*AN ECOLOGICAL ANALYSIS OF KNOWING BY WIELDING*M. T. TURVEY, H. YOSEF SOLOMON, AND GREGORY BURTON¹CENTER FOR THE ECOLOGICAL STUDY OF PERCEPTION AND ACTION,
UNIVERSITY OF CONNECTICUT, HASKINS LABORATORIES, AND
UNIVERSITY OF CINCINNATI

The ecological approach to perception, as developed by James Gibson, is described and applied to how one knows, by means of the haptic perceptual system, various properties of hand-held objects. Four sets of experiments are reviewed in which subjects reported on the extent, orientation, shape, and fractional components of unseen objects wielded freely. For each task, an invariant specific to the object property in question is identified in the structured arrays of rotational moments and strains produced by the act of wielding. Results are discussed in relation to the concepts of attention and stimulation, as reformulated by the ecological approach, and the general theory of perception as information pickup.

Key words: ecological approach, haptic perceptual system, information pickup, attention, inertia tensor

The ecological approach to perceiving, as developed by James Gibson (1959, 1966, 1979; Reed & Jones, 1982), dismisses dualism and emphasizes the mutuality of an animal and its environment. In this approach, perceiving is defined as the means by which an individual maintains contact with his or her environment. It is a phenomenon to be understood in terms of lawful regularities and symmetry principles defined at the ecological scale of animals and environments, rather than in terms of mental states and formal languages of representation and computation (e.g., Turvey, 1988; Turvey, Shaw, Reed, & Mace, 1981). The essentials of the approach can be expressed succinctly: Perception is specific to information and information is specific to the environment and to one's movements; hence perception is specific to the environment (exteroception) and to one's movements (proprioception). In this approach, perceiving the environment and conceiving the environment differ only in degree. "Knowing is an extension of perceiving" (J. Gibson, 1979, p. 258).

In more expanded terms, the ecological approach advanced by Gibson comprises a program of research and theory having three parts

relating, in turn, to the nature of information, the basis of perception, and the development of perception. With respect to the first part, it attempts to identify the specificity between the structured energy distributions available to a perceptual system and the environmental and movement properties causally responsible for that structure. This latter specificity is what is meant by "information" in the ecological approach. The specificity is sought at a molar level of description and is expected to be revealed in terms of observables that, in general, have not yet been identified in physical theory. One characteristic of these molar observables is their low dimensionality (meaning, roughly, that very few quantities are needed to describe them). They wrap up in state spaces of minimal dimensions the order present in surrounding energy distributions described molecularly in state spaces of very many dimensions. Another characteristic of these molar observables is that they are noninertial. With respect to the so-called fundamental dimensions of mass, length, and time, the class of observables comprising information is not built with mass; rather, it is built from just length and time (kinematic), or length alone (geometric), or time alone (spectral) (Kugler & Turvey, 1987; Turvey & Carello, 1986).

With respect to the second part, the ecological approach asserts the directness of perception in the sense that the specificity of perception to information dispenses with any intervening special process. Integral to this second part is a hypothesis that imposes significant constraints on the conduct of research:

¹ M. T. Turvey is at the University of Connecticut and Haskins Laboratories; H. Y. Solomon is at the University of Cincinnati; G. Burton is at the University of Connecticut. The research reported here was supported in part by a grant from the National Science Foundation (BNS-8720144). Please address correspondence and reprint requests to Michael T. Turvey, Center for the Ecological Study of Perception and Action, 406 Babbidge Road, University of Connecticut, Storrs, Connecticut 06269-1020.

For every property perceived there is a molar noninertial property of the structured energy distribution to which the perceived property corresponds. This generalized hypothesis of information-perception specificity directs investigation to the uncovering of one-to-one mappings between information and perception. A particular perception results if and only if a particular informative structure is detected, recognizing at the same time that a number of informative structures may be equivalent in this respect. At a deeper level, the challenge of this second part is the development of theory and research directed at understanding how specificity is preserved over the components of an animal-environment system and the perception-action cycles that it manifests. (In cases of perceiving adjacent surfaces by active touch, for example, the aforementioned components would include properties of surface layout, patternings of mechanical energy, and the states of muscular, connective, and neural tissues.)

With respect to the third part of the program, it suggests that improvement in perceiving in any given situation follows from the discovery of, and attunement to, information. The specificities in any given situation—the lawful regularities between aspects of surface layout and macroscopic properties of structured energy distributions—vary from embracing more than or less than the environmental property of interest to only the environmental property of interest. The improvement is gradual (to a greater or lesser degree) because the perceiver, in order to improve, must come to attend to the exact specificity rather than to the narrower or broader specificity. That is, with respect to learning to perceive an environmental property, the perceiver progresses from under- and over-differentiating the ambient energy distribution to differentiating it exactly (E. Gibson & J. Gibson, 1972; J. Gibson & E. Gibson, 1955).

Haptic Subsystems and Smart Perceptual Instruments

In the present article we illustrate the ecological approach, in particular the information-perception specificity hypothesis, through an experimental and theoretical analysis of certain aspects of the haptic perceptual system. The body's tissues are penetrated throughout by receptive units that are excited by mechanical disturbances—stretching, pulling, bend-

ing, squeezing, and so on. These units are the microstructure of the haptic system, the perceptual system by which an individual gains awareness of the world adjacent to his or her body by the use of his or her body. In achieving this awareness, multitudes of mechanoreceptive units must gather into macroscopic functional organs. For example, it is a (remarkable) fact that when a person touches a surface with a stick, the person feels that surface at the end of the stick, and not in the hand. Classically, such a phenomenon has been difficult to accommodate (how can sensations be projected outward from the body?). The hypothesis pursued under the ecological approach is that information for the mechanical disturbance at the end of the stick is obtained by the hand as a functional perceptual organ, together with information about the length and direction of the stick (J. Gibson, 1966). This hypothesis is part of a larger hypothesis that such functional organs are *smart perceptual instruments*. A smart perceptual instrument is specialized in performing a particular (type of) task in a particular (type of) situation and does so by capitalizing on peculiarities of the task and the situation. Such an instrument consists of a few, specialized components. It executes a single valued function: In haptic instances, a single kinetic property is transduced into a measure of a single geometric (environmental) property. Such an instrument can be, and often is, assembled "softly" and temporarily.

There are two reasons for supposing that smart perceptual instruments exist (Runeson, 1977). One reason is that the everyday tasks of perceiving, and the information supporting their execution, are stable properties of the ecological scale. Taking advantage of the peculiarities, and developing smart solutions, are well within the scope, therefore, of evolutionary processes and the physical conditions of self-organization (Kugler & Turvey, 1987, 1988). The second reason is the intuitive one that biological design, on close inspection, is rarely (if ever) more complicated than necessary. The simplicity of smart perceptual instruments, however, will not be an easily recognized simplicity. That is, it will not conform to the simplicity criteria of conventional geometry and logic. It is supposed that living systems operate easily, and quite generally, with solutions to measurement problems that

tax the human intellect; they should not, therefore, be judged in terms of the complexity metrics that are applied to artifactual instruments. In other words, for a perceptual capacity to be adaptive, it need not be "simple" or "fundamental" by mathematical standard—it need only be reliable and realizable physically.

Dynamics of Wielding

The most accessible and interesting components of the human haptic system are the upper limbs and hands. These have the capability to act as both exploratory and performatory organs. They are capable of feeling (as organs of perception) and doing (as organs of action). An object held in one hand, or in both hands, can be wielded—the person can shake it, can strike other objects with it, can prod surfaces with it. If the goal is to perceive a particular property, such as the distance reachable with the hand-held object or the slant of a surface, then the manner of the wielding may be particular; that is, it may be the case that the wielding has to be a special kind of exploration. The essence of perceiving a property by wielding is that there is a (relatively) continuous cycle of wielding → tissue deformation → wielding → tissue deformation → . . . and so on, in the course of which the tissue is *deformed over time* in a way that is specific to the said property. The acting-perceiving cycle is allied, in mathematical and physical terms, to the reciprocal notions of transformations and invariants. The person must effect the right transformations in order to reveal the right invariant.

Previously, the mutuality of the organism and environment was emphasized as a fundamental assertion of the ecological approach. Perception is one of the means of contact between these interacting systems; it is not an aspect of the organism only. Any case of perception, therefore, is an instance of a physical interaction between two systems, one that is a component of the organism and one that is an aspect of the environment. For knowing about an object by wielding, these systems are the haptic perceptual system (S_h) and the rigid body system of hand-and-object (which can be termed S_o), respectively. The act of wielding under the intention to perceive a particular property will require mutual changes in the interacting systems; the haptic system will have to act on the environment and the wielded

object will have to act on the perceiver. Specifically, the wielding produces a three-space motion of S_o about a fixed point (say, in the wrist), and this three-space motion induces a particular dynamic (change of state) in S_h . The assembly of such an interaction entails a number of ingredients—for the sake of completeness, three of these will be mentioned. Collectively, these components define the problem of the assembling of smart, haptic perceptual instruments.

1. A dynamical interaction (one in which one system induces a dynamic on another) must take place through a distinct, observable variable. Consider, for example, a weathervane, a device that detects the orientation of the prevailing air currents. The variable through which the atmosphere interacts with the device is the gradient of air pressure surrounding the vane. When one of the systems is an organism, the observable in question is harder to fix. In our case, the answer is constrained by the fact that the observable is an aspect of tissue deformation causally entailed by an aspect of the play of mechanical forces on the tissues.

2. A second critical ingredient is the meter that registers the observable. By a meter we mean a subsystem of the perceiving system that only takes into account the interactions with states of S_o through the observable o (cf. Rosen, 1978). Sensitivity of one system to the other is insufficient if this sensitivity is not specific to the desired property. To identify the meter is equivalent to detailing the boundary conditions on the interaction between systems that support specificity, which is a priority for any dynamical systems analysis. Potently, if one property rather than another property (or all possible properties) is to be perceived, then one dynamic rather than another dynamic (or all possible dynamics) must be induced. For example, most environmental objects are affected by the wind; in order to serve as a meter for the direction of wind (and not just the force), a device must be able to rotate freely around a fixed point. In the present context, the boundary conditions reflect the person's intentions; in general terms, intentional contents act as extraordinary constraints to harness dynamics (Kugler & Turvey, 1987; Solomon & Turvey, 1988; Turvey, 1986).

3. The linkage between the variable to be perceived and the observable is the third component of this interaction. Most often the en-

vironmental property (e) to be perceived is unrelated to the observable (o) conceptually. The question is: How is it known that the meter to be assembled in order to effect the measurement of e is one that detects the tissue property o ? There seems to be a naturalness to the linkages that are exploited in smart haptic perceptual instruments that might imply the possibility of a (local gauge?) symmetry underwriting the assembling of smart instruments (Turvey, 1988, in press).

To the foregoing remarks we add that the study of smart haptic perceptual instruments bears on a general theory of knowing in terms of efforts to ground the understanding of cognitive function in special purpose abilities that are executed fluently (e.g., Fodor, 1983; Marr, 1977, 1982). Studying cognitive problems that humans and nonhumans solve readily promises an understanding of cognitive mechanisms that is both basic and sound (Marr, 1977). In studying the haptic problems identified in this article, the experimenter has the distinct advantages of being able (a) to observe a perceptual system behave in a certain way in order to perceive a certain thing and (b) to measure most of the observable quantities significant to the system's special purpose behavior. As a result, there is an improved chance at understanding the sound method underwriting the system's fluent performance.

We will review four types of experiments. The first type addresses knowing the whereabouts of the end point of a hand-held rod that one can wield but not see. The second type addresses knowing the orientation of an object in the hand, specifically, knowing the direction in which a bent stick is pointing, again under conditions where the object can be wielded but not seen. The third type addresses knowing the shape of an object where interaction with the object is restricted to wielding; the object cannot be seen nor can it be explored tactilely. The fourth type addresses knowing about fractional pieces of a hand-held and wielded object, where once again perceptual contact is limited to wielding. Our main goal is to portray what is entailed by the information-perception specificity hypothesis as a strategy for investigating and understanding how an animal knows what it knows about its surroundings. To anticipate, we will demonstrate the individual reliability of the haptic capabilities in question, and we

will demonstrate what it means to isolate the information to which the perception is specific.

EXPERIMENTS

Knowing About the Extent of a Rod by Wielding

Various hand-held implements are used as extensions of the upper limbs. Most tools fit into this category, which also includes canes and sticks used as probes for exploring surfaces at a distance from the skin. These artificial extensions of the haptic system probably rely for their success on a capability of great generality. Many animals possess cutaneous appendages, such as vibrissae, hairs, claws, horns, and the like, that function as a means for knowing about distant things. The research summarized here may provide insights into the basis of this general capability implicit in nature's successful exploitation of cutaneous appendages.

An experimental arrangement for investigating the haptic ability to perceive the distance to the tip of a visually occluded hand-held object is shown in Figure 1. The subject freely wields the object, a rod held firmly in the hand, by three-space motions about axes in the right wrist, with the right forearm resting on the arm rest of a chair. The rod, the arm, and the wielding activity are occluded by a curtain. On the other side of the curtain the subject can see a surface perpendicular to the ground. The surface can be moved freely by the subject, with the use of the left arm, toward or away from the subject's position. For a given hand-held rod the subject's task is to position the surface so that it aligned with the tip of the hand-held rod that the subject can wield but not see. The subject is free to wield and to adjust the surface for as long as is needed to reach a confident judgment.

Figure 2 shows the results of an experiment (Experiment 1, Solomon & Turvey, 1988) on 7 subjects with seven rods ranging from 0.305 m (12 in.) to 1.219 m (48 in.). The mapping from actual length to perceived length was highly linear (and was so for all subjects with all r^2 s in the vicinity of .99) with slight overestimation at the shorter lengths and slight underestimation at the longer lengths. It cannot be the case, however, that rod length is the variable of relevance to the haptic subsystem.

Mechanical variables constructed with the dimension of mass—such as torque, kinetic energy, moment of inertia, and so on—affect the tissues of the haptic subsystem during welding. Length per se is not a mechanical variable.

Figure 3 shows the results of an experiment (Experiment 5, Solomon & Turvey, 1988) in which a weight was added to otherwise uniform rods at three positions. For a rod of a given length the moment of inertia I of the rod—that is, the rod's resistance to rotational acceleration—increases as the location of the added weight increases in distance from the axis of rotation. Figure 3 (left) shows that perceived length is not a single-valued function of actual length. Perceived length is, however, a single-valued function of I , as shown in Figure 3 (right).

The magnitude of I about any arbitrary axis is equal to the moment of inertia about a parallel axis through the center of mass (I_c), plus the mass (m) of the body times the square of the distance (a) between the two axes. That is $I = I_c + ma^2$. The preceding is the parallel axis theorem. An important corollary of this theorem is that I is least when the axis of rotation is through the center of mass (CM) ($ma^2 = 0$). If the perception of a rod's length is tied to I , then a rod grasped at and swung about its CM should be perceived as shorter than the same rod grasped at and swung about a position other than CM. Figure 4 shows the results of an experiment (Solomon, Turvey, & Burton, 1989a, Experiment 1) in which rods of three different lengths were held at $\frac{1}{4}$ length, $\frac{1}{2}$ length, or $\frac{3}{4}$ length. For each axis of rotation, the subject's task was to judge how far he or she could reach with the distal end of the rod if it were held at its proximal end. Subjects met the requirements of the task successfully and ordered their judgments in accord with I as given by the parallel axis theorem, and did so whether the rod was wielded horizontally or vertically. The theorem not only identifies that an axis of $\frac{1}{2}$ yields the smallest I but that the I values for axes at $\frac{1}{4}$ and $\frac{3}{4}$ are identical. The fact that subjects could distinguish accurately among the three rods when held at $\frac{1}{2}$ length, that is at CM, has other important consequences. It rules out any hypotheses about CM or center of oscillation (CO) as the basis of perceived length. When held at CM the distance a from the axis of rotation

Fig. 1. An experimental arrangement for studying the perception of the distance reachable with a hand-held rod that can be wielded but not seen. See text for details.

to CM is identical, and practically zero, for the three different rod lengths. The axis-to-CO distance is given by I_c/ma , and is, therefore, undefined when the axis and CM coincide.

As intimated above, the strategy of the ecological approach is to uncover the specificity that, by hypothesis, underlies any given instance of perceptual knowing. It is clear from the research just summarized that a person's awareness of the extent of a hand-held object by wielding has something to do with the object's resistance to rotational acceleration—its inertia for rotation. How might we express this fact in a way that has bearing on the information-perception specificity hypothesis? The first thing that is needed is an appreciation of information as it pertains to haptic perception. In the case of visual perception, information is defined over lawfully generated distributions of light energy in air or water. In the case of haptic perception, information is defined over lawfully generated distributions of mechanical energy in biological tissue. These mechanical energy distributions comprise pat-

Fig. 2. Perceived length as a function of actual length for each of 7 subjects. (Taken from Figure 2 of Solomon & Turvey, 1988; copyright 1988 by APA; reprinted by permission.) The average data are presented in the lower right panel.

Fig. 3. Perceived length as a function of actual length (left) and of moment of inertia (right) for three locations of added weight. (Taken from Figure 6 of Solomon & Turvey, 1988; copyright 1988 by APA; reprinted by permission.)

ternings of tissue deformation. With respect to the problem under inquiry, therefore, there must be an isolable molar aspect of tissue deformation that is related causally and invariantly to the extent of a hand-held rod and to which the perception is specific. This molar aspect would define the information of relevance.

The tissue deformation arises from the motions in three dimensions of the hand-rod system. Because the motions of the hand-rod system during wielding are the three-dimensional motions of a rigid body about a fixed axis, the inertia that enters into the equations of motion is in the form of the inertia tensor. A tensor is a mathematical way of capturing states comprising different quantities in different directions. The inertia tensor is written as a matrix with nine entries. The off-diagonal entries identify what are known as the centrifugal moments or, more commonly, products of inertia. They are associated with centrifugal forces to be balanced by dynamical bearing forces acting on the axis of rotation. The diagonal entries identify the moments of inertia with respect to the three coordinate axes. There is a formal operation that can be performed that eliminates the products of inertia and leaves only the principal moments of inertia on the diagonal. The operation is that of a transformation to principal axes, the symmetry axes of the rigid body. Because wielding is done about an axis in the wrist, it is physically impossible for a subject in the experiments to restrict the motion of the hand-rod to the hand-

rod's symmetry axes. Diagonalization, as formally interpreted, cannot be achieved. Nonetheless, the research conducted thus far suggests that the haptic subsystem, in perceiving rod extent, is attuned to the maximal moment of inertia, meaning that it must be able to separate the principal moments of inertia from the products of inertia (Solomon & Turvey, 1988; Solomon et al., 1989a, 1989b). That is, it must be able to behave in a manner that is functionally equivalent to the principal axis transformation.

The hand-muscles-joints-nerves haptic subsystem defines an elastic deformable body. As noted, rotation of the hand-rod system induces a pattern of deformation on the haptic subsystem. The pattern consists of elongations and compressions (changes in the x , y , and z directions) and shears and rotations (displacements of planes of the elastic body). The strain tensor captures this patterning. As with the inertia tensor, the strain tensor can be diagonalized formally by an orthogonal matrix that rotates the coordinates into alignment with the principal axes of strain. The result is that the shears disappear, leaving only the pure elongations or compressions (the principal strains). The latter are the properties of the elastic body—the haptic subsystem—that remain invariant throughout the swingings and shakings of a rod. We are now in a position to make a stab at defining the haptic information to which the haptic perception of rod extent is specific: It must be an invariant of the pattern of tissue deformation that is entailed causally by an in-

Fig. 4. Perceived length as a function of hand position for horizontal and vertical welding for 5 subjects. (Adapted from Figures 2 and 3 of Solomon *et al.*, 1989a; copyright 1989 by Lawrence Erlbaum and Associates; adapted by permission.) The average data for the two welding styles are plotted in the lower left panel (3 judgments $\times$ 5 subjects $\times$ 3 rod lengths); the lower right panel shows the average data for the three rod lengths (3 judgments $\times$ 5 subjects $\times$ 2 styles).

variant of the pattern of three-space rigid body motions. A rod of uniform density, with negligible sidewise dimensions, has only two moments of inertia, and these are of the same magnitude. Consequently, the dynamical behavior of a hand-held rod can be expressed in terms of a single I . Given that perception of extent is a single-valued function of rod moment of inertia, it is reasonable to assume that the tissue invariant that we seek is tied to moment of inertia and is similar in form. That is, the information for rod extent is probably expressed in terms of principal strains. For this to be so, then the wielding activity must functionally diagonalize the inertia and strain tensors simultaneously. The terms in the diagonalized inertia and strain tensors are the eigenvalues or characteristic values of the rigid body and deformable body motions. They are the invariants of the motions. It seems, therefore, that the haptic subsystem, in the act of perceiving the length of hand-held objects, is sensitive to (or capitalizes on) the characteristic values of its own dynamics.

Knowing About the Orientation of an Object in the Hand by Wielding

When we hold an object in the hand we have an impression of balance, of how the object lies in the hand. The impression is more pronounced, it would seem, when the object is wielded. This impression may be interpretable through the conceptions found relevant to understanding the perception of rod extent.

The off-diagonal terms of the inertia tensor reflect the asymmetry of an object (the uneven distribution of its mass) about its axis of rotation. As noted, they comprise centrifugal moments, and are associated thereby with the reactive forces of the axes due to the rotation of the object. These latter reactions comprise dynamical forces in addition to the static reactive forces due to the weight of the object. In terms of tissue deformation, and the ultimate description of the relevant information, dynamical reactive forces will be realized as shears and rotations—the quantities expressed by the off-diagonal terms of the strain tensor.

Consider an L-shaped rod. The central principal axes of such an object are the orthogonal Cartesian axes passing through its center of mass. About these axes the products of inertia and, thereby, the dynamical reac-

tions, are zero. If an L-shaped rod is grasped at one end and wielded by motions about the wrist, then, by definition, the axes of rotation will not be the central principal axes, products of inertia will exist, and dynamical reactive forces will be present throughout the wielding. The products of inertia for rotation about each of the axes in the wrist are constants; they comprise invariants over the activity of wielding. Now it is important to note that for a fixed system of coordinates with origin at the wrist, the products of inertia will vary with how the rod is placed in the hand. Let the longer piece of the L-shaped rod be called the "stem," let the shorter piece be called the "branch," and let the stem be the piece that is held. Then it is clear that the rod can be placed in the hand such that, if the longitudinal axis of the stem parallel to the body's sagittal plane is the x axis, then the branch can be oriented in the yz plane at any angle between 0° and 360° . For each orientation of the rod—meaning the angle made by the branch in the yz plane—there will be a different alignment of the rod's mass in the wrist-based coordinate system. What would it mean, therefore, for a person to know, without the aid of vision, the direction in which the branch of the rod is pointing in the body's coordinate system? The answer, it seems, must lie with the fact that the wielding explorations reveal the invariant moments specific to the distribution of mass in the L-shaped object relative to the coordinate system anchored in the wrist. In short, if a person can attend selectively to the invariant tissue distortions induced by the patterning of reactive or bearing forces, that is to say, the patterning of the quantities associated with the off-diagonal terms of the inertia tensor, then it should be possible to know the direction of pointing of the branch of an L-shaped rod held and wielded in the hand.

An experiment was conducted² that used a single lightweight L-shaped rod constructed from two wooden rods of different lengths (35 cm and 9 cm) but of the same radius and density. The rods were connected at their ends so as to form a right angle at the joint. The

² Solomon, H. Y., Turvey, M. T., Burton, G. & Runeson, S. *Perceiving the orientation of a hand-held object by wielding*. Manuscript submitted for publication.

Fig. 5. An experimental arrangement for studying the perception of the direction of pointing of a hand-held L-shaped rod that can be wielded but not seen. See text for details.

subject held the longer piece—the stem—and attempted, by wielding, to identify the direction in which the shorter piece—the branch—was pointing. The arm and the hand-held object were obscured by a curtain, and the subjects were given no training in the task and no feedback during the experiment. The procedure is depicted in Figure 5. The subject indicated direction by means of a dial that was not marked from the subject's view but was marked fully in units of 1° from the experimenter's view. In the experiment, each of 6 subjects were presented the same L-shaped rod repeatedly from trial to trial. It was placed into the right hand aligned with one of eight directions that varied randomly from trial to trial. Taking the longitudinal axis of the stem as y , the directions were all in the xz plane at 45° intervals from 0° . Wielding was restricted to motions about axes in the wrist, and the subjects were not informed as to how many different orientations would be presented.

Circular statistics (Batschelet, 1965, 1978) were applied to the data. In these statistics the mean response angle for a trial with a given stimulus angle is computed by taking the sine

and cosine of each response angle, summing these measures over the trials with the same stimulus angle, and converting the sine-cosine combination back into an angular quantity. Essentially, the angular quantity thus obtained is the resultant of the various response angles for the given stimulus angle. It is referred to as α . The plots of α against the angle of the L-shaped rod (the stimulus angle) are given in Figure 6 for each of the 6 subjects participating in the experiment. As can be seen, each subject was able to distinguish reasonably well among the orientations of the hand-held rod. The average data show a very tight relation between the stimulus angle and the response angle as measured by α . The implication is that a person can detect the invariants of tissue deformation (strain) causally entailed by the invariant products of inertia specific to rod orientation.

Another circular statistics measure is of relevance here. The so-called homing tendency, h , takes into account both the relationship of alpha to the "home" orientation (in our case, the original setting of the L-shaped rod) and the reliability of the judgments among themselves (there is also a circular statistic that measures the reliability separately). Thus, the homing tendency can be used as a composite index of accuracy. It permits an evaluation of whether or not some stimulus angles are perceived more accurately than others. It addresses the question of whether or not there are any orientation biases—that is, more accessible orientations—for the conditions of wielding imposed by the experiment. Figure 7 shows for each subject the accuracy values corresponding to each of the eight stimulus orientations. Subjects were slightly more accurate when the branch was oriented at 90° and at 135° ; however, as Figure 7 makes clear, this pattern was by no means uniform across subjects. Consequently, the relative advantage of those two settings was not significant statistically. It would be premature to assert that the orientation of the L-shaped rod was easier to perceive at some settings than at others.

Fig. 6. Response angle (α), as a function of the angle of the stimulus rod for 6 subjects in Experiment 1 of Solomon, Turvey, Burton, and Runeson (submitted). Points are plotted at the appropriate point of a circle closest to the setting (e.g., a response of 45° to a setting of 315° would be plotted as 405° and a response of 315° to a setting of 45° would be plotted as -45°). Each data point represents four reports.

Fig. 7. Accuracy (h) as a function of the angle of the stimulus rod for 6 subjects in Experiment 1 of Solomon, Turvey, Burton, and Runeson (submitted). Each data point represents four reports.

Knowing About the Shape of Objects by Wielding

Custom interprets shape perception as based on Euclidean forms. The interpretation is motivated by ideas about the retinal image as the proper description of the optical support for vision: Because the retina is two-dimensional, environmental objects can be represented on the retina only as two-dimensional forms, the projective profiles of the object. In this classical formulation, mechanisms of deduction and/or integration produce (internally) the three-dimensional shape. Ecological analyses suggest, however, that the visual perception of an object's shape is not inferential and based on retinal forms but is direct and based on invariants of optical structure. To draw the contrast, J. Gibson (1979) referred to the invariants as *formless*. This qualifier underscores the fact that the description of the optical support for vision is in terms of abstract (but formulatable) relations defined locally or globally over the structured energy distribution. The haptic system provides a rich context within which to explore and understand this ecological notion of shape perception being grounded in the detection of formless invariants.

Evidence for the haptic system's exploitation of the patterning of different quantities in different directions as expressed through the inertia and strain tensors raises the possibility that information about shape will be available to a person who wields an object that he or she cannot see. The shape of any individual object is defined uniquely by its three principal moments of inertia. If an object of a given shape is varied in size, then the three principal moments will vary significantly in magnitude but relations among them will be reasonably constant. For example, the ratio of an object's maximal principal moment to its minimal principal moment will vary little with change in object size. If tissue deformations over time are causally linked to an object's principal moments of inertia, then they may be causally linked to the relation among the moments. In approximate terms, there may well be a formless haptic invariant (an abstract description of tissue deformation) that is shape specific. Can it be capitalized upon by a haptic subsystem? Can a smart perceptual instrument for registering shape by wielding be assembled?

An example of an experiment that addresses

Fig. 8. An experimental arrangement for studying the perception of the shape of a hand-held wooden object that can be wielded but not seen. See text for details.

this question involved 10 solid objects of five different shapes (pyramid, cube, half sphere, cylinder, and cone). The objects were of two masses. That is, there were five different shapes at one mass, and five different shapes at another mass. In the experiment, therefore, we varied shape (holding mass constant) and varied mass (holding shape constant). Attached to each object was a slim rod whose length and width were the same for each object. To wield an object one grasped the attached rod. In the experiment a subject wielded an object in one hand, in any preferred manner and for any length of time within reasonable bounds, without being able to see it (see Figure 8). Visibly available to the subject was an array of the five shapes. These inspection shapes were different in size from the shapes that were wielded. On any given trial, the subject identified the shape wielded by choosing one of the visible shapes. Each of 10 subjects received 30 trials. Five of the subjects were each shown the wielded shape on a trial after he or she had responded; the other 5 subjects received no feedback whatsoever during the performance of the experiment. Across trials each shape at each of the two sizes was presented three times. Distribution of shapes and sizes across trials and subjects was randomized. Figure 9 presents the overall picture. In this figure we can see the proportion of times that a wielded object was identified correctly and the proportion of times it was confused with an object of different shape. Examining the diagonal, it can be seen that object recognition was easily greater than chance (12/60) for three shapes and marginally so for two shapes. Examining

Fig. 9. A summary of the data from 10 subjects in an experiment in which different shapes were wielded but not seen. The responses are expressed in terms of the total number of times out of 60 occasions (3 judgments $\times$ 10 subjects $\times$ 2 sizes) that a particular response object was reported for a given stimulus object.

the off-diagonals, it can be seen that confusions were not random. Figures 10 and 11 show the data for the 2 subjects who were correct in their recognitions most often. One received feedback, one did not. Overall the feedback variable was insignificant.

Let us see how well the pattern of results depicted in Figure 9 can be addressed through the principal moments of inertia and, thereby, the invariants of strain causally entailed by them. With respect to the symmetric inertia tensor, its principal moments (its eigenvalues) are invariants, and all of its other invariants are functions of them, most notably the trace (the sum of the three principal moments) and the determinant (the product of the three principal moments). The invariant that we seek for the haptic perception of shape cannot be either of the preceding well-established physical invariants. Whereas both are coordinate-system free quantities, they are quantities that vary with change in size. As intimated above, a more likely candidate is the ratio of principal moments; this would be indifferent to size variation. All of the objects used in the present experiment were objects for which the principal moments about two of the three principal

Fig. 10. Response objects as a function of stimulus objects for an individual subject with feedback on each trial. The figure along the side of the grid depicts the shape of the solid that was presented to the subject; the figure along the top represents the subject's judgment. The responses are expressed in terms of the total number of times, out of six occasions, that a particular object presented was judged to be of a particular shape.

axes were coincident. (The third principal axis in each object is an axis of more than twofold symmetry.) Consequently, the ratio of the two different principal moments is a good index of the shape of an object. We define the *inertial index of shape* for the present set of objects, therefore, by the ratio: larger principal moment/smaller principal moment. Given this index we can proceed to address the pattern of perceptual confusions. We would expect the ratio of the inertial index of shape of one object to the inertial index of shape of another object to predict the degree of confusion between the two objects. Putting the smaller index as the numerator, this prediction amounts to an expectation of most confusion when the ratio is close to unity and increasingly less confusion as the ratio gets larger. In Figure 12 we plot the number of confusions as a function of the ratio of inertial indices of shape. As can be seen, perceptual confusion increases linearly with similarity in inertial indices of shape. All in all, the data of the experiment suggest that, under the intention to perceive an object's shape by wielding, a person detects a formless invariant of tissue deformation causally entailed

Fig. 11. Response objects as a function of stimulus objects for an individual subject with no feedback on each trial. The figure along the side of the grid depicts the shape of the solid that was presented to the subject; the figure along the top represents the subject's judgment. The responses are expressed in terms of the total number of times, out of six occasions, that a particular object presented was judged to be of a particular shape.

by an invariant expressible by the ratio of larger and smaller principal moments.

Knowing about Parts and Wholes by Wielding

We now consider a class of experiments that has bearing on the notions of selective attention and the stimulus control of behavior, as those notions are discussed in the cognitive psychology literature and the operant learning literature, respectively. It is self-evident that an animal can focus on, and behave with respect to, different aspects of an object depending on the occasion. This nondeterminacy, termed the *puzzle of perceptual variety* by some commentators (e.g., Michaels & Carello, 1981), opens two critical issues. First, what are the criteria by which one aspect of an object or event, rather than another, is more likely to be perceived in a given situation? Second, what is the nature of the mechanism by which this selection is effected? The second question has perhaps attracted more interest in psychology; it is the problem of attention. One says that

Fig. 12. Number of times shape x was confused with shape y as a function of the ratio of shape x 's inertial index (largest principal moment of inertia divided by smallest principal moment of inertia) to shape y 's inertial index.

the animal has filtered out the temporarily irrelevant aspects, or that its behavior is under the stimulus control of only some properties of the object. In the ecological perspective we underscore an aspect of attending that is overt and observable, contrasting with, and complementing, the covert, internal attending implied by filtering and, perhaps, stimulus control. The control of detection is emphasized rather than the filtering of stimulation. In other words, attention is not a process of sorting through a pool of sensations that are given free of charge, but the result of particular exploratory actions that support the detection of specific information. To employ a fanciful analogy, we might contrast fishing with a net to angling with a hook and line; a skillful netminder knows how to recognize the desired fish among the worthless within a particular catch, whereas a skillful angler constrains what he or she might catch before casting the line. Five modes of control are identified. These involve exploratory adjustments of the eye-head system, the ear-head system, the hand-body system, the nose-head system, and the mouth-head system (J. Gibson, 1966). These explorations enhance the available information and clarify perception. The key idea is that attention is not, as customarily formulated, an intervening process performed on the data of the senses, but a kind of activity that permeates the perceiving-acting cycle.

Thus, the mechanism of attention can be, in significant degree, external and observable.

The wielding of concern to the present article is an exploratory adjustment of the hand-body system. We have shown above how wielding makes available information about various properties of hand-held objects. The information is in the form of invariants specific to the properties in question. One implication of the invariant perspective on information, as noted in the introduction, is that the wielding must be regarded as comprising the transformations over which the invariant is defined. This way of talking facilitates the discussion of smart haptic perceptual instruments; in principle, each can be identified objectively with a particular style of exploration. In a recent article extending earlier observations by Lotze (1856/1885), Katz (1925), and Gibson (1962, 1966), Lederman and Klatzky (1987) have provided examples of a number of particular exploratory styles associated with the perception of specific object properties.

The first question stemming from the puzzle of perceptual variety is addressed less often. What the animal intends in a situation can be as crucial an issue as how it attends. For some scientists, the term *intention* has dangerous implications in that it is sometimes thought to imply an internal, unconstrained processor or mediator. Indeed, there has been some success in demonstrating that the criteria for attention sometimes simply involve the temporal or geographical affinity of stimuli and responses (e.g., Testa, 1975). In other contexts, however, similar external stimuli give rise to different responses, and the instructions communicated to the perceiver are the best predictors of the response yielded. Of course the instructions heard by a human subject are part of the stimulus picture, but they provide only an operationalization of what we call intention, and not an explanation. (For example, the experimenter, in planning the experiment, might carry out some of the same tasks as the subjects without being instructed by anyone.) One of the ongoing goals of ecological science in general is to discover the natural organizations and self-organizations that support the operation of an intentional system. The reformulation of attention discussed above indicated the role of intentionality but not, as yet, its nature. Ecological psychologists tend to agree with contemporary behaviorists that accounts of action and perception can be developed without a firm explanation of intentionality. These two

groups might disagree in that, to most ecological psychologists, intentionality will have to be addressed eventually.

Consider the following example of a subject perceiving different properties in response to differing instructions. Imagine wielding a rod about a hand grip intermediate between the rod's end under the intention to perceive the distance reachable with the whole rod if it were held at the end closest to you versus the intention to perceive the distance reachable with the portion of the rod forward of the hand. Satisfying the former requires detecting the rod's maximal moment of inertia; satisfying the latter requires detecting the maximal moment of inertia of the rod fraction. Let us see what is entailed by the contrast in terms of the underlying laws and principles, and the constraints that must be placed on them.

The only factors that can affect an object's resistance to rotational acceleration are the shape of the body and the distribution of mass in the object. Consider again the rotational configuration of a uniform slender rod of mass M and length L . With respect to an axis perpendicular to the rod and passing through its mass center, $I = ML^2/12$. With respect to an axis passing perpendicularly through one of the rod's ends, $I = ML^2/3$. A change in the axis of rotation is thus seen as a change in the configuration of the body. Further, if the axis passes through a point that partitions the rod into the ratios of a and b ($a + b = 1$), then the rod can be considered as composed of two pieces of lengths aL and bL . It is easily shown that I for the single piece of length L about the given axis is equal to the sum of I_a and I_b , the respective moments of inertia of the pieces aL and bL as defined with respect to the axis passing through a piece's end. Similarly, if a block of mass is attached to the uniform rod, the distribution of mass is altered and $I = I_{\text{rod}} + I_{\text{block}}$, where the component moments of inertia are calculated according to the parallel axis theorem. Both of the preceding facts demonstrate the principle that a system of forces acting on a body can be equated with a single force acting on the body about a suitable base point.

We reported above experiments in which subjects held and wielded a uniformly dense rod at positions intermediate between its two ends with the purpose of perceiving the rod's total length ("how far could you reach with it

if you were to hold it at its proximal end?"'). As Figure 3 reveals, they performed the task successfully, with perceived total rod length tracking the rod's moment of inertia about the axis of rotation as computed through the parallel axis theorem. In one experiment in the series conducted by Solomon and Turvey (1988), rather than having to perceive the total length of the rod, subjects had to perceive the length of rod that extended beyond where the rod was grasped ("how far could you reach with the portion of the rod forward of the hand?"). This task was also performed successfully; partial rod lengths were distinguished reliably, with perceived length tracking the moment of inertia of the rod fraction. Presumably, in the partial task, the activity of wielding an unseen rod must distinguish the torques and motions of the partial rod from the torques and motions of the rod as a whole. The implication of the experimental results just noted, therefore, is that the haptic subsystem can decompose a torque into component torques and decompose a principal moment of inertia into compound moments of inertia.

In two further experiments we manipulated both the rotational configuration and the mass distribution to address directly this decomposition capability of the haptic subsystem (Solomon et al., 1989b). On each trial, a visually occluded rod was wielded by the subject at a position intermediate between two ends. The position was either $\frac{1}{2}$ or $\frac{3}{4}$ of the rod's length. On $\frac{2}{3}$ of the trials a weight was attached to the rod at a point either above or below its center of gravity and not coincident with the hand's position. In the first experiment the subject's task was to perceive the distance reachable with the portion of the rod extending beyond the position of the grasp. In the second experiment, the subject's task was to perceive the distance reachable with the entire rod if it were held at its proximal end.

With respect to the first experiment, if the haptic subsystem can partition the rod into its component moments of inertia for a rod of length L , the perception of $\frac{1}{2}L$ should be the same for the unweighted rod and for the rod with the weight attached at $\frac{1}{8}L$; and the perception of $\frac{1}{4}L$ should be the same for the unweighted rod and with the weight attached at $\frac{1}{8}L$. That is, the perception of the partial lengths forward of the position of the hand should be unaffected by the increase in moment

of inertia brought about by adding a weight below the position of the hand. Similarly, if the haptic subsystem can separate the moments of inertia above and below the fixed point, then for the rods with a weight added above the axis of rotation at $\frac{7}{8}L$, the lengths of $\frac{1}{2}L$ and $\frac{1}{4}L$ should be perceived as longer than when the rods are unweighted. The three basic conditions of the experiment, with respect to the presence and position of the added weight, can be referred to as Condition N (for none), Condition $\frac{1}{8}$, and Condition $\frac{7}{8}$. The following outcomes were expected, therefore, under the decomposition of the moment of inertia hypothesis: (a) when the added weight is below the fixed point (the grasp) it should not affect the perception of the length above the grasp, that is, we expected the equality Condition $\frac{1}{8}$ = Condition N; (b) when the added weight is above the fixed point it should affect the perception of the length above the grasp, that is, we expect the inequalities Condition $\frac{7}{8}$ > Condition N and Condition $\frac{7}{8}$ > Condition $\frac{1}{8}$; and (c) the perceived distances reachable with rods held at $\frac{1}{2}L$ should be longer than the perceived distances reachable with rods held at $\frac{3}{4}L$.

Very different outcomes were expected for the second experiment: (a) a rod held at $\frac{1}{2}L$ should be perceived as longer when weighted than when unweighted (because its total moment of inertia is greater by the parallel axis theorem), and similarly for a rod held at $\frac{3}{4}L$, that is, we expected the inequalities Condition $\frac{7}{8}$ > Condition N and Condition $\frac{1}{8}$ > Condition N; (b) the distances reachable with rods held at $\frac{1}{2}L$ should be perceived as shorter than when held at $\frac{3}{4}L$ (because at $\frac{1}{2}L$ the moment of inertia is least by the parallel axis theorem); (c) position of weight should have no differential effect for rods held at $\frac{1}{2}L$ (because of same moments of inertia by the parallel axis theorem) but should have a differential effect for rods held at $\frac{3}{4}L$ (because of different moments of inertia by the parallel axis theorem).

The results of the two experiments were in agreement with expectation. In the first experiment, perceived reaching distance was a function of the moment of inertia of the amount of rod forward of the grasp about an axis through the proximal end of the rod segment. In the second experiment, perceived reaching distance was a function of the moment of inertia of the entire rod about the given axis of rotation intermediate between the rod's ends.

The subjects in the experiments were able to perceive either the extent of the whole object or the extent of a part. The contrast between the two experiments is striking, given that they differed only in the instructions to the subjects. Further research will be required to determine how well the contrast can be understood in terms of observable exploratory adjustments. Do the different intentions realize different patterns of filtering or do they realize different haptic instruments in the sense of different patterns of exploration? The question can be answered only by a rigorous examination of the dynamics of the exploratory behaviors.

GENERAL DISCUSSION: SOME ECOLOGICAL THEMES

J. Gibson (1966, p. 127) claimed that "The stimulus information from wielding can only be an invariant of the changing flux of stimulation in the muscles and the tendons: an exteroceptive invariant in the play of forces." In the present article we have reviewed experiments in support of this claim. People can know, to a greater or lesser degree, the extent, orientation, shape, and fractional components of unseen objects wielded by hand. It seems that they know these facts by detecting invariants of tissue deformation made available in the course of wielding. In this final section we hope to underscore some major themes of the ecological approach, taking advantage of the research we have reported on haptic knowing.

Structured Arrays versus Stimuli

Although there are many uses of the term (see J. Gibson, 1960), a stimulus in the strictest historical sense is an event that excites a receptor and triggers activity in afferent fibers. By this definition, a group of mechanoreceptors comprising a haptic subsystem can be excited only by a group of stimuli. To the extent that the stimuli within the group are independent of one another, processes must be postulated that group and organize the relatively independent neural activities that they give rise to. An ecological approach rejects the thesis that perception is based on stimuli and the internal processes that this thesis implies. With respect to the haptic system, perception is based on the information contained in structured arrays of deformations or contacts. Such structured arrays consist of different magnitudes in

different directions (J. Gibson, 1979) and comprise information about the mechanical events that generated them. For the wielding of an object in three space, we described one structured array by the inertia tensor, a quantification of the different rotational moments in different directions. Over the medium of biological tissue, we described the structured array in terms of the strain tensor, a quantification of the different strains in different directions. We saw that these arrays contain invariants that are specific to environmental properties, and to which perception, in turn, appears to be specific.

Discussions of the concept of the stimulus in psychology have included the question of whether the stimulus (construed broadly and loosely) can be defined independently in physical terms rather than in terms of behavior or sensory reactions. Skinner (1959, p. 355) noted: "... we frequently define the stimulus by the very doubtful property of its ability to elicit the response in question, rather than by any independent property of the stimulus itself." The examples given above of environment-specific invariants present in structured arrays identify bases in stimulation for successful perception that are defined independently of the organism. They are examples of what might be called potential stimulation (J. Gibson, 1960). They derive from a consideration of the connection or specificity between structured arrays and their natural sources. They are expressions of a general strategy for classifying stimulation that contrasts with more traditional efforts at classification in terms of sense organs, types of energy, or behavior. Identifying these specificities broadly is a problem of ecology, more exactly, of ecological physics. In our view such an enterprise is essential to the development of a rigorous account of knowing (Shaw & Turvey, 1981; Turvey, 1977; Turvey & Carello, 1981; Turvey & Shaw, 1979; Turvey *et al.*, 1981). From this perspective one would say that what an understanding of cognition requires is not more psychology but more physics.

Information Pickup

The preceding underscores that the available stimulation has structure, and that this structure depends on sources in the surrounding environment. A haptic subsystem is a system for sampling this structure and extracting

its invariants. J. Gibson (1966, 1979) called the activity of getting information from ambient structured arrays *information pickup* and noted that it involved orienting, exploring, adjusting, optimizing, resonating, extracting, and equilibrating. These physical metaphors contrast sharply with the metaphors of inferring, hypothesis testing, constructing, conceptualizing, and so on, that tend to dominate most interpretations of how an animal knows about its surroundings. In an early formulation of the notion of pickup, Gibson (1966, p. 267) wrote:

If the invariants of this structure can be registered by a perceptual system, the constants of neural input will correspond to the constants of stimulus energy, although the one will not copy the other. . . . The brain is relieved of the necessity of constructing such information by *any* process—innate rational powers (theoretical nativism), the storehouse of memory (empiricism), or form-fields (Gestalt theory). . . . Instead of postulating that the brain constructs information from the output of a sensory nerve, we can suppose that the centers of the nervous system, including the brain, resonate to information.

Terms such as resonance, tuning, equilibration, invariants, and the like, are terms that point to lawful relations among observables. Can the law-based perspective implicated in the notion of pickup be developed? With respect to the kinds of data reported in the present article, a description of the hand-muscles-joints-nerves haptic subsystem has been given as a particular embodiment of particular lawful regularities suitably harnessed by the person's intentions. The variables defining the haptic subsystem with respect to the goal of perceiving rod extent can be identified in the form of operator equations (Solomon, 1988; Solomon & Turvey, 1988; Solomon et al., 1989a, 1989b), where the operators are taken to be natural laws. A brief overview of this enterprise follows.

Let a vector quantity $\mathbf{r}$ represent the hand-rod, rigid body system. Then the matrix $\mathbf{A}$ represents an operator such that $\mathbf{A}\mathbf{r} = \mathbf{y}''$ is a description of rigid body motion about a fixed axis in the wrist. Now let a vector quantity $\mathbf{h}$ represent the haptic subsystem, a functional organ comprising mobile, mechanoreceptive tissues. The effect of the rigid body motion, expressed as $\mathbf{A}\mathbf{r} = \mathbf{y}''$, is a deformation of the

haptic subsystem. The resultant deformable body motion is described by the operator equation $\mathbf{D}\mathbf{h} = \mathbf{y}''$. Now assume an invariant property of the tissue deformation $\mathbf{y}''$ that is specific to the particular object property on which the perception of object length is based. This assumption can be expressed as the claim that there exists an operator $\mathbf{Q}$ such that when it acts or operates on $\mathbf{D}\mathbf{h}$ it yields the transform $\mathbf{y}'$, where $\mathbf{y}'$ is an invariant of this deformable body motion specific to the object property on which the perception of object length is based: $\mathbf{QDh} = \mathbf{y}'$. $\mathbf{y}'$ is not the ultimate measurement of the haptic perceptual instrument, that is, it is not the locations reachable by the hand-held rod. Consequently, to complete the description, a further operator is needed. This operator $\mathbf{L}$ must render $\mathbf{y}'$ as a location in a coordinate system centered at the subject. That is, $\mathbf{LQDh} = \mathbf{y}$, where $\mathbf{y}$ is the location of the distal tip of the hand-held rod.

The operators $\mathbf{A}$, $\mathbf{D}$, $\mathbf{Q}$, and $\mathbf{L}$ are, in principle, embodiments of physical laws. Thus, we can note, on the basis of the discussion in Section 2.1, that $\mathbf{A}$ is the inertia tensor, $\mathbf{D}$ is the strain tensor, and $\mathbf{Q}$ is functionally equivalent to a nonsingular matrix that diagonalizes simultaneously the symmetric inertia and strain tensors. These operators connect the exploratory activity of the haptic subsystem, the rigid body motions produced by that activity, the tissue deformations that they, in turn, induce, and the property of the environment that the subject intends to perceive. Collectively, they (a) define the haptic perceptual instrument that measures the extent of a hand-held object and (b) preserve specificity over the various components of the perceiving-acting cycle. The central idea is that, given the operators, a single-valued, determinate mapping is guaranteed between a hand-held object's resistance to rotational acceleration and the perception of its length. Ideally, the operator formulation of information pickup can be pursued for the other haptic subsystem capabilities noted in the present article. In each case further experimentation and theoretical work will be required to establish the relevant operators and the laws thereby embodied.

Concluding Remarks

To reiterate, information in the ecological approach is conceptualized as molar, noninertial properties of structured energy distribu-

tions generated lawfully by properties of the environment and by properties of the perceiver's movements. As such, information is determined; it abides the principle of causality (Kugler & Turvey, 1987). From our point of view this is a most significant fact. The determinate nature of information means that it can provide a reliable, incorrigible basis for perception and behavior. This phrasing is meant to highlight that information is wholly constraining of behavior but does not cause it. There may be a commonality here with the claim by behaviorists of the operant learning school that discriminative stimuli are occasions for behavior, not causes of behavior.

Information's determinacy in relation to behavior's nondeterminacy is an important aspect of current efforts to exploit patterns of coordination and self-organization as studied by physicists when considering behaviors in the bailiwick of psychology (such as perceptual explorations and coordinated actions). For example, Kugler and Turvey (1987, 1988) have dealt at some length with information, behavior, and their relation, from the perspective of a physical biology that addresses living systems through the concepts and methods of non-equilibrium (nonlinear) thermodynamics and dynamics. It is hoped that this enterprise within the ecological approach will contribute to the historic and ongoing intention of behavioral science to treat behavior as a naturally occurring and naturally developing phenomenon.

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