Skill Acquisition: An Event Approach with Special Reference to Searching for the Optimum of a Function of Several Variables*

Carol A. Fowler† and Michael T. Turvey††

ABSTRACT

Our paper divides into three parts. The first is a roughly hewn statement of the general orientation we wish to take toward the problem of skill acquisition. The second part develops a level of analysis that, in our view, is optimal for the examination of the problem; essentially, it is an ecological level of analysis that promotes the event rather than the performer as the minimal system that will permit an adequate explanation of the regulation and acquisition of skilled activity. The principal claims of the first two parts are highlighted in the third and final part through a detailed examination of a specific but prototypical coordination problem, namely, the problem of how one learns optimally to constrain an aggregate of relatively independent muscles so as to regulate a simple change in a single variable.

MOTOR TASKS, ACQUISITION PROCESSES AND ACTORS: A GENERAL ORIENTATION

It is prudent to preface a theoretical analysis of learning by some general comments on what the incipient theorist takes to be the nature of tasks that are learned, the nature of the processes that support the learning and the nature of the agent doing the learning. In the vocabulary of Shaw and McIntyre (1974), those three topics refer, respectively, to the three primary analytic concepts of psychology, namely, the what, how and who concepts. One can argue that this set of analytic concepts is closed, that is, that the concepts are logically co-implicative (Shaw and McIntyre, 1974; Turvey and Prindle, 1978). The closure of the set is illustrated by the following example (Shaw and McIntyre, 1974):

---


†Also, Dartmouth College, Hanover, New Hampshire.

††Also, University of Connecticut, Storrs.

Acknowledgment: This work was supported by NIH Grant HD-01994 to Haskins Laboratories.

The degree of hardness of a sheet of metal tells us something about the nature of the saw we must use to cut it (i.e., something about what is to be done); a blueprint or pattern must be selected in the light of what can be cut from the materials with a given degree of tolerance (i.e., how it is to be done); while both of these factors must enter into our equations to determine the amount of work that must be done to complete the job within a reasonable amount of time. This latter information provides a job description that hopefully gets an equivalence class of existing machines rather than a class that might accomplish the feat in principle but not in practice (i.e., implies the nature of the who or what required to do the task). (p. 311)

A Parallel Between Evolution and Learning

In search of a general orientation to the nature of tasks, processes and agents as they bear on the issue of skill acquisition, we are drawn to the parallel between a species participating in the slow process of evolution and an individual animal participating in the comparatively rapid process of learning.

From a perspective that encompasses the whole evolving world of living systems, any given species appears to be a "special purpose device" whose salient properties are those that distinguish the given species from other species. These salient properties, synchronically described, mark the state of adaptation of the species to the special and relatively invariant properties of its environment. In the course of time, the species maintains its special attunement by coupling its evolution to that of its changing environment.

If the perspective is considerably narrower, encompassing only the lifetime and habitat of an individual animal, then the system being observed appears to be a "general purpose device" to the extent that the individual animal can enter into various temporary relationships with its environment. In the course of ontogeny, the individual animal adds to its repertoire of skilled acts.

It is roughly apparent that the "evolution" in ontogeny of a skilled act parallels the evolution of a species. Adaptation to an environment is synonymous with the evolution of special biological and behavioral features that are compatible (symmetrical) with special features of the environment. Similarly, we may claim that facility with a skill is synonymous with the ontogeny of special coordinative features that are compatible with the special features of the skill. Insofar as an environment has structure that provides the criteria for adaptation, so we may expect, not surprisingly, a task to have structure that provides the source of constraint on skilled solutions. Insofar as a species is said to be a particular biological attunement to a particular niche, we may wish to say, perhaps curiously, that the individual animal, as skilled performer, is a particular attunement to the particular task that it performs skillfully. This last and cryptic parallel must be commented on further, for aside from requiring clarification, it contains within it a potentially useful metaphor for the understanding of coordinated activity.
Consider the proposition that an animal and its environment are not logically separable, that one always implies the other. An animal's environment should not be construed in terms of the variables of physics as we commonly understand them; a considerably more useful conception is in terms of affordances (Gibson, 1977). An affordance is not easily defined, but the following may be taken as a working approximation: "The affordance of anything is a specific combination of the properties of its substance and its surfaces taken with reference to an animal" (Gibson, 1977, p. 67). Thus, for example, the combination of the surface and substance properties of rigidity, levelness, flatness and extendedness identifies a surface of support for the upright posture and locomotory activity of humans. Put another way, an object or situation, as an invariant combination of surface variables, affords a certain activity for a given animal if, and only if, there is a mutual compatibility between the animal, on the one hand, and the object or situation on the other.

Affordances are the aspects of the world to which adaptations occur. Consequently, we can now identify the special features of the environment referred to above as a set of affordances, equate a "set of affordances" with a "niche" (Gibson, 1977) and recognize that a set of affordances is perceptually and behaviorally occupied by an animal. It is in this sense that an animal and an environment are not logically separable; for a niche implies a particular kind of animal and a species implies a particular kind of niche (Gibson, 1977).

A crude but useful metaphor is that the fit between an animal and its niche is like the fit between the pieces of a jigsaw puzzle. Figure 1 depicts the fit for a minimally complex puzzle. Following the jigsaw puzzle metaphor, adaptation and attunement are synonyms for the fit of a species to a niche. It is in this same metaphorical sense that skill acquisition can be understood as attunement: in terms of a two-piece jigsaw puzzle, one piece is an appropriate dynamical description of the skill and the other piece is an appropriate and complementary dynamical description of the animal.

The Actor as a Mimicking Automaton

To pursue further the idea of skill acquisition as attunement, let us return to the notion of the individual animal as a general purpose device. The animal of interest to us is, of course, human. In deliberations on perception, the human is often referred to as the perceiver; in deliberations on action, therefore, it seems appropriate to refer to the human as the actor.

We wish to claim that the individual actor is a general purpose device, not because he or she has the capacity to apply a single, general purpose action strategy to the skill problems encountered, but because he or she has the capacity to become a variety of special purpose devices, that is, a variety of specific automata.1 The distinction between these two kinds of

---

1Turvey, Shaw and Mace (in press) have introduced a similar distinction between "hierarchies" and "coalitions." In the context of the present discussion, a hierarchy is a general-purpose device of the first type and a coalition a general-purpose device of the second type.
general purpose devices is depicted crudely in Figure 2. One device can accept only one program and generalizes that program across a variety of tasks. The other device can accept a variety of programs, one program for each of a variety of tasks. The familiar paradigm for learning theory, associationism, identifies the actor as a general purpose device of the first kind. It can be shown that a formal statement of associationism, the Terminal Meta-Postulate (Bever, Fodor and Garrett, 1968), is formally equivalent to a strictly finite state automaton that accepts only one-sided (right or left) linear grammars (Suppes, 1969). Such an automaton is formally incapable of natural language and complex coordinated movements, to name but a few limitations. A person, on the other hand, is obviously capable of such things and more besides. Nevertheless, it is reasonably fair to claim that, on the grounds of mortality and finite computing capacity, our actor, a person, is a machine with finite states. How then does he behave as if he were a machine of a more powerful kind, such as a linear-bounded automaton that accepts context-sensitive grammars? One hypothesis (Shaw, Halwes and Jenkins, 1966) is that the class of finite state machines that best characterizes the individual person is that of finite state transducers. These machines transduce the behavior of more powerful machines into equivalent finite state behaviors; they are capable of processing the same inputs as more powerful machines, but only up to some finite limit. In short, the individual actor as a finite state transducer can "mimic" the competency of more powerful automata, that is to say, he or she can become, within limits, any one of a variety of special purpose devices whose complexity is compatible with the complexity of the task it must perform.

We do not wish to push the interpretation of the actor as finite state transducer too far. We wish to view it more as an analogy, for there are reasons to believe that the general machine conception, of which finite state transducers and the like are examples, may well be inappropriate for biology. Nevertheless, the preceding is sufficiently instructive for our current purposes: it identifies our general orientation to the agent—that is, the actor—as a mimicking automaton. We can now make a further comment on the idea of skill acquisition as attunement: it is, in large part, the idea that an actor becomes that particular kind of machine that is consonant with the essential feature of the particular skill that the actor is performing.

Summary

We summarize these prefatory remarks with a tentative answer to the question: What is it about an actor and about the skills that he seeks to perform that he can (learn to) make of himself a variety of special purpose devices? First, in reference to the nature of the actor: the relationships among muscles are sufficiently plastic so that within limits, actors are able to constrain or organize their musculature into different systems. From this perspective, learning a skill involves discovering an optimal self-organization. Second, in reference to the nature of skills: skills have structure, and discovering an optimal self-organization is in reference to

---

those variables of stimulation corresponding to environmental and biokinematic relations that specify the essential features of the skill the actor is to perform. This raises the important question of what are the useful skill-specific variables of stimulation that, in the course of acquiring a skill, guide and regulate the current approximation and prescribe the next approximation to the desired performance (attunement). Third, in reference to the nature of the processes supporting learning: insofar as the useful skill-related information must be discovered, the actor must engage certain "search methods" that reveal that useful information to him. These search methods must be compatible with the actor, that is to say, they must be compatible with, for example, real-world mechanical and temporal constraints that natural (as opposed to abstract) actors must obey.

DEFINING THE DOMAIN OF SKILL ACQUISITION FOR A THEORIST

In seeking an explanation of anything, it is important that the forms of theoretical and investigatory attention be a domain of entities and functions that is optimal to the particular problem under investigation. "Optimal domain" means two things. First, any decision to investigate a problem involves selecting some system (some collective of entities and functions) as the minimal one that is relevant to the problem's explanation. If the selected system excludes some entities and functions that are, in fact, crucial to the explanation, they exert an influence on the selected system that, from the observer's perspective, is random (see Bohm, 1957). In consequence, the system's behavior to those perturbations may be inexplicable.

Equally important is the second sense of "optimal domain." Any given system may be described at several different levels where each level is distinguished by the entities and functions to which its vocabulary refers. Importantly, different levels of description of a system make available to the theorist different concepts that he can invoke in his explanation (Medawar, 1973; Putnam, 1973). Which concepts are more useful to the theorist depend on what problem he has elected to explain.

What should be the minimal system for a theory of the acquisition and performance of skilled activity? At first blush, the actor looks to be the appropriate unit deserving observation and systematic measurement. With the actor as the minimal system, the concept of coordination can be judiciously defined in terms of relationships defined over the muscles and joints of the body. The locus of movement control can be given relatively precise coordinates, namely, the nervous system of the actor. However, in taking the actor as the minimal system, we adopt a myopic view of the contribution of the environment to coordinated activity. This is not to say that an actor-oriented approach to the theory rejects the environment's contribution, but rather that it detracts from a serious analysis of the environment as the necessary support for coordinated, skilled movements. An actor-oriented perspective on skill, with its pinpointing of the actor as the source of control, encourages the impoverished description of information about the environment as sensory signals whose meaning is contributed wholly by the actor (see Schmidt, 1975).
The claim we wish to make is that a superordinate system, one that encompasses the actor, his actions and the environmental support for his actions, is the minimal system whose observation will permit an adequate explanation of the regulation and acquisition of skilled performance. To anticipate, this minimal system will be referred to as an event. From the perspective of this system, coordination is a relation defined over the actor and the environment, and control is the exclusive prerogative of neither.

What should be the level of description for this minimal system? Putatively, the theorist who aims to explain the acquisition and performance of skilled activities should select a level of description that is compatible with an actor's own self-description and with the actor's descriptions of the environment. The theorist should select a grain-size vocabulary that, in reference to skilled activity, includes those entities and functions that are regulated by actors and those entities and functions that are regulative of actors.

Our previous discussions of coordinated movement (Fowler, 1977; Turvey, 1977b; Turvey, Shaw and Mace, in press) may be characterized as attempts to select and define an appropriate level of description of acting animals and of the environments in which they act. We will summarize and elaborate on those attempts in the remarks that follow.

Events as Significant Units of Observation in a Theory of Skilled Action

An act performed in a natural context has two sources of control: one is the actor himself, and the other is the environment in which the act occurs.

To achieve some aim, whatever it may be, an actor engages in a systemic relationship with the environment. That is, he regulates his body in relation to environmental sources of control such as gravitational and frictional forces. His task, then, is quite different from one of producing an act in vacuo; it is to generate a set of forces that, together with the environmental forces impinging on him, are sufficient to achieve his aim. In the sense of the jigsaw puzzle metaphor, the forces supplied by the actor complement those supplied by the environment. Furthermore, the actor's aim itself is not entirely a product of his own will. Rather, it must be some selection on his part among the limited possibilities afforded by the environment.

In short, we can say that actors and their environments participate in a larger system that we will call an "event," following the usage of Shaw, McIntyre and Mace (1974). Structurally described, an event includes the actor and the environmental support for his actions. "Environmental support" includes the surfaces, objects and living systems in relation to which the actor governs his behavior and, in addition, the structured media (such as the ambient light and air) that provide the actor with an event's functional description— that is, with a specification of what is happening in the course of an act.

Two principles derive from the foregoing discussion. First, an actor controls the functional description of an event rather than the functional description of his own body; and second, an appropriate observational perspec-
tive of a theorist of skilled action is a perspective that encompasses events rather than actors only. The two principles are illustrated in the following example.

Consider a person changing a flat tire on his car. The tire-changing event includes the actor's removing the spare tire and jack from the trunk of his car, jacking up the car and replacing the flat tire with the spare. The actor's movements in the course of the tire-changing event and his (inferred) self-commands to movement have no apparent rationale if they are observed in isolation. For instance, the rhythmic up and down gestures of the actor's arms during one phase of the event may be rationalized by an observer only if he recognizes that the arms are operating the handle of the jack and that the flat tire is being raised off the ground.

More than simply controlling his own movements, an actor controls the character of the event in which one of the participants is himself and the other is the environment. He deems his performance successful if he imposes his intentions on the character of the event. Put another way, an actor has achieved his aim if an observer's description of the event in which the actor participates is synonymous with the actor's description of his intentions.

In sum, an appropriate observational perspective for a theorist includes both the actor and the environment in which he acts. A more limited perspective that excludes or minimizes the environment is likely to remove the means by which an observer can either detect the actor's intent or rationalize aspects of his performance.

An Appropriate Level of Description of Events, Actors and Environments

Events have been promoted as the minimal systems to be observed for the development of an adequate theory of skilled action. Primarily, the grounds for this selection are that no systems smaller than events encompass those entities and functions over which actors exert their control. The same kind of selection criterion may be invoked in a choice of "level of description." Having selected an observational unit, it is necessary to choose a descriptive vocabulary for it. Again, it seems most appropriate to select a grain-size of vocabulary such that its referent entities and functions are those that populate the actor's habitat from his observational perspective, because those are the things with which he deals in the course of his actions.

In the next sections we will select a level of description of an actor and of his habitat. In the case of an actor, our aim is to select a vocabulary that mimics the effective self-descriptions putatively invoked by actors as a means of controlling their actions. Similarly, our aim is to select a level of description of the environmental media that is isomorphic with the grain-size of the information detected by actors. Hypothetically, a description of the structured media that captures the significant information for actors is concomitantly a description of the environmental entities and functions that, from the actor's perspective, constitute his habitat (see Shaw et al., 1974; Gibson, 1977).
The Actor. An actor can be described exhaustively in several ways where each "way" is defined by the primitive entities to which its vocabulary refers. These ways are significantly restricted if we assume that the aim of a theory of coordinated activity is to specify what an actor controls when he performs an act. In this respect, it is not surprising that no one has ever devised a theory of coordinated activity in which the primitive units of vocabulary are the individual cells or molecules of the actor's body.

Presumably, two reasons why neither cells nor molecules have been proposed as the primitive entities of a theory of action are, on the one hand, that an actor could not possibly control those microscopic entities and, on the other hand, that even if he could, he would not choose to do so. For each cell whose trajectory he wished to control, an actor would have to provide values for as many as six degrees of freedom. It is inconceivable that he could continuously set and reset the values of the six degrees of freedom of the millions of cells whose state trajectories are regulated in the course of an act.

Even if he could control that many degrees of freedom, to do so would constitute a gross violation of a principle of least effort. The cells in the actor's body are constrained to act as systems of cells. The degrees of freedom of these collectives are orders of magnitude fewer than the summed degrees of freedom of the individual cells in the collectives. A more abstract level of description of an actor than one whose primitive entities are cells, captures these constraints on classes of cells by treating each class or collective as an irreducible unit. Thus "deltoid muscle" refers to a collective of cells that are constrained to act as a unit.

If an actor exploits an abstract level of self-description on which muscles are irreducible units, he indirectly takes care of the vast multitudes of degrees of freedom of his individual cells by directly controlling the many fewer degrees of freedom of collectives of cells.

What is more, the "muscular" level of description is less powerful, but in a useful way, than a microscopic level. If an actor were to control his individual cells directly, he would specify values for their trajectories that he could never achieve because they violate the constraints on collectives of cells (for example, the combined trajectories might entail the disintegration of a muscle). In order to preclude such violations, the actor would have to know a set of rules for combining cell trajectories. However, he can avoid knowing anything about these rules if he selects a more abstract way of describing himself.

We have belabored the obvious point that actors control larger entities than cells and molecules in order to bring out some reasons why one level of description of an actor may be more useful to a theorist than another. Let us

---

3The six degrees of freedom are the values of the instantaneous positions and velocities of a cell on each of the three spatial coordinate axes.
summarize these arguments before suggesting a less obvious point—that a level of description on which muscles are the irreducible units may not be sufficiently coarse-grained to be useful either to an actor or to a theorist.

Some levels of self-description are impossible for an actor to use because they demand that he provide values for vast numbers of degrees of freedom. Relatively macroscopic or abstract levels of self-description help to solve the "degree of freedom problem" (see Turvey et al., in press) by classifying the entities of the microscopic level and hence their degrees of freedom. The abstract levels provide one label for large numbers of elementary units that are constrained to act as a collective. By controlling the few degrees of freedom of the collective, the actor thereby regulates the many degrees of freedom of the components. The more abstract description is the less powerful one, but it is less powerful in a useful way. It allows the actor to know less of the details of the system that he controls, but to regulate it more easily and effectively (see Greene, 1969, 1972). Finally, concepts emerge (for example, "muscles") at a macroscopic level of description that do not exist on microscopic levels because the concepts refer to constraints on, or patternings of, entities that are treated as individuals on a microscopic level (see Medawar, 1973; Putnam, 1973).

Several theorists and investigators have proposed that an actor controls groups of muscles rather than individual muscles (for example, Weiss, 1941; Easton, 1972; Turvey, 1977b). Their reasons for preferring the more abstract description of an actor are those given above. An actor cannot govern his muscles individually because to specify values for their total number of degrees of freedom would be impractical if relevant cost variables are considered (Shaw and McIntyre, 1974; Turvey et al., in press). Greene (1969) estimates that there are over forty degrees of freedom in the hand, arm and shoulder alone, and dozens more in the trunk, shoulders and neck. Furthermore, the relationships between a central command to a muscle, the muscle's behavior and the movements of a limb are indeterminate both physiologically and mechanically (see Hubbard, 1960; Bernstein, 1967; Grillner, 1975; Turvey, 1977b). Commands to individual muscles would appear to constitute an inappropriate vocabulary of control for an actor.

Yet, even if an actor could control his individual muscles, there are reasons for believing that he would not choose to do so. First, the actor's muscles are organized into functional collectives. Some collectives, the reflexes, appear to be "prefabricated" (Easton, 1972). However, many—those involved in locomotion for instance (for example, Grillner, 1975; Shik and Orlovskii, 1976)—are marshalled temporarily and expressly for the purpose of performing a particular act. There is ample evidence that these systems of muscles that we have called "coordinative structures" (Fowler, 1977; Turvey, 1977b; Turvey et al., in press) after Easton (1972), are invoked by actors in the performance of large varieties of acts (for example, speech: see Fowler, 1977, for a review; locomotion: see Grillner, 1975, for a review; swallowing, chewing: Doty, 1968; Sessle and Hannam, 1975). The actor's organization of his musculature into coordinative structures that are especially appropriate to the performance of a limited class of acts is what we mean when we describe an organism as a general-purpose device by virtue of its capacity to become a variety of special purpose devices.
The constraints on groups of muscles that organize them into collectives are different in kind from those on some groups of cells, for instance those that constitute a bone and perhaps those that constitute a muscle. The label "bone" refers to a group of cells constrained to adopt a particular macroscopic form. It seems clear in this case that the constraints have exhausted the configurational degrees of freedom of those cells. The result is a rigid body. In contrast, the constraints that yield a coordinative structure appear to be a kind that Pattee (1973) calls control constraints. Control constraints, like structural constraints, are classifications of the degree of freedom of elementary components of a system, but they regulate the trajectories of a system rather than its configuration. Hence, a coordinative structure is a four-dimensional system that may be identified by what it does.

If the actor's vocabulary of self-description or self-control refers to coordinative structures rather than muscles or, equivalently, if it refers to the control constraints on this musculature, then apparently his descriptions are functional in nature.

A level of self-description in which the coordinative structure constitutes the elemental unit of vocabulary is less powerful than one in which muscles are described but, again, the loss of power is beneficial to the actor. If muscles are the primitive units of description for the actor, then he can prescribe combinations of muscle contractions that never occur because they violate the constraints on groups of muscles. In the terms of Weiss (1941), the too-microscopic level of description cannot explain why actors limit themselves to coordinated movements and avoid "unorganized convulsions." The macroscopic level allows an actor to exploit the constraints on groups of muscles that putatively limit him to performing coordinated movements.

Finally, on the coarse-grained level of description, concepts or properties emerge (for example, in coordinative structures) that do not exist on the more detailed levels of description. These concepts or properties derive from the constraints on the individual elements of those detailed levels. For instance, the coordinative structures are nested. This property is well-documented again for the relatively simple act of locomotion (for example, Easton, 1972; Grillner, 1975). Each coordinative structure governs an activity. A nested set of coordinative structures may govern a long sequence of movements with little detailed executive control being required of the actor. In fact, the sequence of autonomously generated movements may be indefinitely long as in walking or chewing or breathing, if the "repertoire" of the nested coordinative structures regenerates itself cyclically (see Fowler, 1977).

Since many of the coordinative structures are not "prefabricated," the problem for an actor is to marshall those groups of muscles that will accomplish his purposes. The view of an actor provided by a coarse-grained description of him suggests the forming of relevant coordinative structures as a primary problem of skill acquisition.

The Environment in Relation to an Actor

Environmental Affordances. A component of an environment populates an actor's world only if the actor can engage in some relationship with it that
has significance for him. More simply, the meaning of the component for an actor is captured by specifying the set of events in which the actor and component may participate (see Sperry, 1952; Shaw et al., 1974; Gibson, 1977). These potential relationships between actors and environment-components are what we called earlier the "affordances" of the components for the actor.

We can provide a different perspective on the concept of "affordance" by reexamining the nature of an event. The character of an event, in particular its functional description, is determined by the totality of forces exerted by and on the various event-participants. Among the forces that shape the character of an event are gravitational forces, which are extrinsic to the actor, and frictional and contact forces, which are generated by the actor's encounter with the environment. In addition to these, are the forces that enable an actor more directly to regulate the character of an event. They are the forces generated by the actor's own muscular activity.

Clearly, actors cannot achieve an aim to perform an act by generating all of the forces necessary to get the job done. Rather, they must contribute to the totality of extant forces just those muscular forces that will bend the character of an event in the desired direction.

By hypothesis, the affordances of an environment for an actor, as given in the structured environmental media, are the sets of forces (of adaptive significance to him) that the actor can generate in collaboration with the extant forces, and the relation to the environment. The totality of forces that the actor selects from among the potential ones defines his intent. For a skilled actor, the intent becomes, through his muscular efforts, the functional description of the event.

The Structured Media. The structured media, that is, the ambient light and air, etc., apprise actors of the properties of an event; they are said to contain information about events in the sense of specificity to events.

The media are components of an environment that, relative to other components, are compliant. Thus, for example, when light contacts some surface, the light but not the surface is significantly altered. In particular, the amounts of light reflected from a surface in a given direction and the wavelengths of the light are specific to various properties of the surfaces; the slant of the surface relative to the source of radiant light, its composition and so on. Hence the light, on contact with the surface, is constrained (or is patterned) in its subsequent behavior by the properties of the surface. Furthermore, the patterning of the rays of light is specific to the source of its patterning. Therefore, the structure in the light is isomorphic, though abstractly so, with the properties of the structure's source. Just as an environment is constituted of nestings of entities and functions, a medium contains structure of various grain-sizes. However, the structure of interest to an actor and to a theorist is only that which is specific to, or isomorphic with, the properties of the event in which the actor is participating. The environmental entities and functions that are specified to an actor by the structure of a medium are just those whose properties are of adaptive significance to him.
We believe that this is a crucial observation. The light to an eye is amenable, as is the actor himself, to various levels of description (see Mace, 1977). Typically, as Gibson has noted (for example, 1961), theorists take as their unit of description the individual ray of light that has only the properties of wavelength and intensity. The individual rays are meaningless to an actor; pursued through his nervous system, they excite receptors on the retina and are transformed into still-meaningless "raw" sensory signals (for example, Schmidt, 1975). They are supposed to acquire significance only as the actor learns to assign meaning to them via the efforts of his community of coactors who provide him with "knowledge of results."

This view is fostered by a too microscopic level of description of the light and of its neural consequences. In particular, it is too fine-grained to represent what in the light is genuinely informative and significant to an actor, just as the levels of description of an actor in which cells or muscles are the descriptive units are too fine-grained to capture the properties of the muscle systems that actors exploit. That level of description of the light that considers only two variables (intensity and wavelength) fails to capture any of the constraints on the paths, spectral compositions and intensities of bundles of light rays that are specific to (and hence that specify to a perceiver) the environmental sources of the constraints. In contrast, if the sensitivity of perceptual systems is not to the microscopic properties of a structured medium, but rather to the constraints or to the structure itself—that is, to a macroscopic level of description of the medium—then actors need not learn to manufacture a significance for stimulation. The meaning or significance is the set of properties in the environment that structured the light and therefore, that are specified by it with reference to an actor.

Other investigators have cataloged some of the information in the structured light available to an actor (for example, Gibson, 1958, 1961, 1966, 1968; Lee, 1974, 1976; Turvey, 1975, 1977a, 1977b). Here we provide only a brief description, but one that is sufficient for our later consideration of the role of higher-order variables of stimulation in the control and acquisition of skilled acts.

The patterning of the ambient light to an eye provides an actor with information about: (1) the layout of environmental surfaces and objects, (2) what is happening in the course of an event, (3) what is about to happen and when it will occur, and (4) the possibilities for control by the actor over what happens. We will consider each in turn.

Information About Layout Provided at a Stationary Point of Observation. The optic array is the set of light rays that reflect off of environmental surfaces and converge at all possible points of observation in the environment (Gibson, 1961). The portions of the array that converge at a single point of observation may be described as a nested set of "visual solid angles"4. A visual solid angle is a closed sector of the array with its apex at the point

of observation. It is set off from its neighboring angles by differences from them in the intensity and spectral composition of its component rays by light. Each visual solid angle corresponds to a component of the environment where a component may differ from its neighbors in shape, slant relative to the source of illumination, distance from the observer, and properties of its material composition that determine its spectral and nonspectral reflectance.

Some properties of the environmental correlates of a visual solid angle are specified by the angle's cross-sectional shape, its intensity, and its spectral composition. The borders of an angle typically correspond to the edges of an object in the environment.

Visual solid angles are nested because environmental surfaces and objects are textured. That is, the structure of an environmental surface or object is specified by a corresponding patterning of visual solid angles in the optic array.

More information about structure, as well as information about change, is given in a transforming, rather than a static, optic array.

The Structural and Functional Descriptions of Events Given by a Transforming Optic Array. According to Pittenger and Shaw (1975), two kinds of information exhaust the information-types provided by the structured media of an event. A structural invariant is information about shape or, more accurately, about persistent identity that is preserved across (physical) transformation. A transformational invariant is information about physical change that is preserved across the different structures that may support the change. (See also Turvey, 1977a). These two kinds of information provide an actor with an event's structural and functional descriptions.

As an actor moves through an environment, he continually changes his observational perspective of it. If (solely for convenience) we describe this continuous change of perspective as a succession of discrete changes, we may say that the moving observer successively intercepts new observation points as he moves. The optic array at each of these fictitiously abstracted observation points constitutes information about layout of the sort described in the preceding section. The information at one observation point may or may not be sufficient to specify unambiguously to an observer the layout of environmental surfaces and other components relative to him. However, there is only one environmental layout that is consistently possible across a set of connected observation points (Gibson, 1966). More accurately, the layout of environmental surfaces that is given in a transforming optic array is just that one layout whose persistent identity is specified throughout the transformation.

A global transformation of the optic array is effected when an actor changes his perspective on the environment. What is invariant (or what has persistent identity) across perspectives is the environmental layout. What changes with the observation point is information about the actor's perspective on the environment. That is, a global transformation of the optical structure is effected by the actor's movements and continually provides information on his relationship to the components of the environment. In short, global transformations of the optic array are specific to an observer.
and to his path through the environment (Lishman and Lee, 1973; Lee and Aaronson, 1974; Lee, 1976; Warren, 1976).

Now consider object motion from a stationary perspective. As an object in the environment changes its location relative to a stationary point of observation, its corresponding visual solid angle in the optic array undergoes transformation. The nature of the changing relationship between observer and observed is specified, in part, by the nature of the angle's transformation (that is, by the symmetrical or asymmetrical magnification or minification of the angle's cross-sectional area). More than this, it is also specified by the angle's progressive occlusion and disocclusion of those components of the optical structure that correspond to foreground and background components of the environment (Gibson, 1968).

For example, as an object approaches an observer head on, the cross-sectional area of the corresponding visual solid angle at the place of observation expands symmetrically. The bottom or leading edge of the angle progressively occludes foreground optical texture, while the top, or trailing edge, disoccludes the optical texture corresponding to the object's background. The lateral edges effect a shearing of optical texture.

Both kinds of transformation (that is, symmetrical magnification of a visual solid angle; occlusion, disocclusion and shearing of optical texture) specify motion in a restricted part of the environment and, in the absence of additional information that the actor is pulling the object towards him, specify motion due to forces extrinsic to the actor.

The Specification of Future Events. If an actor approaches a barrier or other object head on, the visual solid angle corresponding to it undergoes symmetrical magnification. Its rate of magnification specifies the actor's rate of approach. The fact that the magnification is symmetrical indicates to an appropriately attuned actor that he will collide with the barrier if the current inertial conditions continue. (A nonsymmetrical expansion indicates, depending on the degree of asymmetry, that the actor will bypass the barrier or that he will collide with it to the left or right of its center.) More than the fact of imminent collision, Schiff (1965) and Lee (1974, 1976) show that the time-to-collision is also specified to an observer by the transforming optical structure.

Thus, the macroscopic patterning of the transforming optic array provides the actor with information about what is currently happening and with information about what will happen if the current conditions persist (see Lee, 1976).

The Affordance Structure of Events. Of major importance to an actor attempting to impose his intentions on the character of an event is information that prescribes to him the directions in which his contributions of muscular force can alter the current inertial conditions. To take a simple example: when we say that a surface affords locomotion for an actor, we mean, in part, that the ambient light (or some other structured medium) specifies to the actor the nature of the reactive forces (the frictional and contact forces) that the surface will supply, given his attempts to walk on it.
Information about the rigidity of a surface and about its slant and composition is concomitantly information about the surface's potential to participate in an event that includes the actor's walking on it.

This information is only information about walk-on-ability in relation to additional information about the actor's somatotype, however. That is, the affordances of a surface (or object) are the events in which the surface and the actor may participate, and they are contingent on the properties of the surface considered not absolutely, but relative, to properties of an actor. Hence, to detect the affordances of an environment-component, the actor has to detect body-scaled information—that is, information about the component's properties relative to his own.

Lee's (1974) analysis of the optical information available to a locomoting observer indicates that information about the position coordinates of objects in the environment and information about the actor's rate and acceleration of movement are provided in units of the observer's own height. Is it possible that information about the actor's general build and perhaps, therefore, about his potential to contribute to the forces governing an event is provided in global transformations of the optic array? When he is walking, there are global transformations due to his sinusoidally shifting center of gravity. The extent of shift in the left-right and up-down directions as well as in the direction of walking may correlate with an actor's size and weight.

These shifts in the center of gravity effect rhythmic changes in the horizontal and vertical distance of the actor's head from components of the ground plane. Hence, the actor effects a transformation of optical structure that is specific to his rhythmically changing perspective on the environment. If the transformation in turn is specific to the actor's somatotype, it also provides information about his potential to contribute muscular force to an event.

Concluding Remarks: Increasing Controllable Degrees of Freedom so as to Secure Certain Reactive Forces

We began by selecting an observational domain for a theory of skilled action that we labeled an "event." We considered events to be the minimal observational domains that include, on the one hand, all of the entities and functions over which actors exert their control and, on the other hand, the entities and functions that are regulative of actors. Following that, we selected compatible descriptive vocabularies for the different components of an event. Our selections are more coarse-grained than the vocabularies typically adopted by theorists of skilled action. However, we defended them on the grounds that it is precisely the patternings over microscopic entities and functions that are signified to actors and not the microscopic components themselves.

Our method of selecting the descriptive vocabularies was one that fractionated the event into its components. We will conclude this section of the paper by reconstructing the event concept and by describing one way in which it enriches a developing theory of skilled action and skill acquisition.
One orientation to coordinated activity, as cited above, is that acts are produced through the fitting together of autonomous subsystems (coordinative structures), each of which "solves" a limited aspect of the action problem. In this orientation, the actor's plan, that is, his abstract self-description, is regarded as the specification of that which remains when the contribution of the autonomous subsystems is subtracted out. The action plan supplies the coordination that is not supplied by the coordinative structures.

Precisely what is it that coordinative structures supply? One answer might be that they autonomously supply certain relations among various parts of the body. The difficulty with this answer is that, left unqualified, it steers dangerously close to an "Air Theory" formulation (see Gibson, 1950) of coordinated activity in which the actor, for all intents and purposes, is construed as suspended in a vacuum oblivious to external environmental forces. An "Air Theory" formulation speaks more to the mining of coordinated activity than to coordinated activity itself, for coordinated activity requires environmental support for its proper functioning.

Necessarily, an event perspective expresses the contribution of the environment to coordination. Coordination in the event perspective is defined not in terms of biokinematic relationships (that would be so if the actor were taken as the unit of analysis), but in terms of relationships among forces, those forces supplied muscually by the actor and those supplied reactively and otherwise by the environment. The surfaces of support, the participating structures (such as other actors, striking implements, etc.), the biokinematic links and gravity, provide the actor with a large potential of reactive forces. This emphasis on what the environment provides characterizes the event perspective as a "Ground Theory" formulation of coordinated activity: an activity cannot logically be separated from its environmental support.

Consider environmental surfaces. These afford reactive forces that are opposite and approximately equal (although not always equal; it depends on the composition of the surface) to the forces generated by muscle activity. Thus in walking, the actor secures by his muscular efforts reactive forces that propel the body forward at one moment and restrain the forward motion of the trunk at the next. In leaping a high barrier, the actor applies his muscular forces in such a fashion as to secure reactive forces that are more nearly vertical than horizontal.

Of course, when the actor is not in contact with a supporting surface but is moving in the air, then the equal and opposite reaction to a motion of parts of the body occurs within the body itself. Swiftly moving the arm at shoulder level from a sideward to a forward position will rotate the body about its longitudinal axis in the direction of the moving arm. This aside bears significantly on the contrast between the actor/air theory formulation and the event/ground theory formulation in that the same movement performed when the body is in the air and when it is in contact with a rigid surface secures very different reactive forces with very different coordinative consequences.

Consider biokinematic chains. These obey the principles of kinematic chains in general; for example, a controlled movement of one link of the chain
Figure 1: The jigsaw puzzle metaphor.

Figure 2: Two kinds of general purpose devices. The one on the left accepts only one program and generalizes that program across a variety of tasks. The one on the right accepts a variety of programs, one program for each of a variety of tasks.
Figure 3: Exemplary solution strategies for two Krinskiy and Shik problems. The starting coordinates represent the angles of the subject's joints at the outset of the task and the target coordinates represent the values which minimize the function.

Figure 4: An individual control system.
Figure 5: A stack of control systems: three first-order systems nested under one second-order system.

Figure 6: Movement strategies of the computer model (compare with Figure 3).
will be accompanied by relatively uncontrolled movements in the other passive links of the chain. Obviously, for a biokinematic chain such as an arm or a leg, muscular forces are not the only forces acting on the chain; besides gravity there are the kinetic energies and moments of force that necessarily accompany movements of the individual links.

A further and related principle of kinematic chains is that the design of a chain—the lengths and masses of its links, the manner of their joining and the degrees of freedom of the joints—determines the kind of curves that the chain can trace out over time. Now an actor can modify the design of a biokinematic chain and, therefore, its potential trajectories, in a very simple way: he can selectively freeze the degrees of freedom and vary the range of joint movement. The significance of this is that for any desired trajectory of a limb, elaborate control on the part of the actor—even moment-to-moment computation—may be needed to secure the trajectory given one "design" of the limb, yet very little computation may be needed given another, very different "design." The point is that, with an appropriate design, the reactive forces that are concomitant to movement of the chain as a whole may contribute significantly to the production of the trajectory, but with an inappropriate design, the reactive forces that accompany the chain's movement may contribute little to the desired trajectory and may even oppose it.

In this regard, consider the emergence of an effective sidearm strike pattern (hitting a ball baseball-style) in preschool children (see Wickstrom, 1970). The development of the skill is realized through the following changes: a more liberal swing due to an increase in the range of motion of the participating joints; increasing usage of the forward step or forward weight shift to initiate the strike pattern, and increasing pelvic and trunk rotation prior to the swing of the arms (in the earliest stages of acquisition, pelvic and trunk rotation occur as a result of the strike with the pattern being initiated by the arm motion). One way of looking at these changes is that they index transformations in the "design" of biokinematic chains. The two arms, coupled at the bat, constitute a biokinematic chain whose design is made more effective for the task by increased unlocking of the wrists and greater flexion at the elbows. The body as a whole is a biokinematic chain, the design of which is made more effective for striking by adding the degrees of freedom of trunk rotation and pelvic rotation. To paraphrase our remarks above, a more effective design of a limb or a body is one in which the reactive forces concomitant to movement are largely responsible for the achievement of the desired trajectory.

Another way of looking at these changes, however, observes that an actor, naive to a particular skill, curtails biokinematic degrees of freedom—through the complete immobilization of some joints (that are used when the skill is performed expertly) and a restriction on the range of motion of other joints—because he or she lacks a means of controlling the biokinematic degrees of freedom in the manner that the skill demands. It then follows that increasing expertise is indexed by a gradual raising of the ban on degrees of freedom (to borrow Bernstein's most apt phrase). Or, to put it slightly differently, increasing the number of controllable biokinematic degrees of freedom is synonymous with becoming more expert. As Bernstein (1967, p. 127) remarks: "The coordination of movement is the process of mastering redundant degrees of
freedom of the moving organ, in other words its conversion to a controllable system."

In short, the changes indexing the acquisition of the batting skill can be interpreted in (at least) two ways: in one, as the converting of biokinematic degrees of freedom into controllable systems (coordinative structures), and in the other, as the designing of biokinematic chains so as to secure certain reactive forces. Surely these two interpretations are dual. By increasing the controllable degrees of freedom, the actor increases the potential variability of reactive forces that accompany the activity, thereby increasing the opportunity to discover what the activity-relevant reactive forces might afford by way of control. In the discovery of activity-relevant reactive forces, the actor prescribes the conversion of redundant degrees of freedom into controllable systems.

Let us summarize the tenor of these remarks. On the "Air Theory" formulation of coordinated activity, an executive must supply that control that the coordinative structures do not supply. On the "Ground Theory" formulation, an actor must supply that control that the external force field does not supply. In a blend of the two formulations we can say that, in the performance of an athletic skill, coordinative structures are so organized as to secure certain reactive forces; by the felicitous organization of coordinative structures the actor bends the force function that is given to yield the force function that is desired. In the grain-size of analysis prescribed by the event perspective, it is neither muscles nor joints that are coordinated in the performance of athletic skill, but forces--those supplied by the actor and those supplied by the environment.

ON CONVERTING BIOKINETIC FREE-VARIABLES INTO A CONTROLLABLE SYSTEM

In this third section we address the question of how an actor forms a controllable system [in Bernstein's (1967) terms] or a coordinative structure (in our terms). In the description of the actor developed in the second section, it was concluded that an act is more optimally described in terms of autonomous collectives of free-variables than in terms of the free-variables themselves, that is, the individual muscles or joints. To lay the groundwork for the analysis that follows, we identify three aspects of the problem of forming such collectives. These aspects are described abstractly; they are, however, reasonably intuitive. Moreover, they may be considered as fundamental aspects of all coordinative problems and we will attempt to show how they relate closely to the summary remarks of the first section.

Three Intuitions Relating to Action Problems

First, we believe that in a general but nontrivial sense, the problem of forming a coordinative structure or controllable system may be characterized, in part, in the following fashion: given an aggregate of relatively independent biokinematic degrees of freedom, how can the aggregate be so constrained, the individual degrees of freedom so harnessed, as to produce a particular,
simple change in a particular single variable. Thus, for example, to minimize the displacement of the point of intersection of the line of aim with the target, experienced marksmen constrain the joints of the weapon arm in such a fashion that the horizontal displacements of the individual kinematic links are reciprocally related (a form of constraint that is not at the disposal of the novice) (Arutyunyan, Gurfinkel and Mirskii, 1968, 1969). In paraphrase of the above intuition we may say, therefore, that the problem of forming a coordinative structure or controllable system is, in part, the problem of discovering the relevant constraint for a collection of many (fine-grain) variables, such as individual joints, that will realize a particular (coarse-grain) variable, such as a limb trajectory. In a somewhat different vernacular, it is the pattern of discovering the equivalence class of optimal combinations of these variables (Greene, 1969).

One easily appreciates that during the acquisition of a skill the fine-grain variables do not present themselves in precisely the same way every time. The specific details, that is, the initial conditions of the fine-grain variables, are not standardized. Nevertheless, the actor must select, on each occasion of the problem, one combination of the variables from the set of all possible combinations, and ideally, on each successive occasion the combination selected should approximate more closely the desired objective.

It is often remarked that the felicitous solution to problems of coordination is made possible by "knowledge of results" identified as information about whether an attempted solution (say, a particular movement) was right or wrong (qualitative knowledge of results), and if wrong, by how much (quantitative knowledge of results). Thus, Adams (1976) comments:

The human learning of motor movement is based on knowledge of results, or information about error in responding. Knowledge of results can be coarse, like "Right" or "Wrong" or it can be fine grain, like "You moved 2.5 inches too long." (p. 216)

In our view this is a gratuitous claim. In the general case, information about degree of nearness to a desired outcome will be insufficient informational support for arriving at a solution to the coordination problem. Let us elaborate.

We identify the general case as discovering an optimal organization of, or constraint for, a number of free biokinematic variables. The argument can be made—consonant with the jigsaw puzzle metaphor—that for a system with \( \eta \) biokinematical degrees of freedom there ought to be at least \( \eta \) degrees of freedom in the information that supports the control of that system (Turvey et al., in press). These informational degrees of freedom can be most usefully understood as degrees of constraint (Turvey et al., in press). We can suppose, therefore, that discovering an optimal relation on \( \eta \) free-varying

---

5 We owe this manner of describing controllable systems to H. H. Pattee (for example, 1970, 1973). He considers the existence of control constraints an essential and distinguishing property of living systems.
biokinematic degrees of freedom requires that at least \( \eta \) degrees of constraint be available perceptually. We may hypothesize that in general, the ease and probability of discovering an optimal organization (that is, learning) relates directly to the extent to which degrees of constraint match degrees of freedom.

In discrete movement tasks (for example, Trowbridge and Cason, 1932), the actor must learn to move a limb or a limb segment a fixed distance. It is not difficult to imagine that in the acquisition of such simple tasks the actor freezes all the free-variables (joints) but one; that is, the actor manipulates a single biokinematic degree of freedom. The quantitative knowledge of results about how closely the movement approximated the desired distance is one degree of constraint that matches the one degree of freedom of the movement. Hence, in this case, quantitative knowledge of results is sufficient informational support for learning (see Adams, 1971). In the acquisition of an activity involving the regulation of more than one biokinematic degree of freedom, the single degree of constraint provided by quantitative knowledge of results would be inadequate. The fundamental point is this: quantitative knowledge of results specifies, in a limited sense, what not to do next but, significantly, it does not specify what to do next. The novice golfer who puts two meters to the right of the hole sees that he has erred, but this information, in and of itself, cannot tell him how to change the organization of his biokinematic free-variables so as to err less on the next occasion. If quantitative knowledge results were the only source of constraint on selecting combinations of biokinematic free-variables, then we may suppose that the search for the optimum combination would be essentially blind (that is, the combinations would be chosen at random) and, in principle, the search could proceed indefinitely.

A remedy for the inadequacy of quantitative knowledge of results is suggested by the two remaining notions. On the acceptance of the actor as a special-purpose problem solver, Gel'fand and Tsetlin (1962, 1972) asked what it is that might characterize, in general, the problems posed to the actor so that he might bring to bear specialized search procedures, tailor-made (presumably in the course of evolution) for such problems. They suggest that the actor might operate on the tacit assumption that the problems he encounters are well-organized in the sense that (1) the variables indigenous to a problem may be partitioned into essential (intensive) and nonessential (extensive) variables, and (2) that a variable is consistently a member of one or the other class. Given the assumption that the problem is well-organized, the actor can successfully apply a certain method of search through the space of constraints (for Gel'fand and Tsetlin it is the Ravine Method that is described below). The actor initiates the specialized search method ignorant of the actual pattern of organization of the problem; it is only in the course of the search that the pattern is disclosed (Gel'fand and Tsetlin, 1962).

Our second intuition, therefore, is that in a general but nontrivial sense, each and every problem confronting the skill-acquirer may be characterized as follows: with reference to the objective, there is an organization defined on the participating elements. The organization may be described as a function that is preserved invariantly over changes in the specific value of
its variables. We will speak, therefore, of the organizational invariant of a coordination problem. An invariant may be usefully defined for our purposes as information about something, in the sense of specificity to that something, that is preserved over relevant transformations (see Gibson, 1966; Shaw, McIntyre and Mace, 1974). By implication, the style of change imposed by an actor on the aggregate of variables is significant to the determination (detection) of the organizational invariant; put bluntly, not all classes of change will reveal the organizational invariant (see footnote 7).

The third intuition relates to the issue of how a search through combinations of many variables may be guided. Whatever we imagine the search method to be, it must necessarily be the case that the successive "experiments" conducted on the variables exploit information realized by the experiments. Our third intuition, therefore, is that in a general but nontrivial sense, there is available to the actor seeking to solve a coordination problem, information that specifies, relatively precisely, what to do next. Such information, we believe, may often take the form of abstract relations defined over variables of stimulation over time, and that becoming attuned to such information is part of the solution—developing, pari passu, with the isolating of the organizational invariant.

Let us relate the above three essential components of the acquisition of a controllable system to the concluding remarks of the first section, as follows:

1) An actor learns to make of himself a "special-purpose device" designed optimally for the task at hand. He does so by discovering an appropriate organization of his musculature that differs for different acts (for example, walking versus swimming).

Several sets of muscle-organizations may suffice to get a given job done, but some may be more efficient than others. For example, an actor learns to swim before he learns to swim skillfully. Following the work of Gel'fand and Tsetlin cited earlier, we suppose that species have evolved special strategies for selecting the most harmonious organization of muscle-systems among the restricted set of possible ones. Thus, the idea of the actor as a special-purpose device applies not only to the individual actor acquiring a particular skill, it also applies to the class of actors acquiring any skilled act. At this more coarse-grained level of description, any problem of skilled action may be described in part as a problem of optimizing a function of several variables (see above).

2) The skill to be acquired may be described as a set of potential constraints on the character of an event (as an organizational invariant). These constraints set boundary conditions on the possible muscle organizations that the actor can invoke to achieve his performance aims. Therefore, the actor's discovery of the organizational regularities of a task vastly simplifies his search for an optimal self-organization.

3) The efforts of a novice to perform an act may be viewed, in part, as discovery or search tactics aimed at revealing the organizational structure of the task.
The Experimental Task

The task that we have been investigating was designed by Krinskiy and Shik (1964). A subject is seated before a scale and instructed to make the scale-indicator point to zero. He controls the indicator position in this way: two of his joint angles (typically his elbow joints) are monitored continuously. The values of the two angles are input to a computer that transforms them according to the mapping: \[ E = |x-y-(a-b)| + a|x-a| + a|y-b| \]; \( x \) and \( y \) are variables that take on the values of the joint angles each time they are sampled; \( a \), \( b \), and \( \alpha \) are parameters that are changed across, but not within, experiments or trials. The equation controls the needle position on the scale. That is, the needle position corresponds in some simple way to \( E \). The subject can make the needle on the scale go to zero by finding the angles of his joints for which the mapping takes on the value \( E = 0 \). The needle points to zero when the subject has minimized the mapping.

The subject is unaware of the specific nature of the control that he has over the needle. He knows that by changing his joint angles he changes the needle position. However, he does not know that his joint angles are the \( x \) and \( y \) coordinates of some mapping whose output corresponds to the position of the scale-indicator. The starting position of the subject's joint angles may be varied or kept the same over trials. Likewise, the target values (the values of his joint angles at which the function is minimized) may be varied or maintained over trials.

Krinskiy and Shik provide a limited quantity of data in the form of graphs that depict the solution strategies of their subjects. Sample graphs are shown in Figure 3. The \( x \)-axis represents the value of one elbow-joint angle and the \( y \)-axis the value of the other. A diagonal line on the graph represents simultaneous changes of the joint angles on the part of the subject, while horizontal or vertical lines represent a change in just one angle. (The slopes of the lines in Figure 3 indicate that the rates of change of the two joint angles are the same; the slopes are approximately equal to one.) As the subjects approach the solution, they begin changing the values of the two joint angles individually.

Although the minimization task may seem an artificial one, it does have the essential components of a problem of skill acquisition that we have outlined. First, the equal velocities of the movement of the two forearms suggest an organization of the subjects' musculature that spans both joints (see Kots and Syrovoygin, 1966). In addition, an attractive property of the task for the purposes of investigation is that its organizational invariant is known to the investigator. (It is the mapping \( E = |x-y-(a-b)| + a|x-a| + a|y-b| \).) However, it is not known to the subject until his own movements reveal it to him as a lawful, though complex relationship between the changes of his joint angles and the movement of the needle on the scale. Apparently when the actor has learned the task, he controls the performance of a muscle-system. We will suggest that he does so by detecting the higher-order properties of optical stimulation that prescribe what he should do next, given his aim to set the scale-indicator to zero.

A final attractive property of the task is that it engages the subject in a search for the minimum of a function of several variables. In this regard it mimics a task that Gel'fand and Tsetlin (1962, 1971; see also Gel'fand,
Gurfinkel, Tsetlin and Shik, 1971) argue is characteristic of muscle-systems as they seek a maximally harmonious self-organization. An organization of muscle-systems that is maximally harmonious may be one in which the activities governed by the different muscle-systems do not compete. If we represent the interactions among the muscle systems as variables, then the search for a harmonious self-organization may be conceptualized as the search for the minimum of a function that encompasses the variables. Gel'fand and Tsetlin suggest that a set of search tactics has evolved, which they call ravine tactics, that are tailored to this kind of optimization task, although they may be ill-suited to other ones. We will describe these search tactics shortly. Here we merely note that the task of Krinskiy and Shik may not be, in fact, an artificial one in which an actor will engage. Indeed, it was devised to assess whether or not actors employ ravine tactics when given a task for which the tactics are especially suited.

Our contribution to the investigation of the minimization task has been to ask how a subject might learn to solve it efficiently. We have done so by modeling, with the aid of a computer, a skilled performer of the task. Instead of modeling directly the superficial properties of the strategy depicted in Figure 3, we attempted more simply to design a model that could perform the task without invoking blind or random search tactics. Our model uses a strategy that in its superficial properties is similar to the one depicted in Figure 3. The model initially changes both angles at a constant equal rate and as it nears the target values, changes the angles individually. It adopts this way of doing the task as a by-product of a deeper strategy— which is to exploit the higher-order variables of optical stimulation offered by the changes in the scale-indicator over time, in preference to the relatively uninformative value E given by the instantaneous needle position.

Before looking at this model, it is instructive to look at one that evidently cannot perform the task without invoking random search tactics (hence the model never becomes a skilled performer). This latter model is of interest because it is the model of Powers (1973) and it is consistent with the models of closed-loop motor performance proposed, for instance, by Adams (1971) and described by Greenwald (1970).

By showing that a model consistent with these theories cannot solve the task in a plausible way, we do not mean to imply that actors never use quantitative knowledge of results (here the value E) to regulate their motor performances. Indeed, the evidence cited by Adams (1971) and by Greenwald (1970) suggest this as a potent source of information in the acquisition of some skilled movements. We only wish to propose that actors are flexible and can adapt their acquisition strategies, within limits, to the useful dimensions of information provided by a particular problem.

We have selected the model of an actor/perceiver developed by Powers (1973) to serve as a prototypical model of closed-loop motor performance. This and other models of closed-loop performance evidently are general-purpose devices by virtue of having a single general-purpose acquisition strategy. We will show that the strategy is inappropriate to the solution of the task devised by Krinskiy and Shik; and we will suggest that its inapplicability extends to any skilled performance in which higher-order variables of stimulation provide the useful and controlling dimensions of information to an actor.
A Model of Closed-Loop Motor Control: Powers, 1973

For Powers, the nervous system of an actor/perceiver may be characterized as a hierarchy of control systems. Figure 4 depicts the structure of an individual control system. Each system works to realize a particular perceptual state of affairs and it accomplishes its aim in the way that a mechanical homeostatic device does. Its intent (its intended perceptual state of affairs) constitutes a reference signal, \( r \), for the system. That signal is compared periodically with the actual perceptual state of affairs, \( p \). Both sources of information to the control system, the reference signal and the perceptual signal, are conceptualized as quantities, in particular, as rates of neural firing.

The two quantities, \( r \) and \( p \), are subtracted in a comparator and the difference constitutes an error signal, \( E \). If the value of \( E \) is nonzero, it is transformed into an output signal, or correction procedure, that effects changes in the environment of the control system. (\( E \) constitutes the address in memory of a stored correction procedure.) In turn, the environmental changes alter the perceptual input to the control system in the direction of the reference signal. If the actual and intended perceptual states of affairs are the same, \( E = 0 \), and the control system has achieved its intent.

A condition for the successful performance of the model is that an error signal must correspond in a one-to-one, or, in a nearly one-to-one, way with an appropriate correction procedure. That is, an error signal must specify what needs to be done to nullify it. Apparently this condition is met in the positioning tasks investigated by Adams (1971) and in the line drawing tasks of Trowbridge and Cason (1932). In these tasks, when the experimenter provides quantitative knowledge of results, the subject is given information that specifies what he must do to rectify his error. Similarly, in the tracking tasks described by Powers (1973), the perceived difference in locations of a target spot of light and a cursor specify what must be done to close the gap.

However, the condition is not met in the minimization task of Krinskii and Shik. In that experiment, the error signal \( E \) does not specify to the subject what he must do to correct it. To take just one example, consider the values of \( E \) when \( a, b \), and \( c \), the parameters of the mapping, are set to 15, 10, and \( .2 \), respectively. The mapping is minimized when \( x = a = 15 \), and \( y = b = 10 \). Table 1 displays a set of values of \( x \) and \( y \) for which the error signal is invariably 6. In the first case, the joint angle corresponding to the value of \( y \) is at its target position. In order for the joint angle corresponding to the variable \( x \) to reach its target position of 15, \( x \) has to be increased in value by 5. Hence, the correction procedure that is stored in a memory location whose address is \( E = 6 \), should specify no change in the variable \( y \) and an increase of 5 units in the value of \( x \). That correction procedure is inappropriate to all of the other cases listed in Table 1. To correct an error of 6 when \( x = 12 \) and \( y = 12 \), for instance, \( x \) has to be increased in value by 3 and \( y \) decreased by 2. To correct an error of 6 when \( x = 15 \) and \( y = 15 \), \( x \) has to remain unaltered and \( y \) has to be decreased in value by 5. To correct an error of 6 when \( x = 18 \) and \( y = 8 \), \( x \) has to be decreased by 3 and \( y \) increased by 2. Finally, when \( x = 30 \) and \( y = 25 \), both have to be decreased in value by 15. These examples do not exhaust the ways in which an error of six can be obtained, nor is six the only ambiguous error signal.
TABLE 1: Some ways of obtaining an error of 6 in the mapping:
\[ E = |x-y-(15-10)| + .2 |x-15| + .2 |y-10| \]

<table>
<thead>
<tr>
<th>Component of the mapping</th>
<th>Correction procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>17</td>
<td>7</td>
</tr>
<tr>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>30</td>
<td>25</td>
</tr>
</tbody>
</table>

In short, for the cases presented in Table 1, different correction procedures appropriately correspond to the same error signal of 6. The quantitative knowledge of results that the error signal provides gives little or no information about how it can be nullified, and hence knowledge of results in this task is of limited utility to a subject. On the other hand, \( \Delta E \) or the velocity of the moving needle on the scale does provide useful information to a subject, as we will show. However, \( \Delta E \) information is provided only over successive movements of the actor and over successive loops around the control system, and the individual control system of the kind that Powers describes uses only the current value of \( E \) to guide its behavior.

Power's model and other closed-loop models appear to exclude the use of higher-order relationships that are revealed over relatively long stretches of time between the movements of the actor and their optical or other perceptual concomitants. Furthermore, we can show that the ambiguity and uninformative-ness of quantitative knowledge of results is not peculiar to the task of Kinskiy and Shik. Rather, it is general to most complex tasks, particularly if they are considered to be performed by a hierarchy of closed-loop systems.

**Quantitative Knowledge of Results is Equivocal in Hierarchical Closed-Loop Systems**

In the model of Powers, the nervous system is a nested set of control systems of which only the lowest-level (first-order) systems are in direct contact with the environment. The first-order systems extract information about intensity of stimulation at the receptors. More abstract properties of stimulation (for instance, its form or temporal properties) are constructed by the second- to ninth-order systems based on the first-order perceptual signals. Each superordinate system receives input from several systems on the next level down. It combines them according to some linear transformation that is peculiar to it. The outcome of the linear transformation is a higher-order property of the stimulus input than had been extracted by any of the
At every level of the system, perceptual signals are subtracted from reference signals, the latter representing an intended perceptual state of affairs. The resulting error signal constitutes the address of a stored correction procedure. For a first-order system, the correction procedure effects real changes in the environment of the actor. The correction procedures of the higher-order control systems constitute reference signals for lower-order systems. That is, higher-order systems effect changes in the world only indirectly by changing the reference signals of lower-order systems.

It is easy to show that error signals must almost invariably be ambiguous with respect to their appropriate correction procedures in a hierarchical model of this sort. Figure 5 demonstrates this with a two-tiered nervous system.

Consider a nervous system composed of three first-order systems (CS_{11}, CS_{12}, CS_{13}) and one second-order system (CS_{21}). Each first-order system supplies CS_{21} with a perceptual signal. According to the model, the perceptual signal of the second-order system, P_{21}, is a linear transformation of the three, first-order perceptual signals, P_{11}, P_{12}, P_{13}. Thus, P_{21} = a_{1}P_{11} + a_{2}P_{12} + a_{3}P_{13}. That signal is subtracted from the reference signal, r_{21}, of the second-order system. The result, E = r_{21} - a_{1}P_{11} - a_{2}P_{12} - a_{3}P_{13}, is the

Powers' claim is not unlike that of feature-based theories of visual perception. It is that the abstract, higher-order properties of the world are constructed (rather than being detected) by perceptual systems. The raw material for the constructions are lower-order, primitive properties of the world that perceptual systems detect directly. This claim is in contrast to that of Gibson (1966) and others (for example, Turvey, 1977a). Gibson holds that any properties of a world that an organism perceives, however abstract they may be, are detected by it directly.

We should point out an apparent flaw in Powers' and the feature-based views. Consider a perceptual system that has detected n primitive elements and that is now given the task of constructing a higher-order percept from them.

Even if the domain of possible combinations of the n primitive elements is confined to those in two-space and to ordinal relationships among them, there are n! possible organizations of the elements. If we expand the domain to include the third spatial dimension and if we assign significance to the distances among elements, the number of possible organizations of the n primitives must escalate dramatically. Powers' theory has to endow an organism with the means of selecting the single actual organization of the elements out of the potentially astronomical number of possibilities. A theory can avoid endowing an organism with this mystical ability if it recognizes that the sector of the world being observed gives these hypothetical primitives only one organization. A plausible proposal is that the observer detects the abstract properties themselves, rather than having to build them out of a number of primitives.
error signal of the second-order system. It constitutes the address of a stored correction procedure that will provide the reference signals, \( r_{11}, r_{12} \) and \( r_{13} \), of the first-order systems.

For concreteness, consider an error signal, \( E = 6 \). There are very many possible combinations of values for \( r_{21}, p_{11}, p_{12} \) and \( p_{13} \) that might yield a value of six, even if some boundaries are set on the possible ranges of values that each might take. The error signal might be entirely due to an error of one of the first-order systems; or it could be due to various combinations of pairs of first-order systems; or it could be one of many combinations of errors on the part of all three first-order systems.

Quantitative knowledge of results must rarely be informative in a hierarchical closed-loop system because, typically, there is a one-to-many mapping between an error signal and the conditions that may have provoked it. We can conclude from that, perhaps, that the actor/perceiver is not appropriately characterized as a hierarchy of control systems, at least when he is performing tasks in which he must exploit the abstract information putatively extracted by the superordinate levels of the system.

The closed loop model of Powers characterizes the actor as an inflexible general purpose device. Let us turn now to a different type of model that purports to govern only a limited class of activities. Its performance strategy is tailored to the special features of that limited class of acts but is inappropriate to activities outside of that class. The model that performs the minimization task characterizes just one among the many special-purpose devices that an actor can become, depending on his performance aims.7

---

Searching the Two-Variable Space: The Ravine Method

For Gel'fand and Tsetlin (1962, 1971), a strategy that is tailored to the minimization problems of muscle systems is the Ravine Method. It combines local and nonlocal search tactics and thereby avoids the tendency of strictly local search methods to be deceived by local minima of a search space.

The method works in the following way. A local search strategy is selected. (In the problem of Krinskiy and Shik, the actor selects some way of altering the values of his joint angles.) The strategy is maintained until the value \( \Delta E/E \) reaches some preselected lower bounds. A small value of \( \Delta E/E \) implies that the current strategy has reached a point of diminishing returns.

---

7We should point out that the current model is of a skilled performer of the task. An aim of our preliminary efforts has been to characterize the state towards which a novice is working. By establishing the ways in which a skilled performer coordinates the movements of his limbs in relation to the variables of stimulation provided him by the scale-indicator, we can specify the variables of stimulation to which the novice must become sensitive if he is to learn to perform the task skillfully. Clearly, the discovery tactics of the novice must be such that they reveal that organizational invariant (that is, the invariant relationship between what he does and what he sees).
When the criterial $\Delta E/E$ is attained for the first time, the actor alters his strategy randomly. The new strategy is maintained until $\Delta E/E$ again reaches its criterial value. The next strategy shift (ravine step) is selected, based on which of the previous two was the more successful in approximating the function's minimum. The ravine step is taken in a direction that is nearer to whichever of the first two strategies was the more successful. The procedure is continued until the minimum is reached.

This optimization procedure exploits the special properties of those multi-variable functions that, according to Gel'fand and Tsetlin, characterize the muscle-systems of an actor. (One special property is that the mapping is "well-organized" in the sense described above.) The form of the search methods used by the subjects of Krinskiy and Shik and depicted in Figure 3 is compatible with the hypothesis that they use ravine tactics.

A similar search procedure is also compatible with the graphs in Figure 3. We devised this latter procedure initially as a way of translating the principles of the ravine method, expressed as a set of computational procedures by Gel'fand and Tsetlin, into a set of principles of joint-angle movement that could be implemented by an actor. In doing so, we discovered information provided by the scale-indicator that may be more useful to a performer of the task than is $\Delta E/E$. The final model that we will describe rarely shifts its search strategy blindly, as that of Gel'fand and Tsetlin does on the first ravine step. It avoids having to do so by maximally exploiting the information provided by the values $\Delta E$ and $\Delta (\Delta E)$, the velocity and the acceleration of the scale-indicator. These properties of the event in which the performer participates prescribe to him what he should do next, given his performance aims.

**Searching the Two-Variable Space: Sensitivity to Rate of Change and Rate of Rate of Change**

The model is instantiated as a computer program that has available eight possible strategies of joint-angle movement. Four strategies change both joint angles simultaneously and the other four change just one of the angles. The four strategies of simultaneous movement are to increment both angles, decrement both, increment the angle corresponding to the variable $x$ and to decrement $y$, and to decrement $x$ and increment $y$. The four strategies of the second type are to increment or decrement $x$ or $y$.

On each pass, the program alters the value of $x$ and/or of $y$ in the direction dictated by its current muscular organization—that is, by its choice of movement strategy. The two joints are potentially a single coordinative structure; hence, it is simplest for the model/performer to move his two forearms at the same rate.

After altering the values of $x$ and $y$ by equivalent amounts on each pass, the new value of $E$ is computed. If $E = 0$, the program halts because the function has been minimized. If $E$ is nonzero, the values of $\Delta E$ (the current value of $E$ subtracted from its previous value) and of $\Delta (\Delta E)$ (the current value of $E$ subtracted from its previous value) are computed. These higher order properties of the moving scale-indicator provide a fairly rich source of information to the model that uses it to guide its next step.
The Information Provided by $\Delta E$

Let us look separately at the three components of the organizational invariant $E = |x-y-(a-b)| + \alpha |x-a| + \alpha |y-b|$, as a way of seeing how the various higher-order variables of stimulation specify to a skilled performer what he is to do next. The first component of the mapping, $C_1 = |x-y-(a-b)|$, is least useful because its contribution to the movement of the needle on the scale provides primarily "proprioceptive" information and little information about whether the movement strategy is working or not. In contrast, $C_2 = \alpha |x-a|$ and $C_3 = \alpha |y-b|$ provides "exteroceptive" information; the coefficients, $\alpha$, of $C_2$ and $C_3$ are different from that of $C_1$, and therefore their contribution to the value of $\Delta E$ can be distinguished from $C_1$'s contribution.

Table 2 provides some examples of the information provided by $E$. Six cases are represented in the table. Three correspond to a movement strategy in which the performer increments the values of both joint angles, and three correspond to a strategy in which he increments $x$ and decrements $y$. The remaining strategies of simultaneous movement may be observed by reading the cases from bottom to top. For each strategy, in one instance represented in the table, the strategy is correct for both joint angles (Ia and IIa in Table 2). That is, both angles are approaching their target values. (In the examples given, the target values are $x = 15$ and $y = 10$.) In a second instance (Ib and IIb), the strategy is appropriate for $x$, but not for $y$, and in the last instance (Ic and IIc), it is appropriate for neither. The first component of the mapping, $C_1 = |x-y-(a-b)|$, contributes a value of $0$ to the scale-indicator velocity ($\Delta E$), if both joint angles are incrementing or if both are decrementing (I a-c in Table 2). It contributes a value of 2 (more generally, twice the value of the coefficient of $C_1$) if one angle is being incremented and one decremented (II a-c). Thus, the proprioceptive information that the subject obtains from the scale-indicator tells him whether or not his joint angles are moving in parallel. The sign of the contribution of $C_1$ to $\Delta E$ (that is, the direction of needle movement) provides general information about whether or not the current strategy is working to make the needle point to zero.

The other two components of the mapping, $C_2 = \alpha |x-a|$, and $C_3 \alpha |y-b|$, contribute exterospecific information to the value $E$. Independently of the particular movement strategy that the performer has adopted, they contribute values to $\Delta E$ that are different, depending on whether both joint angles, just one joint angle, or neither joint is approaching the target. If both angles are approaching their targets (Ia and IIa in the table), $C_2$ and $C_3$ contribute a value of $-2\alpha$. When one angle is moving towards its target (Ib and IIb), then the contribution of $C_2$ and $C_3$ is zero, because one contributes $\alpha$ and the other $-\alpha$. The contributions of $C_2$ and $C_3$ can be distinguished from that of $C_1$ because their coefficients are different from $C_1$'s coefficient (here $\alpha = .2$).

Let us briefly consider an example that illustrates how the value of $\Delta E$ can guide the movements of a skilled performer of the task. If the value of $\Delta E$ is 2, the skilled performer knows two things. First, he knows that his joint angles are changing in opposite directions (one is incrementing and one is decrementing). In addition, because $C_2$ and $C_3$ are not represented in the needle velocity, he knows that only one of his joint angles is moving towards its target value. He then should alter the direction of movement of just one
TABLE 2: Information provided by scale-indicator velocity, $\Delta E$.

<table>
<thead>
<tr>
<th>Pass through the computer program</th>
<th>Component of the mapping</th>
<th>$X$</th>
<th>$Y$</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$E$</th>
<th>$\Delta E$</th>
<th>$(\Delta E)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.a. Incrementing $X, Y$: appropriate strategy</td>
<td></td>
<td>10</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>6</td>
<td>0</td>
<td>.8</td>
<td>.8</td>
<td>1.6</td>
<td>.4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>7</td>
<td>0</td>
<td>.6</td>
<td>.6</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I.b. Incrementing $X, Y$: appropriate only for $X$</td>
<td></td>
<td>10</td>
<td>11</td>
<td>6</td>
<td>1</td>
<td>.2</td>
<td>7.2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>12</td>
<td>6</td>
<td>.8</td>
<td>.4</td>
<td>7.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>13</td>
<td>6</td>
<td>.6</td>
<td>.6</td>
<td>7.2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>I.c. Incrementing $X, Y$: inappropriate strategy</td>
<td></td>
<td>16</td>
<td>12</td>
<td>1</td>
<td>.2</td>
<td>.4</td>
<td>1.6</td>
<td>-.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>17</td>
<td>13</td>
<td>1</td>
<td>.4</td>
<td>.6</td>
<td>2.0</td>
<td>-.4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18</td>
<td>14</td>
<td>1</td>
<td>.6</td>
<td>.8</td>
<td>2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II.a. Incrementing $X$, Decrementing $Y$: appropriate strategy</td>
<td></td>
<td>10</td>
<td>14</td>
<td>9</td>
<td>1</td>
<td>.8</td>
<td>10.8</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>13</td>
<td>7</td>
<td>.8</td>
<td>.6</td>
<td>8.4</td>
<td>2.4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>12</td>
<td>5</td>
<td>.6</td>
<td>.4</td>
<td>6.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II.b. Incrementing $X$, Decrementing $Y$: appropriate only for $X$</td>
<td></td>
<td>10</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1.2</td>
<td>3.2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>3</td>
<td>3</td>
<td>.8</td>
<td>1.4</td>
<td>5.2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>2</td>
<td>5</td>
<td>.6</td>
<td>1.6</td>
<td>7.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II.c. Incrementing $X$, Decrementing $Y$: inappropriate strategy</td>
<td></td>
<td>17</td>
<td>5</td>
<td>7</td>
<td>.4</td>
<td>1</td>
<td>8.4</td>
<td>-2.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>18</td>
<td>4</td>
<td>9</td>
<td>.6</td>
<td>1.2</td>
<td>10.8</td>
<td>-2.4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19</td>
<td>3</td>
<td>11</td>
<td>.8</td>
<td>1.4</td>
<td>13.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
angle. It cannot be determined which one should be altered because the coefficients of \( C_2 \) and \( C_3 \) are the same. If the performer happens to choose the correct angle to change, on the next pass \( \Delta E \) will equal .4 (that is, \( 2\alpha \)), indicating that the angles are now changing in parallel and that both are moving toward their targets. If the choice was incorrect, \( \Delta E = -.4 \), and the performer knows to shift the direction of movement of both angles.

The Contribution of \( \Delta E \)

The velocity of needle movement changes when one of the actor's joint angles reaches and goes beyond its target value. Consider the example in Table 3. In the example, both joint angles are being incremented. Hence \( C_1 \) contributes a value of zero to \( \Delta E \). In addition, on going from the first pass to the second, both angles are approaching their target values; hence \( C_2 \) and \( C_3 \) contribute a value of .4 to \( \Delta E \). Going from the second pass to the third, however, \( x \) moves away from its target value of 15, while \( y \) continues to approach its target value of 10. Therefore \( C_2 \) contributes -.2 and \( C_3 \), +.2 to the value of \( \Delta E \). The new \( \Delta E \) is zero, and \( \Delta(\Delta E) \) is .4. This deceleration of the needle is an indication that one of the two angles has reached and surpassed its target. When that occurs, the model shifts from a strategy of simultaneous movement of both joint angles to one of changing a single joint angle.8

<table>
<thead>
<tr>
<th>Pass through the computer program</th>
<th>Component of the mapping</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
</tr>
<tr>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
</tr>
</tbody>
</table>

Figure 6 displays the movement strategies of our model. They are similar in form (but are more efficient than) those of the subjects of Krinskiy and Shik depicted in our Figure 3.

8The human subjects in the experiments of Krinskiy and Shik typically shifted from a strategy of simultaneous change of the two joint angles to one of successive change as they neared the target. The strategy of simultaneous change best reveals the "organizational invariant" of the task, and therefore is an optimal strategy of movement until one target value is reached.
CONCLUDING REMARKS

Our model and the mathematical model of Gel'fand and Tsetlin both perform the minimization task successfully. Furthermore, in their superficial properties, the strategies of these two models match the performance of the subjects of Krinskiy and Shik. Both models perform the minimization task by adopting procedures that are tailored to the special features of that task, but that are inappropriate to the features of other ones. We can perhaps conclude from these observations, and from the apparent incapacity of Powers' model to solve the task in an efficient way, that the human subjects in the experiment of Krinskiy and Shik likewise adopted a task-specific strategy. Given that those human subjects presumably are capable of performing other kinds of acts for which these tactics must be inappropriate (for example, the positioning task of Adams, 1971), we may consider this work to provide preliminary support for our conception of the actor as a general-purpose device by virtue of the capacity to become a variety of special-purpose devices.

The procedures of our model are distinguished from the mathematical optimization procedures of Gel'fand and Tsetlin in a way that seems significant to us. We suggested a principle (see also Turvey et al., in press) which holds that for the degrees of freedom necessitating control, there must be at least as many degrees of constraint in the information supporting that control. We suggested also that the two sources of control constraints are the environment and the actor (second section).

In the model of Gel'fand and Tsetlin, as applied to the minimization task of Krinskiy and Shik, degrees of constraint are largely supplied by the actor. The environment supplies the values $\Delta E$ and $E$, whose ratio guides the actor's selection of a new strategy. However, its guidance is minimal. That is, the ratio $\Delta E/E$ tells the actor when he should adopt a new strategy of movement, but it does not prescribe which strategy he should select. The actor selects a ravine step based on calculations on his part that compare the degrees of success of the two preceding sets of local search tactics.

Relative to this minimal use of environmental sources of constraint, our model yields up more of the responsibility for control. The environmentally-given values $\Delta E$ and $\Delta(\Delta E)$ not only tell the actor when to shift strategies, they also prescribe how he should alter his strategy to achieve his aim. In short, in this model, relative to that of Gel'fand and Tsetlin, the actor supplies few degrees of constraint and the environment supplies correspondingly many.

We find it intriguing to speculate that these two models may characterize actors at different phases of the skill-acquisition process. The model of Gel'fand and Tsetlin may characterize an actor who is sufficiently skilled to solve the task, but who does not yet perform it in the most efficient way. The actor provides some degrees of constraint that the environment would provide were he organized or attuned to detect them. Our model, in contrast, yields up to the environment as much of the responsibility for control as we have been able to uncover.

In the second section of the present paper, we sought to outline the kinds of information available to an actor, given an optimal level of
description of the environmentally structured energy distributions that surround him. The potential sources of controlling information available to an actor in a natural environment exceed in number and in level of abstraction those sources made available to the actor in the experiment of Krinskiy and Shik. Nevertheless, as we have shown, the relatively limited information manifest in the Krinskiy and Shik task can tightly constrain the performance of that task. Collectively, these concluding remarks reiterate a major theme of the present paper, namely, that a careful examination of the environment as a perceptually specified source of constraint is mandatory to the understanding of the acquisition and performance of skilled activity.

REFERENCES


Powers, W. T. (1973) Behavior: The Control of Perception. (Chicago:
Aldine).


