacle, such information specifies time-to-collision. In this context, Lee described time-to-collision margin values at which the driver would have to start decelerating with a given braking power when traveling at a given current velocity in order to stop short of the obstacle (assuming steering controls are ignored). With reference to problems of coordinated movement, we should point out (in the spirit of Warren & Shaw's (1981) discussion) that such margin values may be used to scale spatiotemporal perceptual information to the power-generating capacities of the actor in a given task situation. For example, there exists a margin value for the time at which one can initiate a successful jump when running toward a jumppable obstacle at a given speed. This time-to-jump margin value will vary across organisms with different power to body-mass ratios; i.e., organisms with greater power/mass ratios can initiate successful jumps at smaller margin values.

2.2 Assumption 2: General Purpose Processes and Devices

Those of us who were in graduate courses in psychology of learning in the 1960s and 1970s were likely impressed by the enormous efforts of our predecessors to provide a general theory of learning. This was truly an admirable goal and most of us would still like to believe that a small set of general principles underlies all forms of learning. A claim that has recently been made (Johnston, 1981) is that such general principles should be sought in the relationships between animals and their natural environments. This ecological approach contrasts with previous "general process" efforts that have restricted their studies to defining the characteristics of animals themselves. For example, a tacit assumption of the latter type of approach was what Seligman (1970) called the "equivalence of associability" assumption, that it was equally possible to learn any relationship between stimulus and response. Much recent work, however, has shown that there are biological constraints on what can be learned (e.g., Bolles, 1972). Animals do not operate in universal contexts; they are not general-purpose machines. The elegant conditioning experiments of Garcia and colleagues attest to this claim (e.g., Garcia, 1981; Garcia & Koelling, 1966, for review). Briefly, Garcia showed that rats can learn to avoid sweet-tasting water when it is paired with toxicosis, but not if it is paired with foot-shock. Moreover, in the former case the pairing does not have to be temporally contiguous; delaying the noxious US (unconditional stimulus) up to two hours still resulted in learning to avoid the sweet-tasting water (CS). All of this evidence (and much more, see Johnston, 1981) contravenes the principle of equivalence of associability and strongly supports the view that those activities that are part of the animal's natural habitat or niche can be learned easily while others cannot.

The biological-constraints perspective appears to have had no visible impact in the motor behavior literature (where it should be most relevant). For example, it was totally ignored in a recent meeting on motor memory and learning (North American Society for the Psychology of Sport and Physical Activity, Asilomar, CA, 1981). The area of motor memory, borrowing heavily from the verbal learning area, continues to deal with "items of information" or "items to be remembered" as its relevant stimuli. In fact, the more novel
and arbitrary the "item" to the activities that people perform—so the argument goes—the better we are able to understand how new "items" are learned and remembered. This view of movements as "items" is a vestige of associationism; in fact it is associationism (cf. Jenkins, 1979). It assumes that perception, learning, and memory are general-purpose processes; it assumes that anything that will produce an effect constitutes a stimulus item; it evokes descriptions of the information base that are animal-neutral (hence "items"); it rejects the claim—supported by much recent work—that behavior is constrained by particular aspects of environmental structure to which an animal is sensitive. According to Assumption 2, then, movements are learned, controlled, and remembered by general purpose devices that process movement information in the same manner regardless of the functional or task context. It should be noted that this assumption is evident not only in human motor control and memory research, but also in the field of robotics. Thus, for example, it has been generally assumed that robot limbs can perform different tasks according to the same general purpose planning and control operations, e.g., joint velocity planning and servoing for both manipulator arms (e.g., Whitney, 1972) and hexapod walker legs (e.g., McGehee & Iswandhi, 1979).

In contrast with the general purpose approach, we wish to argue that motor learning, memory, and control processes are not neutral to an action's functional or task context. In this regard, one assertive claim to be made here is that we should reject "items" as constituting the what of memory, just as we should reject "muscles" (admittedly less arbitrary to the control of activity than "items" are to memory) as the what of control and coordination (cf. Kelso & Saltzman, in press). Instead, we should give a good deal of thought to the types of tasks organisms (including humans) perform, in recognition of the fact that tasks that meet existing constraints are easier to perform than others that do not. Consequently, any natural informational units that may be relevant to understanding that which we call memory and control need be defined functionally; that is, with respect to the tasks that animals can perform. General purpose theories of control and memory are too powerful in this regard, because they offer viable accounts of phenomena that never occur naturally as well as those that do. They fail to acknowledge that evolution and development play an economizing role by restricting the types of activity that creatures perform to those that are behaviorally useful.

We have invested a good deal of effort in identifying what we believe to be significant units of control. These are not individual degrees of freedom of the system like muscles, or preestablished arrangements between receptor and effector elements (the reflexes that Sherrington (1906) referred to as "likely fictions"), or prescribed arrangements among instructions (central programs, etc.). Rather, they are functionally specified ensembles of muscles and joints that act as coherent units during task performances and whose component elements vary autonomously in a mutually constrained manner (e.g., Boylls, 1975; Fowler, 1977; Greene, 1971, Note 1; Kelso, Southard, & Goodman, 1979; Saltzman, 1979; Turvey, Shaw, & Hace, 1978). We shall have much more to say about the organization of these action units as discussion proceeds.

2.3. Assumption 3: Cues and Features

An extension of the "movement as a to-be-remembered item" approach is to partial up the movement and identify the various "features" or "cues" that
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could be coded by a subject in a reproduction task. Thus the problem for motor memory becomes one of identifying which cues are "codable" and which are not. The prototypical case is the distinction between distance and location cues—an issue that on its own must have provoked thirty or forty articles. If one accepts that these aspects of movement can in fact be differentiated, the result is that location reproduction is better than distance. Numerous accounts have been offered for this finding. Many of the early studies (and many of the later ones as well) argued that location is more effectively reproduced because there are kinesthetic receptors for joint position but not for distance (but see Kelso, Holt, & Platt, 1980), or that distance is less directly coded because it requires an interpolation of velocity. Another type of interpretation followed Lashley's idea of a space coordinate system. Limb positions were thought to be more easily coded than distance because they were referred to an internal representation of spatial coordinates rather than being kinesthetically determined. Thus, identical spatial positions could be reproduced with either limb (as long as direction of movement remained constant) and would not require the continuous availability of kinesthetic information from the same limb (cf. Wallace, 1977). More recent interpretations have kept in vogue with the visual and verbal memory literature. With respect to the former, information about end location has been viewed as "centrally arousing a visuo-spatial map" for "retrieval purposes in subsequent reproduction" (Housner & Hoffman, 1981). With respect to the latter there has been a good deal of attention given to using verbal labels as retrieval cues for movement positions (e.g., Shea, 1977) or to subjecting location to greater depths of processing (cf. Craik & Lockhart, 1972). Thus location "persists" because it can be analyzed more deeply than distance.

All of these accounts commit what has been called a first-order isomorphism fallacy (FOIF for short; Summerfield, Cutting, Frishberg, Lane, Lindblom, Runeson, Shaw, Studdert-Kennedy, & Turvey, 1980), namely, of taking the predicates that result from describing or observing a phenomenon (e.g., the position of a limb), assigning those predicates to a memory structure in the brain (e.g., as a location code, a visuo-spatial map, perceptual trace...) and of claiming, thereby, to explain the phenomenon. One problem with this strategy, of course, is that we could take any observable kinematic or kinetic movement feature (e.g., relative force, movement distance or duration, hand location, etc.) to which an organism is behaviorally sensitive and posit an entity in the head that is responsible for detecting, coding, or remembering it. The same criticism also applies to studies of motor control that investigate the so-called "content" or "structure" of central motor programs. Thus, reaction time to initiate a movement can be related to many measurable or observable dimensions of upcoming movement with little or no guarantee that the said dimension is coded in the motor program (cf. Kelso, 1961). Assigning movement cues and various kinematic/kinetic dimensions to isomorphic memorial counterparts as agents of recall and regulation is tautological, and appears to confirm only the assumptions of the experimenter.

This FOIF is not restricted, however, to research in control and memory of limb movements; it is common in speech perception research as well. There the concept of detectors for phonetic contrasts has gained prominence even though virtually every such contrast differs along many distinct dimensions (e.g., Liberman, 1982; Studdert-Kennedy, 1982). Is there a contrast detector for each dimension or cue? Consider the well-studied case of voicing

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distinctions in stop consonants, e.g., /b/ versus /p/ (Lisker & Abramson, 1964). Up to now nearly twenty different cues have been found that distinguish the contrast, among them aspiration energy, first formant onset frequency, fundamental frequency, the timing of laryngeal action, and burst energy. No limit for the number of possibilities—according to some authors—is in sight (e.g., Bailey & Summerfield, 1980; Lisker, 1978).

In short, many studies in motor control and memory (as well as in other areas, e.g., speech perception) have revealed that organisms can respond to a wide range of isolable and distinctive event features that experimenters manipulate. Such behavioral data, however, do not constitute evidence for the psychological reality of the corresponding isomorphic feature codes or detectors.

3. MOTOR CONTROL: A GENERALIZED DYNAMICAL PERSPECTIVE

A recent theoretical approach to motor control (cf. Fitch & Turvey, 1978; Fowler, 1977; Fowler & Turvey, 1978; Greene, 1972; Kugler, Kelso, & Turvey, 1980) has looked to nested structures of constraints on dynamic system parameters (e.g., stiffness and damping coefficients) as sources of movement organization. According to this view, higher order global constraints specify a pattern of such parameters that allows the limbs (or any articulators) to become task-specific, functionally defined, special purpose devices. This constraint structure will be referred to below as the organizational invariant (cf. Fowler & Turvey, 1978) characterizing a given action type. Lower order, local constraints specify values for those parameters left free to vary once the global constraints have been implemented. We shall refer to these local constraints as tuning parameters. For example, the arm will behave as a reaching device if globally constrained by the organizational invariant to behave as a damped mass-spring system; and the leg will behave as a hopping device if constrained to behave as a limit cycle system. These global functions may be tuned by local constraints specified by perceptual information specific to the immediate actor-environment context. Thus, the reaching arm will self-equilibrate to a value specified by the perceived location of the target, and the hopping leg will cyclically attain a peak hopping height specified by the perceived heights of hop-overable obstacles in the path of locomotion.

We would like to promote a perspective on action that argues that coordinated movements are functionally defined and (ideally) adaptive events whose spatiotemporal coherence and power requirements are governed by the simultaneous confluence of global and local constraints. In this framework, defining one's units of analysis is a critical first step in understanding the bases of movement coordination and regulation. The argument has been made in numerous places (e.g., Bernstein, 1967; Boylls, 1975; Fowler, 1977; Gelfand, Gurﬁinkel, Tseltin, & Shik, 1971; Greene, 1971; Kelso & Saltzman, in press; Kelso et al., 1979; Kugler, Kelso, & Turvey, 1980; Saltzman, 1979; Turvey, 1977; Weiss, 1969) that single muscles and/or joints are not the proper elements with which to build an adequate theory of multiple degree of freedom systems able to perform sensorimotor tasks successfully in the real world. Rather, the appropriate elements are collectives of muscles/joints that act as coherent units according to the global, functionally specific task constraints defined across actor and environment. Such units have been called synergies,
coordinative structures, linkages, etc. These terms reflect the synchronic or spatial coherence that this type of constraint organization bestows upon the actor's musculoskeletal system. Thus, if one analyzes a movement into discrete time slices, such synchronic organization may be observable as ratios of muscle activity or joint motion that remain relatively invariant across time slices. Although such time slice descriptions are useful for movement analysis and robotics control applications, one should not be seduced into thinking that coordinated, biologically controlled actions can be reduced to transformationally related, time slice concatenations of linkage motions. Biological actions are best viewed as events that have diachronic or temporal as well as spatial coherence; they span a characteristic, intrinsically defined period of time according to the global, task-specific function by which the movement is organized. This position echoes Bernstein's (1967) assertion that movements may be likened to morphological objects in that "they do not exist as homogeneous wholes at every moment but develop in time, that in their essence they incorporate time coordinates" (p. 66). Further, "movements are not chains of details but structures which are differentiated into details" (Ibid., p. 69).7

Finally, biological actions are characterized not only by their spatiotemporal properties but also by their power-generation requirements. Consider, for example, running to intercept a soccer pass. For this task to be successfully accomplished, information must be specified about where the ball is spatially, where and when it will arrive at an interceptable location, and how much energy must be dissipated by the body to reach that particular space-time locale (Lee, 1980). The earlier discussion of Lee's (1976) braking problem and the time-to-collision margin values (see Assumption 1 section) underlines the relations between perceptual information and energetic constraints on activity. Let us now proceed to a more detailed treatment of organizational invariants and the rather abstract bases of their dynamic organization.

3.1. Organizational Invariants, Degrees of Freedom, and Task-spatial Axes

It is worth emphasizing that skilled actions are goal-directed. Such goals are defined in terms of environmental outcomes that are relevant to the actor's desires and current behavioral repertoire. For example, skills entailing the limbs typically involve creating characteristic patterns of motion and/or force at the limb-environment interface; speech entails articulator motions that shape the vocal tract to create characteristic acoustic energy patterns in the airstream produced by the lungs. In all cases, however, the effectors relevant to the task are parts of a coherent multi-degree of freedom ensemble. The coherence of such ensembles arises from the functionally specified, task-level structure of constraints (i.e., the geometry of constraints) defined over the dynamic system spanning the actor and environment. Thus, for example, the act of reaching entails a global, functional organization of the joints and muscles in the arm that guides the hand to a target under the influence of gravity. It is reasonable to hypothesize that this organization is invariant across different specific instances of reaching. Fowler and Turvey (1978) have spoken of such global principles as comprising the organizational invariant of a coordination problem, as the "function that is preserved invariantly over changes in the specific values of its variables" (p. 23).
In this framework, understanding the functional basis of a particular skill involves discovering the system of global control constraints that characterizes that skill's organizational invariant. Such discovery presumably underlies both the developmental/skill acquisition process and the process of analyzing experimentally the skilled performance of well-learned behavior. Obviously, there is an important difference between the discovery tasks in the two cases. Adapting Pattee's (1975) discussion of the origin and operation of natural control systems to the present issue of skilled actions, we may say that the problem of the origin of a skilled behavior is quite distinct from the problem of the performance of a skilled behavior. The basic distinction is that the performance of skilled actions assumes the existence of an organized system of control constraints, whereas the origin problem must account for the establishment of these constraints. Such origins "must begin with low selectivity and imprecise function and gradually sharpen up to high specificity and narrow, precise function" (Pattee, 1973, p. 41).

There is a curious and possibly significant parallel between the discovery processes of the unskilled novice and the uninformed scientist. It might be justifiably argued that the novice's and the movement scientist's understanding of the organizational invariant underlying a particular skill may be progressively facilitated by gradually increasing the number of degrees of freedom controlled or measured during performances of coordinated actions relevant to the skill. In the case of skill acquisition, one can characterize the early stages of learning in both adults and children by a tendency to keep much of the body relatively stiff or rigid, thereby reducing the kinematic and kinetic complexity of the performed movement (e.g., Benati, Gaglio, Morasso, Tagliasco, & Zaccaria, 1980; Bernstein, 1967; Fowler & Turvey, 1978; Saltzman, 1979; Wickstrom, 1977). Further refinements of skill are then said to entail selective relaxation of these constraints (i.e., differentiation of the constraint structure), guided by the progressive discovery of the patterning of reactive forces supplied by the functionally coupled dynamic system of actor and environment. The early rigidity or stiffening control constraints on the kinematics and kinetics of limb movements may be likened to the physical constraints provided by training wheels on the motions allowed and forces encountered by a novice bicycle rider. Essentially, these early constraints play two roles. The first is to provide a rough approximation of the skilled action that nevertheless achieves the relevant goal, i.e., satisfies a crudely specified organizational invariant. The second is to facilitate the discovery of the supporting dynamics by extending the time interval over which task-stability is preserved (i.e., the bicycle moves in a controlled manner without falling over). According to Fowler and Turvey (1978), the organizational invariant for a skill is information specific to the underlying, functionally constrained dynamics of that skill. Such information by definition remains invariant and is revealed through time over transformations relevant to that skill. Extending the temporal range of task stability thereby increases the range of time spanned by these exploratory transformations, and enhances correspondingly the discovery and differentiation process.

In the case of the scientist's analysis of a well-learned skill, one can similarly observe that increasing the allowable degrees of freedom of movement in the experimental task can reveal progressively more subtle aspects of the organizational invariant underlying that skill. Consider, for example, the
A well-known mass-spring model of limb control in target acquisition tasks. Many recent studies in motor control involving positional control at a single joint have led to the conception that such movements are controlled by a system qualitatively similar to a (nonlinear) mass-spring system (e.g., Fel'dman, 1966; Kelso, 1977; Kelso, Holt, Kugler, & Turvey, 1980). These movements are characterized by their equifinality in that a given target angle may be achieved despite variation in initial position and despite perturbations to the movement trajectory imposed en route to the target. Fel'dman (1966, 1980) and others (e.g., Kelso, 1977; Kelso & Holt, 1980; Polit & Bizzi, 1973; Schmidt & McGown, 1980) have described such systems as rotational mass-spring systems in which target angles are specified through controllable agonist and antagonist muscle equilibrium lengths. If one were to stop here, one would assume that the organizational invariant underlying such tasks was defined relative to joint-level control systems. However, these tasks are highly constrained instances of well-practiced reaching or pointing actions that are normally defined functionally over time, three spatial dimensions, and the multiple joint hand-arm-trunk linkage system. It is reasonable to assume, then, that the organizational invariant governing the simple joint positional control case represents a constrained version of the global constraint structure underlying the more generalized reaching_pointing skill. That is, one is led to suspect that the mass-spring organization discovered in single joint tasks might not be tied literally to control at single joints, but might rather indicate a more abstract functional mode of organization characteristic of reaching and pointing tasks in general. Since this characterization is one of function and not mechanism, however, it may account for the qualitative behavior of a wide variety of materially different systems (e.g., the compensatory behavior of the jaw and lips to unexpected perturbations, the invariant position of the hip prior to the swing through of the leg in the step cycle).

Recently several investigators (Abend, Bizzi, & Morasso, in press; Georgopoulos, Kalaska, & Massey, 1981; Morasso, 1981; Soechting & Lacquaniti, 1981; Wadman, Denier van der Gon, & Derksen, 1980) have supported such suspicions in reaching studies involving two joints (shoulder and elbow) and two spatial dimensions of hand motion. In these cases, they found a relative invariance of the spatial properties of the hand trajectories across different reaching movements. Typically, the hand moved in an approximately straight line from initial to final positions, and exhibited a single-peaked velocity curve in this tangential direction. If movements were organized solely with respect to a target joint angle configuration, one would expect equifinality, but not quasi-straight line trajectories. The existence of such trajectories suggests that, in addition to specifying an equilibrium linkage configuration, the stiffnesses across the joints are distributed to produce motion approximately in the direction of the current target. It is interesting to note that the single degree of freedom experiments may have precluded discovery of this control constraint on spatial trajectory by physically prohibiting trajectory variation in the non-tangential direction. Thus, relaxing constraints on the degrees of freedom of motion allowed in the target acquisition paradigm has actually enhanced our understanding of the organizational invariant governing such tasks.

One might also speculate that relaxing the experimental constraints further will result in yet richer characterizations of the reaching organiza-
tional invariant. For example, if one restricted hand spatial motion to two dimensions and allowed motion at three joints (shoulder, elbow, and wrist), there would be no unique relationship between hand position and joint angle configuration. If one again found spatial equifinality and trajectory invariance, yet additionally found variation in final hand position-linkage configuration relations, then one might conclude that the organizational invariant underlying reaching tasks was abstract indeed (i.e., abstract in the mind of the scientist—not necessarily abstract in the sense of mechanism). However, just as the earlier invariances could be produced via specification of dynamic system parameters (i.e., equilibrium angles, stiffness distribution), one might again suspect that this configurational equivalence property of the organizational invariant might also be based on dynamic principles.

The type of organizational invariant discussed above was specific to reaching skills, and served to organize the acting upper limb functionally as a special purpose reaching device. In this case, the hand behaved as though governed by an abstract, spatially defined mass-spring system. Different tasks, however, entail different organizational invariants through which the limbs (or any set of articulators) become different functionally defined, special purpose devices. One further brief example from the robotics locomotion literature will illustrate this point. Raibert and his colleagues (Raibert, Brown, Cheponis, Hastings, Shreve, & Wimberly, 1981) have described two aspects of the organizational invariant governing lower limb control during locomotion. They noted that legs do two things during walking or running: a) they change length to establish a cyclic temporal framework of vertical hopping (i.e., they alternate stance and transfer phases); and b) they move back and forth to propel the body and provide balance. For present purposes, we will focus on the vertical aspect, and note that the "vertical controller" is organized to maintain a hopping cycle for any desired peak hopping height of the body, i.e., this aspect of locomotor function is organized with respect to the task-specific, spatially vertical axis between the support surface and body center of mass. Furthermore, this spatially invariant behavior is provided by an underlying limit cycle dynamic organization, analogous to the "squirt" system involved in the escapement mechanism of a pendulum clock. The pendulum clock's escapement mechanism, however, only allows a constant force impulse to be injected on each cycle of pendulum swing. Raibert et al.'s (1981) model of a locomoting device is more complex, since it can adjust the size of the impulse on each cycle to maintain a desired body height. Thus, the vertical behavior of this model shows equifinality with respect to the vertical task-specific spatial (task-spatial) axis, and appears to be organized according to an abstract, spatially defined limit cycle system.

In summary, we are thus led to the following informed intuitions concerning the organizational invariants underlying different functionally specified skills: a) they may be defined in a highly abstract, geometric manner relative to task-spatial axes; b) satisfying such abstract invariance across task instances may be allowed by appropriate specification of the underlying dynamic parameters that functionally characterize the linkage system in the current task-actor-environment context; and c) the subtleties of the organizational invariant's structure may be progressively revealed and differentiated by selectively increasing the controllable degrees of freedom in the task at hand, and by permitting variation in the transformations imposed on these degrees of freedom.
3.2. Motor Memory Revisited

In the introductory portion of this paper, we suggested that motor memory phenomena might arise from dynamic aspects of movement. In Section 3.1 we argued that the correct units of analysis for coordinated actions were functional units defined in a task-specific manner across actor and environment. A given coordinated movement was viewed as an event possessing intrinsic spatial and temporal coherence, and a characteristic constraint structure (an organizational invariant) was described that might provide such coherence by establishing a functionally appropriate global organization over the dynamic parameters of the actor’s linkage system. The dynamics involved were defined in an abstract manner, and governed behaviors showing point or limit cycle stabilities relative to task-spatial locations or axes.

If movement reproduction is a task that is sensitive to movement dynamics, it is sensitive to this highly abstract type of dynamics. From this perspective, it is not surprising that spatial and/or joint configuration equilibrium positions might persist over time, given the underlying generalized task-spatial mass-spring system described above for reaching tasks. Additionally, it may not be too surprising that the direction of motion toward a target in such positioning tasks influences reproduction accuracy (e.g., Wallace, 1977), since trajectory direction was suggested to be controlled dynamically by appropriate, perceptually specified constraints on the pattern of linkage joint stiffness parameters. Given that equilibrium configurations and stiffness distributions may be characterized as local constraints (i.e., tuning parameters), one might arrive at the hypothesis that motor memory phenomena are related to the relative persistence and stability characteristics of tuning constraints. Suspecting such a relationship, we would wonder why such a relationship should exist in the first place. Why might dynamically defined tuning constraints persist at all? What is it about motor memory that it should be selectively sensitive to such motor control parameters? And finally, could motor memory itself be a consequence of a more general ability to detect control constraints persisting after movement execution?

By couching one’s questions concerning motor memory and learning in the context of functionally specified and dynamically implemented global and local control constraints, we believe that the crude beginnings of a unified account of control, memory, and learning of coordinated actions may be within reach.

4. CLOSING COMMENTS

Here we would like to summarize briefly and selectively our main points:

(1) There is information that is unique and specific to the organism's dynamics and to the spatiotemporal and energy demands of the tasks that organisms perform. Thus, attention to the informational basis for knowing what to do, when to do it, and how to do it is a first step to exploring mechanisms. In this regard, margin values of detectable information may be discovered that are specific to an action's power requirements. As skill develops, the detected information pertaining to the guidance of activity becomes more subtle and increasingly precise. Skill acquisition need not be equated with the elaboration or strengthening of internal memorial knowledge structures.
(2) The language of motor control and memory processes is not likely to be one of cues or features based on a movement's observable or measurable properties. We suggest instead that one look to the underlying dynamic system parameterization that gives rise to a movement's kinematic or kinetic observables. In other words, dynamics is the language of motor memory and control. Such dynamics are defined abstractly with respect to functional, task-spatially defined locations or axes.

(3) Motor control and coordination are likely to fall under the rubric of functionally specific, special-purpose processes. They are less likely to depend on general process views obtained from other areas of biology and psychology. The limbs can become different types of functionally defined, special purpose devices for different types of tasks by virtue of global constraints defined over the underlying dynamic system parameters. This global constraint structure is labeled the organizational invariant. Nested within these global constraints are a set of local constraints or tuning parameters by which a movement is tailored to the specific details of the task's actor-environment context. We suggest that one can gain a better experimental portrait of an action type's organizational invariant by systematically increasing the degrees of freedom controlled and observed in the experimental task. Finally, we also suggest that motor memory phenomena in reproduction paradigms may be intimately related to the degree of persistence of a movement's local tuning constraints.

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FOOTNOTES

'Almost of the work in the area of motor memory has been done by researchers in physical education, kinesiology, and human performance, while control is a much larger field. Even in the area of control, however, some apparently simple problems have resisted consensus. For example, Stein (in press) poses the question "What muscle variables does the nervous system control?" without providing a definitive answer, yet this question has been on the neuroscientist's mind for at least 50 years.'
At a larger scale, attributing a person's erroneous behavior in certain laboratory tasks to a lesion in the frontal lobe leads to elegant cause-effect neurological models of apraxia. Unfortunately, such models are embarrassed if not informed by the patient's ability to perform the same tasks when the situational context is sufficiently rich (e.g., wife to husband: "Hang that picture on the wall," versus neurologist to patient: "Show me how you hammer a nail," cf. Kelso & Tuller, 1981).

Note that the "generalized IQ" of such special purpose devices may be quite low. The polar planimeter, for example (cf. Runeson, 1977), is a rather simple mechanical device that provides a sensitive measurement of the area of a bounded planar figure. However, it can perform only crude measurements of the conceptually "simpler" perimeter length of the figure.

Introspection as a methodology for psychology has had its day, but it can often help us to appreciate the nature of the problem. In the case of motor memory, what actually is remembered? A movement? Or a piece of it such as a cue? If the reader was asked what movement she produced yesterday at 3:00 p.m., how would she respond? If anything is remembered it would be task referential—like drinking, going to the toilet, talking to a colleague—but the movements associated with such actions are hardly remembered. In riding a bicycle after many years, what is remembered? Hardly a sequence of movements. More likely it is the capability to transform the system (person—bicycle—environment) such that the right properties are revealed, i.e., that transformation across the links of the body that allows one to achieve equilibrium on an unstable object.

The reader should note that the present use of parameter tuning is distinct from two previous uses of the term "tuning" (i.e., spinal tuning and biomechanical tuning) in the motor control literature. Spinal tuning describes physiological patterns of modulation of the spinal cord elements as discussed by Gelfand, Gurﬁnkel, Tsetslin, and Shik (1971), Gurﬁnkel, Kots, Krinskiy, Paltsev, Peli’dman, Tsetslin, and Shik (1971), and Kots (1977). Biomechanical tuning (cf. Greene, Note 1; Saltzman, 1979) is defined relative to skeletal joint motions and muscle forces. In this biomechanical sense, a movement can be described by the contributions of main biomechanical variables and tuning biomechanical variables. Main variables provide a joint motion or muscle force pattern that roughly approximates a desired movement pattern. Tuning variables are used to improve the movement approximation provided by the main variables.

At first glance, organizational invariants and tuning parameters appear similar to the concepts of generalized motor programs or schemas and variable parameters (cf. Keele, 1961; Pew, 1974; Schmidt, 1975, 1980), respectively. They are quite distinct, however. The latter concepts are based on a movement's observable kinematic or kinetic features (e.g., movement time, measured force output, muscle/joint groups, etc.), whereas the former are based on the movement's underlying dynamic parameterization, which gives rise to its kinematic/kinetic observables.

The mass–spring model of position control at a single joint is appealing within this framework since it provides a movement with intrinsic temporal coherence, i.e., the movement's duration is specified by the system's mass and
stiffness parameters. It is impossible by definition, however, to talk of spatial coherence across joints in single joint motions. Thus, in our later discussions of a generalized mass-spring model for multiple degree of freedom positioning tasks, we will suggest a possible way to define such synchronic constraints with reference to underlying dynamic parameters.