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Ecological Constraints on Internal Representation: Resonant Kinematics of Perceiving, Imagining, Thinking, and Dreaming

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This article attempts a rapprochement between James Gibson's ecological optics and a conviction that perceiving, imagining, thinking, and dreaming are similarly guided by internalizations of long-enduring constraints in the external world. Phenomena of apparent motion illustrate how alternating presentations of two views of an object in three-dimensional space induce the experience of the simplest rigid twisting motion prescribed by kinematic geometry—provided that times and distances fall within certain lawfully related limits on perceptual integration. Resonance is advanced as a metaphor for how internalized constraints such as those of kinematic geometry operate in perception, imagery, apparent motion, dreaming, hallucination, and creative thinking, and how such constraints can continue to operate despite structural damage to the brain.

Oxford philosopher of science Rom Harré in his book *Great Scientific Experiments: Twenty Experiments That Changed our View of the World* (Harré, 1983) includes James J. Gibson's work on perception along with experiments by such giants of the natural sciences as Aristotle, Galileo, Newton, Boyle, Lavoisier, Rutherford, and Pasteur. Counting myself among students of perception who have come to recognize the challenge that Gibson posed to many long-accepted ideas, I have been moved to work out how the essential insight that informs Gibson's ecological approach might be extended into a realm that has been for me of great and continuing interest.

My efforts in this direction have not proceeded without trepidation. Gibson himself is widely considered to have regarded this realm as insignificant or, worse, nonexistent. I refer to the realm of what I have called *internal representation* (Shepard, 1975; Shepard & Chipman, 1970). Even in my title, which begins auspiciously enough with that good word *ecological,* I have risked anathema by moving immediately on to those very words *internal representation.* How can one who finds Gibson's insight into perception to be so congenial persist in exploring the application of this insight to a realm that Gibson himself never countenanced? At least part of the answer must be that even investigators who agree that they are studying perception

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This article, which I dedicate to the memory of James J. Gibson, is an expanded version of the Gibson Memorial Lecture, which I gave at Cornell University on October 21, 1983. I thank the members of the Department of Psychology at Cornell for providing me with an opportunity to clarify the relation of my thinking to Gibson's, and the National Science Foundation for supporting both the preparation of this article and most of the research on which it is based (especially through Grants GB-31971X, BNS 75-02806, and BNS 80-05517).

The faults that undoubtedly remain have at least been greatly reduced as a result of the helpful suggestions made by numerous colleagues including Fred Attneave, Maya Bar-Hillel, Lynn Cooper, Joyce Farrell, John Flavell, David Foster, Jennifer Freyd, Randy Gallistel, Frank Keil, Edward Kessler, Carol Krumhansl, Laurence Maloney, Ann O'Leary, Edward Oshins, Herbert Simon, Elizabeth Spelke, Richard Thompson, Brian Wandell, Benjamin White, and, especially, Gerald Balzano, James Cutting, Julian Hochberg, Michael Kubovy, and Ulric Neisser. Each of these last five contributed extraordinarily painstaking, thoughtful, and enlightening comments.

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may be found, on closer examination, to have quite different objectives.

Differing Goals in the Study of Perception

Goal of Understanding a Sensory Organ's Transduction of Incident Energy

Those who call themselves psychophysicists or vision researchers tend to seek laws relating judgments about sensory events to physically measurable properties of proximal stimuli, and those who call themselves sensory psychophysiologists seek, in addition, relations of these kinds of variables to physically measurable activities within the nervous system. The primary goal for both of these classes of researchers seems to be the elucidation of the mechanisms whereby energy impinging on a sensory organ is transduced into neural activity and thence into behavior.

Goal of Understanding an Organism's Perception of its Environment

Helmholtz (1856/1962, chap. 1), while pursuing the goal of understanding sensory transduction of proximal stimulation, also recognized that an organism must interact appropriately with distal objects in its environment. Yet this latter, ecologically oriented objective was not fully articulated as the primary goal of the study of perception until Brunswik (1956) and J. Gibson (1950) stressed that as the organism, objects, and sources of illumination move about in space, the variations in proximal stimulation bear little resemblance to the particular unidimensional variations of retinal size, brightness, wavelength, or duration that psychophysicists and psychophysiologists have typically manipulated in their laboratories.[1]

True, early investigators such as Hering (1878/1964), Mach (1886/1959), and even Helmholtz (1856/1962) suggested that the flux of proximal stimulation does contain some features that are invariantly related to distal objects. For example, although the light energies reaching the eye from two surfaces of different reflectances vary widely with changes in illumination, the ratio of those two energies remains constant. Then Cassirer (1944) explicitly introduced the mathematical concept of invariance over a group of transformations as a characterization of such perceptual constancies. Nevertheless, it remained for Gibson to adopt the radical hypothesis of what he called the *ecological* approach to perception (Gibson, 1961, 1979), namely, the hypothesis that under normal conditions, invariants sufficient to specify all significant objects and events in the organism's environment, including the dispositions and motions of those objects and of the organism itself relative to the continuous ground, can be directly picked up or extracted from the flux of information available in its sensory arrays.

In the case of the modality that most attracted Gibson's attention—vision—the invariants generally are not simple, *first-order* psychophysical variables such as direction, brightness, spatial frequency, wavelength, or duration. Rather, the invariants are what J. Gibson (1966) called the higher order features of the ambient optic array. (See J. Gibson, 1950, 1966, 1979; Hay, 1966; Lee, 1974; Sedgwick, 1980.) Examples include (a) the invariant of radial expansion of a portion of the visual field, *looming,* which specifies the approach of an object from a particular direction, and (b) the projective cross ratios of lower order variables mentioned by J. Gibson (1950, p. 153) and by Johansson, von Hofsten, and Jansson (1980, p. 31) and investigated particularly by Cutting (1982), which specify the structure of a spatial layout regardless of the observer's station point.

For invariants that are significant for a particular organism or species, Gibson coined the term *affordances* (J. Gibson, 1977). Thus, the ground's invariant of level solidity affords walking on for humans, whereas its invariant of friability affords burrowing into for moles and worms. And the same object (e.g., a wool slipper) may primarily afford warmth of foot for a person, gum stimulation for a teething puppy, and nourishment for a larval moth. The invariants of shape so crucial for the person are there in all three cases but are less critical for the dog and wholly irrelevant for the moth.

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[1] Correspondingly, I have elsewhere argued for a kind of psychophysics that does not restrict itself to the consideration of proximal variables (see Shepard, 1981a, 1981b, 1982a).

Although the goal of identifying the invariants in the optic array that correspond to all such affordances is far from having been attained (Hochberg, 1982; Neisser, 1977), progress has been made in identifying the invariants underlying the perception of individual human gaits (Cutting, Proffitt, & Kozlowski, 1978; Kozlowski & Cutting, 1977) and of age in human and animal faces (Pittenger & Shaw, 1975; Shaw & Pittinger, 1977), and in establishing that the ability to pick up such invariants as rigidity versus nonrigidity emerges early in human infancy (E. Gibson, 1982; E. Gibson, Owsley, & Johnston, 1978; E. Gibson & Spelke, 1983; Spelke, 1982).

According to James Gibson, the notion—widely accepted since Helmholtz—that we must construct our percepts by combining sensory cues was a misguided consequence of elementaristic, ecologically invalid laboratory experiments in which, for example, a physically restrained observer was permitted only a brief, monocular glimpse of the stimulus. In natural settings we enjoy binocularity, free mobility, and persisting illumination. In that case, Gibson claimed, no inference is required because invariants in the shifting optic array uniquely specify the layout of the environment.

Goal of Understanding the Capabilities of an Organism Under Reduced Circumstances (of Incomplete Information, Insufficient Time, or Damaged Brain)

Even those who follow Gibson this far in pursuing the goal of understanding how organisms function in their natural environment may nevertheless disagree about what to include under its heading. For most of those who follow the ecological approach, the goal has been confined to the identification and specification of the invariants that are sufficient for the veridical perception of the local environment under favorable conditions of visibility, mobility, and neural integrity. They have manifested little interest in three other kinds of questions: First (noted, e.g., by Ullman, 1980), they have not pursued questions, raised by students of neurophysiology and artificial intelligence, concerning the mechanisms that enable an individual to extract the appropriate invariants from the information available at its sensory surfaces.

Second, they have neglected questions, raised by students of cognitive science, concerning how we know about (a) objects, relations, and events that are obscured by darkness or by obstructed, monocular, brief, or intermittent access and also (b) those that are beyond the region that is directly affecting us during a given period of time. There often is no information in sensory arrays about events that have occurred in the past, that are occurring in another place, that will occur in the future, or that might occur under altered circumstances, even though such events can be of great importance and can be known to us in our natural environment.

Third, students of ecological optics have ignored questions, raised by experimental cognitive psychologists and by clinical neurologists, concerning what happens when the information available in the sensory arrays—although sufficient to specify the immediate environment—exceeds the processing capabilities of the individual. I argue that there are limits on the intervals of space and time over which we can integrate information available in the sensory arrays and that these limits are themselves lawful in ways that cry out for explanation. Moreover, there are questions of what happens when this processing capability is further reduced as a result of brain damage, which also occurs in our natural environment as a result of injury, disease, or (as I am increasingly reminded) advancing age. Why do brain lesions lead to particular perceptual dysfunctions, and especially, how can the brain often reestablish more or less normal functioning despite such lesions?

In short, although I agree with Gibson that the brain has evolved to extract invariants under favorable conditions, I also presume that it has evolved to serve the organism under less favorable conditions of nighttime, obstructed, and spatially or temporally limited viewing and, even, of structural damage to the brain itself.

Proposed Extension of the Ecological Approach

In striving to accommodate questions from all three classes just mentioned, without abandoning Gibson's essential insight, one seemingly has to come to terms with the relation between the organism's representation of objects that are and those that are not immediately affecting its sensory arrays, that is, with the relation between perception and mental imagery.

Problem of Mental Imagery

I conjecture that Gibson disavowed the term *mental image* because he could not imagine what sort of thing a mental image could be. He readily spoke of *perceiving* an object, because that object is a physical thing. But in his view "the notion of 'mental images' as distinguished from 'material images' seems to be wholly wrong" (J. Gibson, 1974, p. 42). On the one hand, if a mental image is not a physical thing, what on earth is it?

> We certainly do not summon up pictures inside our head for they would have to be looked at by a little man in the head. . . .Moreover, the little man would have eyes in *his* head to see with and then a still littler man and so *ad infinitum.* (J. Gibson, 1974, p. 42)

On the other hand, if a mental image is a physical (i.e., neural) process in the brain, we must admit that we know next to nothing about the process. Surely, what determines whether an animal survives is its interaction with its external environment, regardless of which of the possible internal mechanisms for mediating that interaction is realized in that particular animal. However, in neglecting the representation of objects and events that are not physically present, Gibson seems to have given up too much.

I proposed to accommodate mental imagery by saying that (a) imagining, like perceiving, is surely performed by physical processes in the brain but (b) we do not need to know any details of these processes in order to study imagining (any more than Gibson had to have such knowledge in order to study perceiving). What we imagine, as much as what we perceive, are external objects; although in imagining, these objects may be absent or even nonexistent. We can therefore carry out experiments on both perception and imagery by probing individuals with appropriately chosen external stimuli (Podgorny & Shepard, 1978, 1983; Shepard, 1975, 1981b; Shepard & Chipman, 1970; Shepard & Cooper, 1982; Shepard & Podgorny, 1978; and, for a brief overview, Shepard, 1978c).

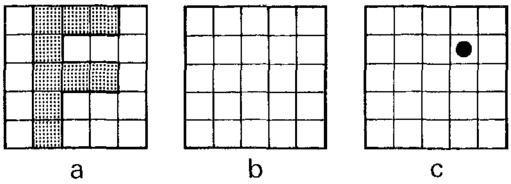

Figure 1. Displays used for the perceptual condition (Part a), the imaginal condition (Part b), and the ensuing test probe (Part c) in one of the experiments by Podgorny and Shepard (1978). (From "The Mental Image" by R. N. Shepard, 1978, *The American Psychologist, 33,* p. 133. Copyright 1982 by the American Psychological Association. Adapted by permission.)

An experiment that Podgorny and I carried out illustrates the point. On each trial, a person looked at a square grid. In the perceptual condition, some squares had been shaded to form a certain object (such as the block letter F in Figure 1, Part a); in the imaginal condition, no squares were shaded but the person was asked to imagine that the same squares had been shaded (Figure 1, Part b). In both conditions, we then flashed a colored probe dot in one of the squares (Figure 1, Part c) and measured the latency of the person's response indicating whether the dot did or did not fall on the (perceived or imagined) object. With experiments of this type, we obtained two major results: First, the reaction times depended on the position of the probe relative to the figural object in a way that implicates orderly constraints in the perceptual mechanism. For example, responses were consistently slower to probes that were closer to boundaries between figural and nonfigural squares. Second, the reaction times exhibited virtually the same pattern in the imagery and the perceptual conditions, suggesting that the object was internally represented in the same way regardless of whether it was physically present or only imagined. (Podgorny & Shepard, 1978, 1983.)

Although I thus speak of internal representations, I agree with J. Gibson (1970, p. 426) as well as with Neisser (1976, p. 57) that one invites unnecessary perplexities by speaking—as imagery researchers sometimes carelessly do—of "seeing," "looking at," "inspecting," or "rotating" one's images or internal representations. Rather than say that one sees or rotates the image of an object (as if the image were itself a physical thing), one can avoid such perplexities by simply saying that one imagines the object and/or its rotation (which *are* potentially physical things). The distinction is, for example—as Michael Kubovy (1983) has well put it—between the acceptable formula *Imagine* [*Rotation of (Object)*] and the problematic *Rotate* [*Image of (Object)*]. On occasion, I have spoken of "experiencing" an image or similarly a percept, but only as a kind of shorthand for "undergoing the corresponding (but largely unknown) physical processes in the brain" (cf. Place, 1956; Smart, 1959). Properly speaking, our experience is of the external thing represented by those brain processes, not of the brain processes themselves. At the same time, by acknowledging that perceiving and imagining—as well as remembering, planning, thinking, dreaming, and hallucinating—do correspond to brain processes, we at least open the door to possible connections with evolutionary biology, clinical neurology, and artificial intelligence.

Evolutionary Perspective on Perception and Representation

Whatever we possess in the way of a perceptual and/or representational system must be the product of a long evolutionary history. Our remote ancestors, like many surviving primitive species (ranging from single-celled animals to worms), could not extract *higher order* invariants corresponding to distal objects of the sort that usually concern us now. Instead, they proceeded on the basis of proximal stimuli of a chemical or mechanical nature. Only with the evolution of increasingly powerful mechanisms for the processing of optical, acoustical, and tactual information have we gained access to remote objects and events.

In keeping with the ecological approach, I believe that (initially) the primary function served by this more sophisticated perceptual processing was to partition the information available in these various incoming forms into (a) the invariants uniquely corresponding to distal objects, events, and layouts, and (b) the complementary variables corresponding to the moment-to-moment changes in the disposition of those objects, events, and layouts, and of the self in relation to them. Such a partitioning is now pervasive: We visually perceive both a persisting object and its current spatial relation to us. We also recognize both the face of a friend and its momentary expression, both what has been written and the format in which it is written, both what has been said and the emotional state of the speaker, and both a particular melody and the pitch height and timbre at which it has been played.

However, this is not the end of the evolutionary story. As Gibson emphasized, higher organisms are not merely observers; they are active explorers and manipulators of their environment. If such exploration and manipulation is not just random trial and error, it must be guided by some internal schema (Hochberg, 1981, 1982; Neisser, 1976) or hypothesis (Krechevsky, 1932). At this point, a new type of function emerges that is related to perceptual and to motoric functions, but is not identical to either. I refer once again to the ability to remember, to anticipate, and to plan objects and events in their absence. The alternative claim (cf. Gibson, 1970), that such functions are entirely separate from perception, is untenable in view of experimental results of the sort reported by Podgorny and Shepard (1978, 1983) and others (as reviewed in Finke, 1980; Finke & Shepard, in press; Shepard & Cooper, 1982; Shepard & Podgorny, 1978). This claim is further weakened by neurophysiological and clinical evidence from brain injuries in which failures in the perception of objects or their (real) motions were accompanied by corresponding failures in the imagination of those objects (Bisiach & Luzzatti, 1978) or by the experience (of the type to be considered) of their *apparent* motions (Zihl, von Cramon, & Mai, 1983).

Endogenous Biological Rhythms as a Model for Internal Representation

Because the circadian behavioral cycle is correlated with the presence or absence of daylight, people long drew the inference that an animal's emergence from and return to its nest or burrow was wholly controlled by this obvious external stimulus. It was little more than 50 years ago, when experimenters first began to maintain animals in artificial laboratory conditions of constant illumination and temperature, that they discovered that the circadian (and even the circannual) rhythm had in fact been internalized (Bünning, 1973). Hamsters, for example, would continue their cycles of alternating activity and sleep indefinitely in the absence of a corresponding environmental periodicity, each animal maintaining a cycle of 24 hours plus or minus no more than a few minutes per day (see Rusak & Zucker, 1975).

Of course, a few minutes of deviation from a 24-hour cycle in each animal would cause it gradually to drift out of phase with other animals in the laboratory and with the true diurnal cycle. Yet, no more than a brief period of increased illumination introduced at the same time each day, or even at the same time just on occasional days, would entrain the endogenous cycles and resynchronize all the animals in the laboratory.

Here is an environmental regularity that has continued with celestial-mechanical precision throughout biological evolution. Even though it is correlated with the waxing and waning of daylight, this periodicity has become internalized so that it continues autonomously in the absence of the correlated stimulus, freeing the animal from a direct dependence on that stimulus. Thus, a diurnal animal while still in the darkness of its burrow can begin to awake and to prepare for active emergence toward the onset of sunrise, and can do so as well on a cloudy as on a sunny day. At the same time, the animal can use what photic cues (weak or strong) are available as to the true onset and offset of daytime to keep its internal cycle in synchronous tuning.

Perception is very much like this. Under favorable conditions of illumination, mobility, and so on, our experience of the environment is so tightly guided by the externally available information that we readily feel the appropriateness of Gibson's term *direct perception* (J. Gibson, 1972; also see Austin, 1962; Michaels & Carello, 1981). At the same time, however, we know that our perceptual experience is mediated by many complex though highly automatic neural processes. Any interruption of these processes by drugs, accident, or disease can alter or disrupt perception. Moreover, these processes embody constraints appropriate only to the world in which we have evolved. Therefore, just as an animal that had evolved on a planet with a very different period of rotation would not synchronize well to our daily cycle, a being that had evolved in a radically different world would not perceive this one in the way that we do—even under favorable conditions. Precisely because our own internal constraints so well match the external constraints in our world, these internalized constraints reveal themselves only when externally available information is degraded or eliminated. Being less tightly controlled from without, activity in the perceptual system is then necessarily guided more by whatever constraints operate within.

Internalized Constraints of Kinematic Geometry

I believe the external constraints that have been most invariant throughout evolution have become most deeply internalized, as in the case of the circadian rhythm. Such constraints may be extremely general and abstract: The world is spatially three dimensional, locally Euclidean, and isotropic except for a gravitationally conferred unique upright direction, and it is temporally one dimensional and isotropic except for a thermodynamically conferred unique forward direction (see Davies, 1977). In it, material bodies are bounded by two-dimensional surfaces and move, relative to each other, in ways that can be approximately characterized, locally and at each moment, by six degrees of freedom (three of translation and three of rotation). Light, until absorbed or deflected by the surface of such bodies, travels between them in straight lines and at a constant, vastly greater velocity. Consequently, the optical information about other bodies available at the sensory surface of each organism is governed by the geometrical laws of perspective projection.

The constraints with which I am primarily concerned are those of *kinematic geometry* (Hunt, 1978, p. 2), which govern the relative motions of rigid objects, or of local parts of nonrigid objects, during brief moments of time. Although there are infinitely many ways in which an object might be moved from any position A to any other position B, in three-dimensional space there is a simplest way of effecting the displacement—a fact that was established between 1763 and 1830 through the efforts of Mozzi, Giorgini, and finally, Chasles (1830; see Ball, 1900, pp. 4, 510; Hunt, 1978, p. 49). For any two positions, A and B, Chasles's theorem states that there is a unique axis in space such that the object can be moved from A to B by a rotation about that axis together with a simultaneous translation along that same axis: a helical twist or "screw displacement" (Ball, 1900; Coxeter, 1961; Greenwood, 1965). Moreover, even for an arbitrary motion between A and B, the motion at any instant in time will approximate a twisting of this kind about a momentarily unique axis (Ball, 1900, p. 10). A twist thus bears the same relation to a rigid body as an ordinary vector bears to a point, the special cases of pure rotation and pure translation being realized as the pitch of the twist becomes zero or infinite, respectively.

I consider also the two-dimensional case of Chasles's theorem: For any two positions, A and B, of a two-dimensional object in the plane, there is always a unique pivot point, P, such that the object can be displaced from A to B by a rigid rotation in the plane about P (Coxeter, 1961). Here, pure translation is realized as the pivot point P recedes to the *point at infinity* in a direction orthogonal to the direction of the translational displacement. As before, an arbitrary motion between A and B will, at any instant t, approximate a rigid rotation about a momentarily unique point, $P(t)$.[2]

Illustrative Experiments on Apparent Motion

The phenomenon of *apparent motion,* which seems to fall somewhere between perception and imagery, provides perhaps the best illustration of how internalized constraints of kinematic geometry may govern the perceptual/imaginal representation of objects and their transformations. In apparent motion, the alternating presentation of two different views of an object gives rise to the experience of one object smoothly transforming back and forth—provided both that the time between the onset of one view and the onset of the other (called the stimulus onset asynchrony, SOA) is not too short and that the time between the offset of one view and the onset of the other (called the interstimulus interval, ISI) is not too long. That these transformations are experienced as traversing well-defined trajectories is of the greatest significance: In the absence of any external support for such trajectories, the form they take provides an indication of what I call the *internalized constraints.*

Internalized Constraints Revealed in Apparent Motion

In what is perhaps the simplest case of apparent motion, already investigated by Helmholtz's student Exner (1875) and then by the founder of Gestalt psychology, Wertheimer (1912), two laterally separated dots are presented in alternation. For appropriate time intervals, the experience is of a single dot moving back and forth over the straight path between the two positions of presentation. We thus have an intimation that the experienced impletion is an embodiment of general principles of object conservation and least action (Shepard, 1981b). The richness of these internalized principles is revealed in recent experiments in which the two alternately presented stimuli are views of more complex objects differing by more complex transformations—transformations of (in addition to translation) rotation, reflection, expansion or contraction, and various combinations of these. (See Bundesen, Larsen, & Farrell, 1983; Farrell, 1983; Farrell, Larsen, & Bundesen, 1982; Farrell & Shepard, 1981; Foster, 1975; Shepard & Judd, 1976.)

In Figure 2, each of the 12 panels shows a different pair of views of a polygonal object,

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[2] In three dimensions, the displacement of a point has three degrees of freedom (two for the direction of the corresponding vector and one for its magnitude) and the displacement of a rigid object has six (four for the axis of the twist and the fifth and sixth for its pitch and amplitude). Similarly, in two dimensions, the displacements of a point and of a rigid object have, respectively, two and three degrees of freedom.

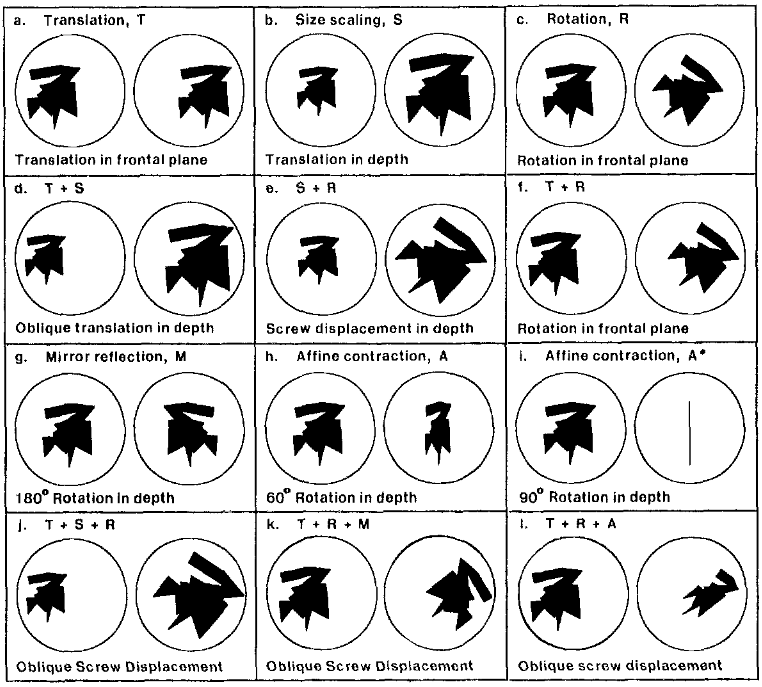

Figure 2. Pairs of two-dimensional shapes that when alternately presented in the indicated positions within the same (circular) field, give rise to rigid apparent motion in space. (For each pair, the transformation that maps one shape into the other has the form indicated above the pair if the transformation is confined to the picture plane, and the form indicated below if it is the simplest rigid transformation in space.)

which might be displayed in alternation within the same two-dimensional field. Thus, Panel a depicts the case in which the polygon alternately appears on the left and the right of a circular field, giving rise to back-and-forth apparent motion. The polygon is one of the forms of the type introduced by Attneave & Arnoult (1956) that Lynn Cooper generated and used to such advantage in her elegant series of experiments on mental rotation (Cooper, 1975, 1976; Cooper & Podgorny, 1976) and that Sherryl Judd and I later adopted for some of our investigations of apparent rotational motion (see Shepard & Cooper, 1982, p. 313).

As indicated at the top of the panels, each pair illustrates a way in which the two views might be related by a transformation in the picture plane: in the top row, shape-preserving transformations of translation (T), size scaling (S), and rotation (R); in the second row, combinations of two of these shape-preserving transformations (T + S, S + R, and T + R); in the third row, shape-altering affine[3] transformations (A, its degenerate case A*, and its negative extension or mirror reflection M); and in the last row, combinations of three transformations (T + S + R, T + R + M, and T + R + A). When they are thus defined as transformations within the plane of the picture, only in 3 of the 12 pairs are the two views related by a rigid motion of the planar polygon: those in Panels a, c, and f, which are composed only of translations, rotations, or both. In each of the nine remaining pairs, the transformation within the plane is nonrigid because it includes a change in the polygon's size, shape, or in both the size and shape.

Nevertheless, in each of these cases, if the rate of alternation is not too great, the motion tends to be experienced as the rigid transfor-

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[3] An affine transformation permits differential linear expansion or contraction along different directions but preserves straightness and parallelism of lines.

mation prescribed by Chasles's theorem, as indicated below each pair. Invariance in perceived size and shape is achieved by liberating the transformation and the object from the confines of the picture plane into three-dimensional space. Thus a viewer tends to experience for Panel b an approach and recession rather than an expansion and contraction; for Panel e a unified twisting approach and recession (the helical or screwlike motion) rather than a rotation, expansion, and contraction; and for Panels h and i, respectively, a 60° or 90° rotational oscillation about a vertical axis, rather than a horizontal compression and expansion.[4]

Out of the infinite set of transformational paths through which the one shape could be rigidly moved into congruence with the other, one tends to experience that unique, minimum twisting motion prescribed by kinematic geometry. The axis of the helical motion may however be aligned with the line of sight (as in Panels c, e, f), orthogonal to the line of sight (as in Panels g, h, i), or oblique (as in Panels j, k, l), and the pitch of the twist may be zero, yielding purely circular motion (as in Panels c and f), or it may become infinite, yielding purely translational motion, whether it is one that is confined to the plane (as in Panel a), orthogonal to the plane (as in Panel b), or oblique (as in Panel d).

Abstractness of Internalized Perceptual Constraints

The two-dimensional case of Chasles's theorem provides the simplest illustration of the abstractness of the internalized constraints. From considerations of physical dynamics, one might guess that two planar figures alternately presented in positions that differ arbitrarily (and hence by both a translation and a rotation, as in Panel f of Figure 2) would give rise to an apparent motion in which the center of mass of the apparently moving body traverses the shortest, straight line between its two terminal positions. Because the two views also differ by a rotation, such a motion would have to be accompanied by an additional, apparent rotational transformation, as illustrated for two rectangles in Figure 3, Part a. Instead of such a double transformation, however, Foster (1975) found that the motion is generally experienced over a curved path. By having observers adjust the variable intermediate rectangle (indicated in Figure 3 by thinner lines) so that it appeared to fall on the path of motion, he found that (under conducive conditions) the motion tended to be experienced over that unique circular path that rigidly carries the one figure into the other by a single rotation about a fixed point, P, in the plane, as shown in Figure 3, Part b.

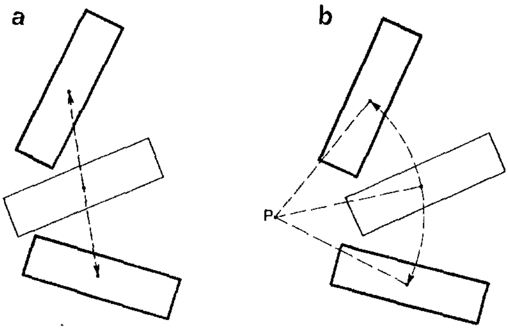

Figure 3. Intermediate positions of a rectangle (drawn in thin lines) between the same two rectangles (drawn in heavy lines), which differ arbitrarily in both position and orientation, along a path consisting of a combined rectilinear translation and a rotation (Part a), and the path (which Foster, 1975, found to be preferred in apparent motion) consisting of a rotation only (Part b). (From *Mental Images and Their Transformations* by R. N. Shepard and L. A. Cooper, 1982, p. 316. Copyright 1982 by The Massachusetts Institute of Technology. Adapted by permission.)

It seems that here, as in the case of the moiré pattern of Glass (1969; an example of which is shown in Figure 4, Part b), the visual system picks out the fixed point implied by the two presented positions of a rigid configuration in the plane and, hence, identifies the two configurations with each other by means of a simple rotation. (See Foster, 1975, 1978; Shepard, 1981b; and for a review and theoretical discussion, Shepard & Cooper,

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[4] In an investigation of apparent motion motivated by similar objectives, Warren (1977) reported that alternation between two-dimensional shapes differing by an affine transformation did not yield rigid apparent motion. However his allegedly affine pair (Panel g) was not affine, and his instructions and resulting subjective reports are open to questions of interpretation, choice of criterion, and effects of perceptual set or expectancy.

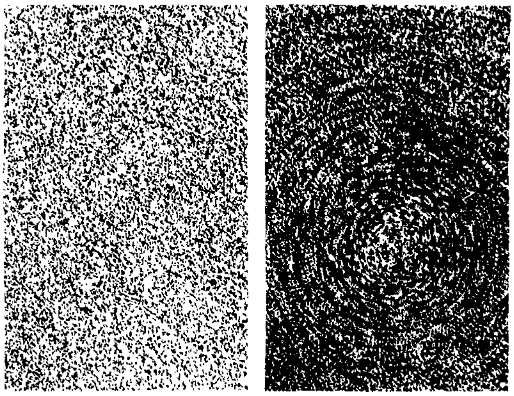

Figure 4. Moiré pattern described by Glass (1969), in which two identical transparencies of a random texture (Part a), when superimposed in an arbitrary misalignment, give rise to the appearance of concentric circles (Part b). (As one transparency is shifted with respect to the other, the center of the concentric circles moves in an orthogonal direction.)

1982.) Incidentally, the visual system also extracts fixed points in the case of nonrigid transformations, as has been demonstrated by Johansson (1950, 1973), Wallach (1965/1976), and most extensively by Cutting and his associates (see Cutting, 1981; Cutting & Proffitt, 1982).

There are good reasons why the automatic operations of the perceptual system should be guided more by general principles of kinematic geometry than by specific principles governing the different probable behaviors of particular objects. Chasles's theorem constrains the motion of each semirigid part of a body, during each moment of time, to a simple, six-degrees-of-freedom twisting motion, including the limiting cases of pure rotations or translations. By contrast, the more protracted motions of particular objects (a falling leaf, floating stick, diving bird, or pouncing cat) have vastly more degrees of freedom that respond quite differently to many unknowable factors (breezes, currents, memories, or intentions). Moreover, relative to a rapidly moving observer, the spatial transformations of even nonrigid, insubstantial, or transient objects (snakes, bushes, waves, clouds, or wisps of smoke) behave like the transformations of rigid objects (Shepard & Cooper, 1982).

It is not surprising then that the automatic perceptual impletion that is revealed in apparent motion does not attempt either the impossible prediction or the arbitrary selection of one natural motion out of the many appropriate to the particular object. Rather, it simply instantiates the continuing existence of the object by means of the unique, simplest rigid motion that will carry the one view into the other, and it does so in a way that is compatible with a movement either of the observer or of the object observed.

Possibly some pervasive principles of physical dynamics (such as a principle of momentum), in addition to the more abstract principles of purely kinematic geometry, have been internalized to the extent that they influence apparent motion (Foster & Gravano, 1982; Freyd, 1983a, 1983c, 1983d, 1983e; Freyd & Finke, 1984; Ramachandran & Anstis, 1983). But there evidently is little or no effect of the particular object presented. The motion we involuntarily experience when a picture of an object is presented first in one place and then in another, whether the picture is of a leaf or of a cat, is neither a fluttering drift nor a pounce; it is, in both cases, the same simplest, rigid displacement. True, we may *imagine* a leaf fluttering down or a cat pouncing, but in doing so we voluntarily undertake a more complex simulation (just as we might in imagining a leaf pouncing or a cat fluttering down). Such mental simulations may be guided by internalizations of more specific principles of physical dynamics and even perhaps of animal behavior.

Pervasive Constraints of Time and Distance

I have taken the sources of the perceptual constraints considered so far to be corresponding constraints in the world, for example, the 24-hour diurnal cycle and principles of kinematic geometry and perhaps of physical dynamics. However, there are other highly orderly perceptual regularities that may not be reflections of constraints that happened to prevail in our world so much as manifestations of constraints that are unavoidable in any system that could exist in this world. Thus, much as the velocity of light limits the speed of communication between distant bodies, the necessarily finite velocity of signal

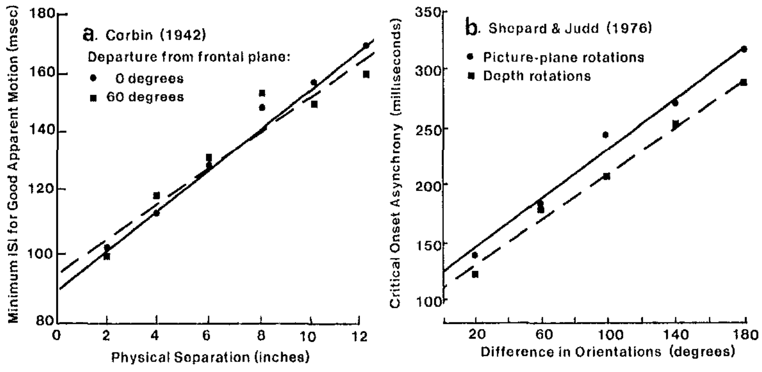

Figure 5. Minimum stimulus-onset asynchronies (critical SOAs) for good apparent motion as a function of extent of transformation in three-dimensional space, as obtained by Corbin (1942) for translational motion (Part a) and by Shepard and Judd (1976) for rotation (Part b). (Note, in both cases, the linearity of the data and the similarity in slope between the data for transformations parallel to the frontal plane and for transformations in depth. Part a is from *Mental Images and Their Transformations* by R. N. Shepard and L. A. Cooper, 1982, p. 306. Copyright 1982 by The Massachusettes Institute of Technology. Adapted by permission. Part b is from "Perceptual Illusion of Rotation of Three-Dimensional Objects" by R. N. Shepard and S. A. Judd, 1976, *Science, 191,* p. 953. Copyright 1976 by the American Association for the Advancement of Science. Adapted by permission.

propagation within a body must limit its processing of information (perhaps with consequences analogous to those of special relativity—cf. Caelli, Hoffman, & Lindman, 1978). Therefore, the possibility of a simple rigid transformation between two alternately presented views is not alone sufficient for the brain to instantiate that transformation as a rigid apparent motion. The extent of the transformation must not be too great in relation to the time available for its neural impletion. Similarly, in connection with the experiment by Foster (1975), the distance to the center of rotation and/or the angle of that rotation must not be too large (cf. Farrell, 1983; Mori, 1982).

In line with these expectations, the minimum SOA that yields apparent motion over a particular path generally increases linearly with the length of that transformational path. In the case of simple translational apparent motion, such a relation was enunciated as the third law of apparent motion by Korte (1915). However, a linear relation of this kind holds for other types of transformations as well, including rotations (Shepard & Judd, 1976), expansions or contractions, and combinations of these with rotations and translations (Bundesen, Larsen, & Farrell, 1983; Farrell, 1983; Farrell et al. 1982). We have also found such a relation for apparent motion over curved paths externally defined by flashing, very briefly and at low contrast, a particular path during the interstimulus interval (Shepard & Zare, 1983).

These critical times have confirmed that what is being represented (in the absence of real motion) is a transformation of the distal object in three-dimensional space and not a transformation of its projection on the retina (Attneave & Block, 1973; Corbin, 1942; Ogasawara, 1936; Shepard & Judd, 1976). Figure 5, Parts a and b, shows the closeness of the agreement between the critical times for apparent motion in the picture plane and in depth for translational apparent motion (Corbin, 1942) and for rotational apparent motion (Shepard & Judd, 1976).

The phenomena of apparent motion arise in the auditory and in the tactual modalities as well (see, e.g., Kirman, 1983). Moreover, the linear dependence of critical time on transformational distance has been found even when the transformation is not literally spatial. For example, there is a similar increase in critical SOA with increasing separation in pitch between two alternately presented tones (see Jones, 1976; McAdams & Bregman, 1979; Shepard, 1981b, 1982a; van Noorden, 1975).

Phenomenally Distinct Modes of Apparent Motion

Some pairs of stimuli can be transformed into each other by different transformations of approximately equal extent. For example, if the two alternately presented orientations of an asymmetric object differ by 180°, the rotational apparent motion can be experienced in either direction through equal angles (Farrell & Shepard, 1981; Robins & Shepard, 1977; Shepard & Judd, 1976). An analogous ambiguity occurs in auditory pitch. I have argued (Shepard, 1982a) that Chasles's theorem similarly constrains the motions of rigid auditory objects (e.g., melodies and chords) in pitch space. Because pitch possesses circular components, one can synthesize tones that differ only in their orientations around a chroma circle (Shepard, 1964). As a consequence, when two tones that are diametrically opposite on this circle are sounded in alternation, they are heard as moving (through a tritone interval of pitch) in either of two ways (up-down-up-down- . . . or down-up-down-up- . . .) corresponding to opposite directions of movement around the chroma circle (see Shepard, 1983, and hear the accompanying Sound Demonstration 4).

In both visual and auditory cases, the apparent motion experienced can depend on the rate of switching between stimuli (Farrell & Shepard, 1981; Shepard, 1981b; Shepard & Zare, 1983). For example, we have replicated Brown and Voth's (1937) finding that when dots are cyclically flashed at the four corners of a square, the apparent motion follows the straight paths between successive corners for slow rates of switching but becomes a continuous circular motion at higher rates. Here too, under conducive conditions, a fixed point is evidently extracted, permitting the representation of a single transformation (a continuous rigid rotation about that fixed point) in place of four successive transformations (e.g., linear translations repeating through the cycle: move right, down, left, up, . . .). The conducive conditions in this case presumably require that the time within which three successive dots appear (the minimum number necessary to define the center of the circle) fall within the relevant perceptual integration time.[5]

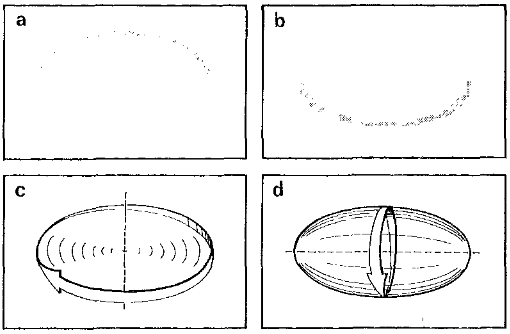

Figure 6. Alternately presented halves of a low-contrast homogeneous elliptical path (Panels a and b), and examples of particular modes of the two principal types of apparent motion experienced: a circular rim spinning about a vertical axis (Panel c) and a "jump rope" whirling about a horizontal axis (Panel d).

Even in the simplest case of the *path-guided* apparent motion studied by Shepard and Zare (1983)—namely, that in which the faint path that is briefly flashed between the two alternately presented dots is the shortest, straight path—the usual report of a reciprocating or back-and-forth motion of a dot is often replaced, at higher rates of alternation, by reports of a rapidly spinning disk viewed edge on or, occasionally, of a horizontal rod rapidly spinning about its own axis. Following up these observations, Susan Zare and I have been systematically investigating a display in which the upper and lower halves of a low-contrast elliptical path are briefly displayed in alternation (Figure 6, Panels a and b). This display gives rise to a variety of alternative percepts.

At high rates of alternation (between SOAs of 50 and 100 ms), observers most often experience a circular rim spinning in a plane tipped back in depth (Figure 6, Panel c), and do so in one of four modes corresponding to whether the plane is experienced as viewed from above or below and whether the spinning motion in that plane is experienced as clock-

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[5] Similarly, I suggest that a seemingly related phenomenon of apparent motion reported by Ramachandran and Anstis (1982), though interpreted by them in terms of a dynamical principle of *visual momentum,* could just as well be interpreted, in terms of the more abstract principles of kinematic geometry advanced here, as the extraction of a globally simpler, overall rectilinear motion.

wise or counterclockwise. These are variants of path-guided apparent motion (Shepard & Zare, 1983) in that the motion is experienced along the presented curve. At slower rates (beyond SOAs of 100 ms), observers more often experience a "jump rope" whirling around a horizontal axis (Figure 6, Panel d) and do so in one of several modes corresponding to whether the rope goes down in front and up in back, whirls in the opposite direction, or oscillates up and down. These are variants of standard apparent motion in that it is the presented stimulus that is experienced as moving—along a path that is not itself presented. Other percepts may also arise; at relatively fast rates, these include what are described as *jaws* or a *clam shell* vibrating between open and partially closed and, at slower rates, something whirling around the perimeter of a disk that is at the same time wobbling up and down. Occasionally, a second-harmonic variation of the jump rope is described, in which one side of the rope appears to go up while the other goes down and then vice versa (yielding a horizontally oriented figure-eight pattern of oscillation). These various preferred modes of experienced impletion may reflect what are, in each case, the simplest motions in three-dimensional Euclidean space for which the distances of motion are compatible with the time allowed for the internal impletion of such a motion (the SOA).

A Competence–Performance Distinction for Perception

The pairs illustrated in Figure 2 generally induce an experience of a transformation in three-dimensional space because only in this way can the size and shape of the object uniformly be represented as invariant. Likewise, the transformations experienced for the pairs shown in Figure 2, Part f, and in Figure 3 consist of a rotation about a point in the plane exterior to the object, rather than about a point that is interior to the object but that also undergoes a translation, because only in this way is the transformation represented as pivoting around an invariant point. This much is harmonious with Gibson's emphasis on invariance. However, unlike Gibson, I have sought quantitative determinations of exactly when the ability of the perceptual system to capture an invariant breaks down, as an experimentally controlled display departs more and more from conditions that are conducive for the capture of that invariance.

Gibson did not concern himself with failures to achieve (or to extract) invariance because he confined himself to the most conducive conditions. Instead of investigating apparent motion, he studied real motion. At the other extreme, many vision researchers, who often presented only extremely impoverished and nonconducive stimuli, have tended to undervalue the capacity of the perceptual system to represent invariances of a high order. I suggested (see Shepard, 1982a) that the two approaches might be reconciled by applying to the study of perception, the competence–performance distinction that Chomsky (1965) proposed for the study of language. Information-processing limitations that prevent people from producing or comprehending certain very long sentences do not preclude that people normally produce and comprehend shorter sentences by means of internalized rules of syntax. Similarly, information-processing limitations that prevent people from computing the rigid transformation between two very widely separated views of an object do not preclude that they normally compute such a transformation between less widely separated view by means of internalized principles of kinematic geometry.

Some Relations to Past and Future Studies of the Representation of Motion

There has of course been a considerable history of investigations into the role of rigidity in the perception of motion (e.g., Ames, 1951; Braunstein, 1976; Dunker, 1929/1937; E. Gibson et al., 1978; Johansson, 1950, 1973, 1975; Metzger, 1953; Proffitt & Cutting, 1979; Restle, 1979; Spelke, 1982; Wallach, 1965; Wallach & O'Connell, 1953) and of apparent motion (e.g., Foster, 1972; Hochberg & Brooks, 1974; Kolers, 1972; Kolers & Pomerantz, 1971; Mori, 1982; Navon, 1976; Orlansky, 1940; Squires, 1959; Warren, 1977). The results are generally consonant with the notion that the perceptual system tends to represent a motion as rigid under conducive conditions. However, in the absence of a unified framework for specifying which particular rigid motion is chosen and for characterizing the conducive conditions, specific conclusions have varied from one study of apparent motion to another.

With regard to the selection of a particular motion, I proposed that out of the infinite set of possible rigid motions, an observer tends to experience the simplest helical motion (including its limiting circular or rectilinear motions) prescribed for three-dimensional Euclidean space by kinematic geometry and, specifically, by Chasles's theorem. In case there are alternative motions of this type that are equal or nearly equal in extent (such as 180° rotations in opposite directions), I claim that observers experience only one of these motions on any one trial but that they can be predisposed towards a particular one of these motions by presenting, for example, a corresponding real motion just before the trial. By implication, I also claim that motions that are not of this simplest helical type, whether rigid or nonrigid, will not be experienced unless they are forced on the observer by external conditions. Thus, one can devise a sequence of stationary views that will induce the appearance of, say, a cat pouncing, (rather than rigidly translating), but only if one presents (a) beginning and ending views that are different, (b) other intermediate views (as in stroboscopically or cinematically displayed animation), or (c) the blurred path of motion (as described by Shepard & Zare, 1983).

With regard to the conducive conditions for impletion of a particular apparent motion, I have proposed two primary requirements: (a) The ISI between sequentially presented views must fall within the appropriate period of temporal integration. (b) Corresponding parts of successive views must fall within the appropriate range of spatial integration relative to the SOA available for making the connections, and relative to the prevalence of similar but noncorresponding parts. Only then can the observer identify corresponding parts of the two views and complete the global transformation that rigidly carries those in one view into the corresponding ones in the other view (Attneave, 1974; Farrell & Shepard, 1981; Shepard, 1981b; Ullman, 1979). More specifically, as a generalization of Korte's third law, I have claimed that in the absence of strongly competing alternative transformations, the critical SOA (i.e., the minimum time between stimulus onsets needed to complete this rigid transformation) increases linearly with the extent of the transformation, whether that transformation is rectilinear (Corbin, 1942; Korte, 1915), circular (Shepard & Judd, 1976; Shepard & Zare, 1983), or helical (Shepard, 1981b).

Putting the considerations concerning preference for the simplest transformation that preserves rigid structure together with those concerning the conducive conditions for impletion of such a transformation, I have posited a hierarchy of structural invariance (Shepard, 1981b). At the top of the hierarchy are those transformations that preserve rigid structure but that require greater time for their impletion. As the perceptual system is given less time (by decreasing the SOA), the system will continue to identify the two views and hence to maintain object conservation, but only by accepting weaker criteria for object identity. Shorter paths that short-circuit the helical trajectory will then be traversed, giving rise to increasing degrees of experienced nonrigidity (Farrell & Shepard, 1981). Likewise, if the two alternately presented views are incompatible with a rigid transformation in three-dimensional space, the two views will still be interpreted as a persisting object, but again a nonrigid one.

These considerations provide a basis for reconciling many of the apparent inconsistencies in the literature on rigid apparent motion. Often, experiments that (a) fail to obtain rigid motion between two views of the same object or (b) fail to obtain the simplest motion prescribed by Chasles's theorem have not ensured that the SOA was sufficiently long (when the transformations were large) and/or that the observers were sufficiently primed for that particular motion (when the competing alternatives were strong).

The theory outlined leads to a number of expectations that remain to be empirically tested. The simplest helical motion that displaces an asymmetric object from one position to another is generally unique, except for cases in which there are equivalent alternative paths (e.g., 180° rotations in opposite directions). However, there are always other helical motions that yield the same result, but by means of a larger number of rotations. Moreover, in the case of symmetrical objects there are still more possibilities. Thus, a horizontal rectangle alternately displayed on the left and right could be seen as translating back and forth, rotating through 180° in the picture plane (either above or below), rotating 180° in depth (either in front or in back), and so on.

All such transformations correspond to *geodesic* or locally shortest paths in the curved manifold of distinguishably different positions of the object, that is, to the analogues of straight lines in Euclidean space, great circles on the surface of a sphere, or helices on the surface of a torus (Shepard, 1978a, 1981b). Accordingly, I predict that when alternative geodesic paths are not too widely different in length, observers can be induced (e.g., by a preceding display) to experience transformations over different ones of these alternative paths, with critical SOAs proportional to the length of each path. I further predict that motions cannot be induced in this way along arbitrary paths that are not geodesic, and that the semantic interpretation of the object will in any case have little or no influence on the path of motion or its critical SOA.

Determinants of Internal Representations

The fact that the same alternating visual or auditory display can lead to distinctly different apparent motions reinforces the point, often made on the basis of other ambiguous stimuli (such as the Necker Cube), that perception cannot adequately be described simply as an individual act of picking up an invariant that is present in that particular stimulus. What is perceived is determined as well by much more general and abstract invariants that have instead been picked up genetically over an enormous history of evolutionary internalization. Although some constraints (e.g., of the sorts considered by Chomsky, 1965; Freyd, 1983b; or Keil, 1981) may not have an external origin, I find such an alternative to be less appealing because it would seem to imply that those constraints are arbitrary (cf. Shepard, 1981b, 1982b).[6] Accordingly, I propose a tentative classification of the determinants of internal representations into immediate external determinants and three subclasses of internalizations of originally external determinants.

Immediate External Determinants

Here I include all (variant and invariant) information that is available in the optic array and in the corresponding arrays of the other senses of hearing, touch, and so on, within what I have been calling the relevant "period of temporal integration."

Internal Determinants

I classify any determinants that do not fall under immediate external determinants as internal because they are, by this rule of classification, not externally acting on the organism within the given period of temporal integration. However, these determinants are mostly *internalizations* of current or previously prevailing external circumstances—although of increasingly remote origin as specified:

1. Determinants temporarily established by the current context. Here I include both (a) transitory bodily or emotional states (which are, in turn, largely determined by preceding external circumstances, such as presence or absence of food or traumatic events) and (b) mental sets or attentional biases (which are largely established by the external context, including such things as preceding stimuli and instructions given in a psychological experiment). For example, we can predispose an observer toward either of two alternative apparent motions by presenting the corresponding real motion just before (see Shepard, 1981b; Shepard & Cooper, 1982). Analo-

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[6] I conjecture that the elaborate, special apparatus of syntax has evolved in humans primarily for one purpose: to furnish automatic rules for mapping between complex, multidimensional structures in the representational system and one-dimensional strings of discrete communicative gestures (vocal or manual). I have also argued, however, that these rules, which could not have sprung full fledged from nowhere, may have been built upon already highly evolved rules of spatial representation and transformation (Shepard, 1975, 1981b, 1982b). If so, syntactic rules may be to some extent traceable, after all, to abstract properties of the external world.

gously, a sequence of two tones on opposite sides of the computer-generated chroma circle will be heard as jumping up or jumping down in pitch when immediately preceded by an unambiguously rising or falling sequence, respectively (Shepard, 1983, Sound Demonstration 4).

2. Determinants acquired through past experience by each individual. These are the more enduring but modifiable constraints that have been internalized through learning or *perceptual differentiation* (E. Gibson, 1969; J. Gibson & E. Gibson, 1955). For example, perceptual discrimination is better (a) in the case of adults, between upright than between inverted faces (e.g., Carey, 1981; Hochberg & Galper, 1967; Yin, 1969), and (b) in the case of chess masters, between board positions that might occur in an actual game of chess than between ones arranged at random (e.g., Chase & Simon, 1973; de Groot, 1965).

3. Determinants incorporated into the genetic code during the evolution of the species. These place constraints on each individual that are predetermined at the time of birth. Because the internalization of these constraints has taken place over by far the longest span of time, they presumably tend to reflect the most enduring and ubiquitous invariances in the world. I have conjectured (Shepard, 1981b) that they include those that enable us to perceive a rigid rotation (or, generally, helical motion) on the basis of a two-dimensional projection of a moving three-dimensional structure (Wallach & O'Connell, 1953; also see Braunstein, 1976; Green, 1961; Noll, 1965), and to do so from early infancy (E. Gibson et al., 1978; Spelke, 1982), but leave us unable to perceive rigid motion on the basis of a similar projection of a moving four-dimensional structure (whether that projection is two-dimensional, as in a computer-generated film produced by Bert Green, or three-dimensional, as in a stereoscopic display later devised by Mike Noll).

After some delay, of course, a stimulus that was an immediate external determinant must become a preceding context and hence an internal determinant; that is, beyond a certain temporal integration time, what was a percept must shade off into a memory. Likewise, there may be a continuum between a short-term memory (as in Determinant 1) and a long-term memory (as in Determinant 2). Moreover, some long-term determinants, although learned (as in Determinant 2), may be acquirable only during a critical period of early development of the individual (Hess, 1959; Lorenz, 1935) and may thereafter remain as unalterable as one that is genetically encoded (as in Determinant 3). Possibly, humans acquire absolute pitch only in this way (Jeffress, 1962). In any case, I assume that determinants of each of the types that I have listed constrain the determinants of all previously listed types. Thus, genetic endowment constrains what can be learned, hence what can be attended to, and thence what will be perceived. If so, the actual extraction of invariants from the externally available information classified under immediate external determinants is made possible by our biologically internalized constraints. Certainly neither an empty black box nor a randomly wired system can be expected to carry out such extractions.

The adaptive significances of all four of the listed types of determinants seem clear. An organism must be perceptually responsive (as under immediate external determinants) to the immediate, locally unfolding events, which (even in a deterministic world) could never be fully deduced or anticipated (see Ford, 1983). In addition, the organism can profit by more or less temporarily and flexibly internalizing (through contextual guidance or through learning) those predictabilities that are likely to prevail in the immediate situation or throughout the current epoch or locale. Finally, there would be an advantage in having the most permanent and certain constraints in its world prewired (as in Determinant 3); then each separate animal need not run the risks of having to learn those constraints de novo through its own trial and possibly fatal error. Such prewired constraints would constitute internalizations of external constraints in the very real sense that a being that had evolved in a very different world would have correspondingly different internalized constraints.

Internal Representation as a Resonance Phenomenon

The closest Gibson came to speaking of internal mechanisms subserving perception was when he likened perception to the physical phenomenon of *resonance* (Gibson, 1966). Despite the reservations that Gibson (p. 271) himself expressed, I believe that the metaphor of resonance, also proposed for cognition by Dunker (1945), alone enables me to make the main points I wish to make about internal representations and their constraints.

Instead of saying that an organism picks up the invariant affordances that are wholly present in the sensory arrays, I propose that as a result of biological evolution and individual learning, the organism is, at any given moment, tuned to resonate to the incoming patterns that correspond to the invariants that are significant for it (Shepard, 1981b). Up to this point I have not departed significantly from what Gibson himself might have said. Moreover, with the notion of selective tuning I can encompass the notion of *affordance* and thus explain how different organisms, with their different needs, pick up different invariances in the world.

However, as I pursue the resonance metaphor further, implications come to light that are at variance with the prevailing ecological approach. Indeed it may have been this potential discord that deterred Gibson from use of the resonance metaphor in his last book (J. Gibson, 1979). However, these further implications seem to be just what is needed to accommodate remembering, imagining, planning, and thinking.

Properties of a Resonant System

The first implication of the metaphor is that a tuned resonator embodies constraints. Resonators respond differently to the same stimuli, depending on their tuning. The second implication is that a resonant system can be excited in different ways. Most efficiently, of course, it is excited by the pattern of energy to which it is tuned. (Indeed, it continues to ring for a while following the cessation of that stimulus, manifesting a kind of short-term memory.) However, it is also excited, though to a lesser degree, by a signal that is slightly different, weaker, or incomplete. Finally, it can also be caused to ring quite autonomously by administering an unstructured impulse from within. An undamped piano string tuned to middle C (262 Hz) resonates most fully to a continuing acoustic signal of that particular frequency. But it also resonates to some extent to a related acoustic signal that is very brief, is of a slightly different frequency, or stands in some harmonic relation to that frequency. Finally, it similarly responds simply to a single blow of the padded hammer inside the piano. The third implication is that a resonant system may have many different modes of excitation. Thus, different disturbances that induce sympathetic vibrations in that same middle-C string may excite the fundamental and its various harmonics to different relative degrees.

Perhaps the perceptual system has evolved resonant modes that mirror the significant objects and their transformations. When stimulated by a strong natural signal, as under favorable conditions of motion and illumination, the system's resonant coupling with the world would be tight enough to give rise to what Gibson called *direct perception.* However, the coupling is tight only because an appropriate match has evolved between the externally available information and the internalized constraints—just as animals behaviorally resonate to illumination briefly introduced at 24-hour intervals only because they have already internalized the 24-hour period of the earth's rotation.

Even when there is generally an appropriate match, the information available in particular situations may be impoverished, as in a nocturnal, brief, obstructed, schematic, or pictorial view. Necessarily, the system is then less tightly coupled to that information. The resulting resonant response may nevertheless be quite complete, as in the many phenomena of perceptual filling in, subjective contours, amodal completion, and path impletion (in the various phenomena of apparent motion), but it may also be much less stable and, as in the perception of ambiguous stimuli, may exhibit different modes of resonance on different occasions. Finally, in the complete absence of external information, the system can be excited entirely from within. Something internal may "strike the mind," giving rise to the various "ringings" that we call mental images, hallucinations, and dreams.[7]

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[7] The first occasion on which I myself advanced the idea that imagery and dreams correspond to the sponta-

Of course, the piano is an inadequate model in several respects. The tendency for one perceptual interpretation to dominate its alternatives at any one time implies a mechanism of mutual inhibition that the piano lacks. Also, unlike the different modes of resonance of a piano string, the different modes of resonance in the perceptual system are not related by anything so rigid as inherent frequency ratios. Through evolution, learning, and contextually induced states of attention, the resonances of the perceptual system have been shaped instead to *mesh* with the external world (Shepard, 1981b).

Hierarchical Organization of the Resonant Modes

Even within a piano, a complex acoustic event may simultaneously excite many different modes of resonance; that is, sympathetic vibrations arise to different degrees at certain harmonics in particular (undamped) strings. Similarly, the perceiving of a complex object or event, such as a rotating cube or a laughing face, presumably corresponds to the excitation of many different resonant modes of the perceptual system. Moreover, these modes vary from those that resonate to very specific, sensory features such as the particular length, direction, and motion of an edge of the cube or the particular size, color, and texture of the iris of an eye, to those that resonate to more abstract, conceptual categories such as the presence of rotation (regardless of the object rotating) or of a face (regardless of age, sex, color, hairstyle, expression, orientation, or distance). There is therefore reason to suppose that perceptual processes are in this sense hierarchical, following neurophysiologists (e.g., Gross, Rocha-Miranda, & Bender, 1972; Hubel & Wiesel, 1965; Konorski, 1967; Lettvin, Maturana, McCulloch, & Pitts, 1959), computer scientists (e.g., Marr, 1982; Selfridge, 1959), experimental psychologists (e.g., Bruner, 1957; Neisser, 1967, p. 254; Posner, 1969; Shepard, 1975), and philosophers (e.g., Price, 1946; James, 1890/1950, p. 49; cf. also Kant, 1781/1961, pp. 104–106, on schemata).

An important qualification, however, is that one mode is not assigned to a higher level than are other modes in the hierarchy because its excitation is preceded or caused by excitation of those other modes. Rather, it is assigned to the higher level solely because it resonates to a wider natural class of external objects or events. Thus the mode that represents *face* is considered a high-level mode because it resonates to any face (but to nothing else), and does so regardless of the identity, expression, orientation, or illumination of that face, whereas a low-level mode resonates to detailed local features of lightness, color, texture, orientation, and so on, which are possessed by only a few faces in a few poses, and perhaps by some stimuli that are not faces at all.

As is indicated by phenomena of perceptual completion, excitation of a mode tends to induce sympathetic activity in other modes. When these other modes are "above" or "below" the initially excited mode, we have what information-processing theorists refer to as *bottom-up* and *top-down* processes. However, in accordance with Gibson's radical insight, a high-level mode may resonate to an abstract external invariant directly; its excitation need not depend on excitation of modes that are lower in the hierarchy and that correspond to more elementary features of the external object or event (cf. Runeson, 1977; and the further discussion in Pomerantz & Kubovy, 1981). Neisser (1976, pp. 112–113) characterized the essential relation between different levels of such a hierarchy as one of *nesting* or *embedding* rather than one of causation.[8]

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neous internal excitation of a perceptual system that has evolved to resonate with natural processes in the external world was a meeting of a student-run Monday Evening Discussion Group at Yale while I was a graduate student there in the early 1950s. The idea has, if nothing else, the virtue of not requiring the assumption that during dreaming, some other part of the brain must, in the manner of a movie projector, play upon the cortex with specifically programmed patterns of excitation—as seemed to be implied by the otherwise admirable neurophysiological account of dreaming offered by Dement (1965).

[8] More accurate than my implied one-dimensional hierarchical scheme, ranging from abstract and conceptual to concrete and sensory, would be a two-dimensional triangular scheme in which the three corners represent (a) abstract concepts (e.g., face, smile, triangle, or rotation), (b) concrete percepts (e.g., John's smiling face or a blue

Externally and Internally Instigated Representational Processes

In Figure 7, I use a vertical rectangle to represent the hierarchy of resonant modes, ranging between those that are most abstract and conceptual, at the top, and those that are most concrete and sensory, at the bottom. Each triangle represents a currently excited mode of the system. I assume that the system preserves no record of the sources of excitation of any mode, which could be primarily from within the system (whether from above or below) or from without. To show how the same system may be differently excited in experiencing sensations and in perceiving, dreaming, hallucinating, imagining, or thinking, I have nevertheless distinguished the active modes in Figure 7 according to whether the primary sources of their excitation were external (triangles pointing up) or internal (triangles pointing down).

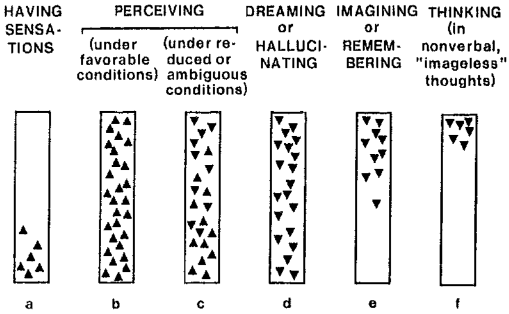

Figure 7. Schematic portrayal of the subsets of excited modes in the perceptual/representational system when it is activated to different extents from without (triangles pointing up) and from within (triangles point down) in sensation, perception, and various types of imagery and thought. (The triangles in the lower and upper extremes of each rectangle correspond to relatively more concrete, sensory modes of resonance and to relatively more abstract, conceptual modes of resonance, respectively.)

Because unstructured stimuli (including direct mechanical, electrical, or chemical irritations of sensory pathways or their cortical projection areas) are not matched to higher level resonances, they produce only the meaningless "lights, colors, forms, buzzes, hums, hisses, and tingles" (see Penfield, 1958, pp. 11–13) that correspond to low-level resonances of the system (as illustrated in Figure 7, Rectangle a). In contrast, perception of meaningful external objects and events arises when resonant activity is induced at all levels of the system (as in Figure 7, Rectangle b).

Even when there is no external input, resonant modes may still become spontaneously excited. Subjective reports, supported by some neurophysiological evidence (e.g., Dement, 1965; Penfield, 1958; West, 1962), suggest that when the system becomes functionally decoupled from sensory input during REM sleep or perhaps in hypnagogic, hypnopompic, or hallucinatory states, even the lowest level resonances may become entrained by higher level activity (as depicted in Figure 7, Rectangle d), giving rise to a full-blown, if illusory, perceptual experience (Shepard, 1978b, 1978c).

Subjective reports concerning waking imagination and memory imagery, as well as objective performance in experiments requiring such imagery, indicate that while these images represent external objects and events (Shepard, 1978c) and obey constraints on their transformations (Shepard & Cooper, 1982), they are fairly abstract or schematic. As shown in Figure 7, Rectangle e, they do not fully engage the lowest, most concrete, and richest sensory levels of the system (cf. also, Finke, 1980; Finke & Shepard, in press). In the extreme case of excitation confined to the highest, conceptual modes (illustrated in Figure 7, Rectangle f), there may be what is called *thinking* or *imageless thought* (Külpe, 1920; Woodworth, 1915).[9]

In *The Interpretation of Dreams,* Freud (1900/1931) similarly contrasted the internal processes of perception, waking memory and

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equilateral triangle rotating clockwise), and (c) sensations (e.g., flashes, colors, buzzes, or tingles). For simplicity of exposition here (and in Figure 7), I have in effect collapsed such a triangle into a one-dimensional (rectangular) scheme by compressing the "percept" corner toward the opposite side, halfway between concepts and sensations.

[9] That thinking is restricted to only the highest portion of the representational hierarchy is an indication not of the unimportance of thought but of the power and generality that it gains through abstraction. I have largely neglected here the special syntactic constraints that underlie verbal productions (whether vocalized or merely thought) and that contribute vastly to the powers of abstract thought. (See, however, Footnote 2 concerning the possible spatial origin of these constraints.)

thought, and dreaming and hallucination. According to Freud, in dreams and hallucinations the normal direction of flow from the perceptual system through memorial and ideational systems (and ultimately to motor actions) is reversed: There is "a retrogression in the psychic apparatus from some complex act of ideation to the raw material of the memory-traces which underlie it" (p. 398) until we have, in the end, "thoughts transformed into images" (p. 400). But in "intentional recollection and other component processes of our normal thinking . . . during the waking state this turning backwards does not reach beyond memory-images; it is incapable of producing the hallucinatory revival of perceptual images" (Freud, 1931, p. 398).

Perceiving under reduced or ambiguous conditions (as at night, in the psychological laboratory, or in looking at pictures) is intermediate between normal perceiving and pure imagining. Although many of the modes are directly excited by the externally available information, other modes, perhaps especially at higher levels, are sympathetically excited by purely internal activities corresponding to set, expectation, and bodily state. The final result tends to be the overall pattern of mutually resonant activity that is most internally consistent throughout all levels of the system.

Thus, although J. Gibson (1970) held that perceiving is an entirely different kind of activity from thinking, imagining, dreaming, or hallucinating, I like to caricature perception as *externally guided hallucination,* and dreaming and hallucination as *internally simulated perception.* Imagery and some forms of thinking could also be described as internally simulated perceptions, but at more abstract levels of simulation.

Resonance as a Spontaneous Emergent in Neural Networks

In proposing resonance as a metaphor, I have intentionally remained noncommittal concerning neural mechanisms. In particular, I am not claiming that resonant activity in the brain is necessarily a periodic oscillation like the vibration of a string, although there is evidence that some responses of the perceptual system do have this character (e.g., Bialek, 1983; Freeman, 1975). Certainly, the most concrete interpretation of the metaphor, in terms of conservation and dissipation of energy, would be inappropriate. Independently of sensory input, the brain's metabolism contributes energy to the process of perceptual interpretation and, hence, provides for a kind of amplification not found in a passive resonator. The resonance I speak of is therefore not strictly a resonance to energy; as J. Gibson (1966) implied, it is a resonance to information. Subject to this proviso, however, resonance may arise in the brain in a more literal sense than I have so far claimed.

Such a notion of neural resonance has a variety of precursors going back over 30 years to related ideas of cortical standing waves or *interference patterns* (e.g., Lashley, 1942), *reverberatory circuits* (e.g., Ashby, 1954; Rashevsky, 1948), and especially, reverberatory *cell assemblies* and *phase sequences* (Hebb, 1949). Moreover, the concept of resonance itself has come into recent prominence in connection with biology and communication (Thom, 1972/1975, pp. 134, 145), brain science (Changeux, 1983), and sensory psychophysiology (Ratliff, 1983). In the latter connection, vision researchers have of course long referred to the *tuning curves* of individual receptor mechanisms. Indeed, in receiving the 1983 Pisart Vision Award, Floyd Ratliff went as far as to say that "the neural networks in our visual systems are not only *figuratively* tuned, they are *literally* harmonic systems" (Ratliff, 1983, p. 10).[10]

Moreover, mathematical analyses have indicated that resonance is to be expected as a natural emergent in neural networks. Drawing on the theory of linear systems, Greene (1962a, 1962b) showed that if information is represented by graded signals (e.g., by dendritic potentials and by rates of axonal firing),

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[10] In connection with the possible harmonic nature of the visual system, I find it amusing that many vision researchers, who (unlike Ratliff) insist on an exclusively nonmetaphorical approach to their subject, nevertheless use the term *octave* to refer to a two-to-one ratio of spatial frequencies. Perhaps they have not noticed that the term does not derive from a physical relation between frequencies but from the fact that the seven-tone diatonic musical scale (which is determined more by cognitive than by physical constraints; see Balzano, 1980; Shepard, 1982a) returns to the tonic with the eighth step.

then even networks composed only of linear elements will possess characteristic resonances, unless "special apparatus is installed to suppress the transients and resonant modes" (Greene, 1962a, p. 257). He concluded that "evolution either suppressed this feature or exploited it. Since its properties resemble those of animal behavior, the latter might be suspected" (Greene, 1962b, p. 395).

Some of the properties that Greene (1962b) derived for nonhomogeneous neural networks are (a) that "resonant modes . . . selected (through natural selection) as the bearers of meaningful information . . . will tend to be stabilized against random disturbances" (p. 409) and (b) that "extremely complex configurations may be represented by a small number of simple intensities," enabling the organism to "switch from one highly integrated behavior pattern to another, without seeming to be required to make adjustments in the multitude of parameters that would be necessary to specify all the individual parts of the patterns" (p. 407). Essentially the same properties have more recently been deduced for hierarchical, nonlinear neural networks by Grossberg (1980), who similarly concluded that "adaptive resonances are the functional units of cognitive-coding" (p. 29).

Greene (1962b), Grossberg (1980), and Anderson, Silverstein, Ritz, and Jones (1977) cited *categorical perception* and the perceptual reversals experienced while viewing ambiguous stimuli as examples of the global switches from one meaningful organization to another that are expected to arise in a resonant network. Of complex resonant systems in general, René Thom said "Usually the system must choose from several possible resonances, and this *competition of resonances* has never been studied mathematically, even though it seems to be of the greatest importance" (Thom, 1972/1975, p. 134). Nevertheless, Greene (1962a), within the context of the particular linear systems investigated by him, derived the reorganizations that occur with increasing speed in the gait of a quadruped as but another manifestation of discontinuous shifts between resonant modes. Shifts of this last type seem suggestively like the discontinuous changes in perceptual organization (e.g., from whirling jump rope to spinning disk) that Zare and I found to occur as the alternation between the apparent motion displays of Figure 6 (Panels a and b) is gradually accelerated.

Apparently then, resonant modes might naturally arise in neural circuits and might contribute to coherence both among internal processes and between those processes and significant environmental constraints. The notion of resonance that I have been advocating differs from the earlier proposals concerning cortical waves and reverberatory circuits in focusing less on the form of the neural activity itself and more on the functional mesh (Shepard, 1981b) that must hold between that activity and the external objects and events that it represents. Admittedly, we have yet to determine exactly how kinematic geometry is embodied in the resonant modes. Nevertheless, if the characteristics of these modes are determined by the connectivity and synaptic transmission coefficients of the neural circuit, there is no obvious reason why evolutionary selection and individual learning could not shape a circuit with the requisite properties.[11]

The most radical departure from the mechanisms usually proposed for perceptual processing is motivated, here, by the desire to encompass dreaming, imagining, and thinking. Even the undamped strings of a piano, in the absence of an acoustic stimulus, begin to vibrate only when struck by their corresponding padded hammers—events that depend on the intervention of an agency external to the piano itself. Has the homunculus of the picture-in-the-head metaphor of perception and imagery (although differently guised as performer rather than perceiver) reared again its ugly head? Not necessarily. The strings of an aeolian harp, for example, are excited not by intentional hammer blows but by random gusts of wind. Yet the ensuing activity is harmonious—provided, of course, that the strings have already been properly tuned.

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[11] See, for example, Changeux (1983). Note that the isomorphism required between the external constraints and their internal representation need be no more than an abstract or second-order type (see Shepard, 1975) and that related, spatially distributed parallel processes (such as *relaxation* methods) for satisfying constraints have already been shown to be effective for scene analysis in computer vision (e.g., see Rosenfeld, 1982; Waltz, 1975).

Similarly, the natural modes of resonance of a neural network, if they are already tuned to naturally occurring external objects and events, tend to ring and hence to represent such objects and events when, in the REM state, under the influence of fever or drugs, or, to some extent, during mere idle meditation, the network is played on by random internal "gusts" of neural or chemical excitation. Of course, to the extent that either abstractly formulated goals or pressing bodily states become ascendent, they tend to entrain the entire ongoing activity into a more directed course.

In his acceptance address, Ratliff (1983) noted that a resonance theory of thinking can in fact be traced back at least to Coleridge, who, in his 1795 poem "The Eolian Harp," after writing (lines 13–17)

"that simplest Lute,
Placed length-ways in the clasping casement,
hark!
How by the desultory breeze carress'd . . .
It pours forth such sweet upbraiding,"

went on to ask

"And what if all of animated nature
Be but organic Harps diversely fram'd,
That tremble into thought?"

(lines 44–46; see Richards, 1950, pp. 65–67).

Implications Concerning Robustness of Brain Function

I have suggested that what is being represented within the system corresponds to which modes are ringing—without regard to which of the complete, incomplete, and generally redundant sources of influence caused each mode to ring. This proposal is, in this one respect, analogous to Müller's (1842) principle of *specific nerve energies,* which asserted that the consequences of the firing of a neuron depend only on the identity of that neuron and not on the events (whether optical, chemical, mechanical, or neural) that precipitated its firing.

A familiar perceptual phenomenon is illustrative: There are many redundant sources of information as to the (relative) distances of an object in depth, for example, binocular disparity, oculomotor convergence, aerial perspective, retinal size, textural gradients, linear size, height relative to the horizon, interposition, motion parallax, and so on. However, only some of these sources may be available in any given situation. Although we experience an object at a definite distance, we have no awareness of how much each of the sources contributed to this experience. Looking at a landscape painting, we may obtain a sense of three dimensions as a result of the artist's rendering of aerial perspective, linear perspective, gradients of size, and so on, but this impression of depth is considerably muted by counteracting information from binocular disparity, which tells us that we are looking at a flat surface. I have found that if I look at the same painting with one eye, from a distance that precludes resolution of the microstructure of the painted surface, and through a reduction tube (formed, e.g., by rolling up a sheet of paper) so as to hide the surrounding frame, I can obtain an experience that seems as vividly three dimensional as if I were looking with both eyes at the corresponding real scene. Although a single source of information may not support as accurate a judgment of depth as would multiple sources, as long as that single source is in no way contradicted by any other source, it may still yield a compelling experience of depth.

In general, an assemblage of partially redundant resonant subsystems, loosely coupled to each other and capable of autonomous excitation, will be robust against structural damage. Each subsystem will resonate in much the same way whether it is excited by all or by only a few of the redundant inputs from other subsystems to which it is coupled. All that is required is that the residual inputs exhibit a sufficient part of the characteristic pattern to which the given subsystem is tuned. In this way we can understand why persons who have undergone a transection of the million fibers of the corpus callosum connecting the two cerebral hemispheres are indistinguishable from intact individuals, except under testing conditions that have been carefully contrived to prevent contralateral transmission of information through other (for example, auditory, kinesthetic, or somatic) channels (Gazzaniga, 1970; Sperry, 1968). Like the perceiver of objects at different depths, each part of the brain resonates to the same world, not knowing which or how many specific channels of input have been left to cause it thus to ring. To venture a revision of Leibniz (and to risk a further mixing of his metaphors!), the mind is no more a "windowless monad" with a "preestablished harmony" (Leibniz, 1714/1898) than it is an unharmonized monad with a picture window. More nearly is it a community of pretuned monads that come into harmonious action, with each other and with the world outside, through many glasses darkly.

Implications Concerning Creative Thought

To the extent that the natural modes of resonance of the representational system embody the constraints governing transformations in the world, we have a unified basis for treating both how we perceive external objects and events and how—in the absence of such objects and events—we remember or think about them. Such a possibility was already envisioned by Heinrich Hertz, who began his 1894 treatise, *The Principles of Mechanics*, as follows:

> The most direct, and in a sense the most important, problem which our conscious knowledge of nature should enable us to solve is the anticipation of future events, so that we may arrange our present affairs in accordance with such anticipations. . . . In endeavouring thus to draw inferences as to the future . . . We form for ourselves images or symbols of external objects; and the form which we give them is such that the necessary consequents of the images in thought are always the images of the necessary consequents in nature of the things pictured. In order that this requirement may be satisfied, there must be a certain conformity between nature and our thought. (Hertz, 1894/1956, p. 1)

In studies that my associates and I carried out on mental transformations (see Cooper & Shepard, 1978; Shepard & Cooper, 1982), we found that the principles that constrain involuntarily experienced real and apparent transformations guide voluntarily imagined transformations as well. The trajectories of imagined translations, rotations, dilations, and combinations of these appear to be exactly the spontaneously occurring trajectories of corresponding rigid apparent motions (Shepard, 1978a). Moreover, the times needed to complete such imagined transformations increase linearly with the extent of those transformations in three-dimensional space just as in the case of apparent motions. Note the similarity between the results of our first study of mental rotation (Shepard & Metzler, 1971), reproduced in Figure 8, and the corresponding results for rotational apparent motion, shown in Figure 5, and between the parallel results obtained for other types of

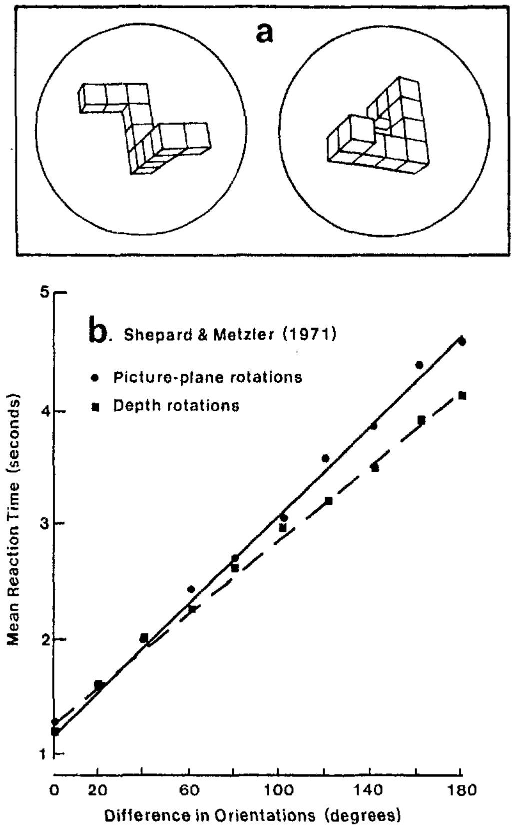

Figure 8. One of Shepard and Metzler's pairs of perspective views of a three-dimensional object (Part a), and the times that people took to imagine such an object rotated from one portrayed orientation into the other to verify that the objects were in fact identical rather than enantiomorphic (mirror reversed) in intrinsic shape (Part b). (The data are plotted as a function of angular difference in portrayed orientations, for differences corresponding simply to a rigid rotation in the picture plane or, as illustrated in Part a, to a rotation in depth. Note the similarity in pattern to the data displayed in Figure 5 for apparent motion of these same objects. From "Mental Rotation of Three-Dimensional Objects" by R. N. Shepard and J. Metzler, 1971, *Science, 171,* p. 702. Copyright 1971 by the American Association for the Advancement of Science. Adapted by permission.)

mental transformations and their corresponding apparent motions, reported by Bundesen, Larsen, and Farrell (1981, 1983).

As I have documented elsewhere (Shepard, 1978b, 1978c), a number of creative thinkers who have most transformed our understanding and control of the world about us have reported that they arrived at their revolutionary ideas through "visualizing . . . effects, consequences, and possibilities" by means of "more or less clear images which can be 'voluntarily' reproduced and combined"—to put together two quotations from Einstein (in Holton, 1972, p. 110, and Hadamard, 1945, p. 142, respectively). Could it not be that the constraints on visualizing that have guided such insights, and whose sources must lie in the world, are like those that we have been investigating in the laboratory?

Epilogue: Two Approaches Reconciled?

For those students of the ecological approach who still reject any talk of internal representation, I cannot refrain from quoting Gibson himself:

> The theory of perceptual systems emphasizes the external loops that permit orientation, exploration and adjustment but it also admits the existence of internal loops, more or less contained within the central nervous system. Only *in this way could the facts of dreaming be explained.* In the waking state, the internal loops are driven or modulated by the external ones but in sleep they may become active spontaneously, the internal component of a perceptual system running free as it were, like a motor without a load. In the case of daydreams and waking fantasies, one can suppose that internal experiencing of a similar sort occurs in parallel with ordinary perceiving, the former being split off from the latter, and the latter being reduced.
>
> There is no doubt but what the brain alone can generate experience of a sort. (J. Gibson, 1970, p. 426)

And, with regard to perceptual ambiguity:

> The fact of two alternative percepts from the same drawing is very puzzling. The light to the eye has not changed when a pair of faces is seen instead of a goblet but the percept has.
>
> If such drawings are analyzed as sources of information instead of mere stimulation, however, the puzzle becomes intelligible. The information in the array is equivocal. There are two incompatible kinds of pictorial information in the light to the eye and the percept changes when the beholder shifts from one kind to the other. (J. Gibson, 1971, p. 33)

Finding that I myself resonate to what Gibson is saying in these excerpts, I have to ask: In what respect, finally, do I go beyond Gibson? Gibson emphasized the strong constraint that external reality places on perceiving when that reality is an integral part of the organism–environment "loop." It was, I suppose, his sense of the objective, shared, and binding character of this direct, external constraint that Gibson (1970) insisted that (a) "the act of perceiving is essentially different from the act of imagining" (p. 427), (b) "what the brain alone . . . *cannot* do is to generate *perceptual* experience," and (c) "the dreamer is *trying to look,* as it were. But since there is no feedback . . . the dream wanders on uncontrolled" (p. 426).

I, on the other hand, have been impressed by how extensively internal loops have incorporated external constraints. When Gibson said that in dreaming and imagining, the perceptual system runs "free . . . like a motor without a load" and that the dream "wanders on uncontrolled," he expressed insufficient appreciation of the fact that a dream, however bizarre or regressive in thematic content, is not a random eruption of meaningless lights, colors, hums, hisses, and tingles but a deceptively realistic simulation of meaningful objects and events unfolding in space.

It was apparently through such dream simulations that Jack Nicklaus changed his golf grip and subsequently improved his waking golf game by 10 points; Taffy Pergament, the 1963 national novice figure-skating title winner, originated her new jump, the "Taffy;" a gynecologist discovered how to tie a surgical knot deep in the pelvis with one hand; Elias Howe had the crucial insight necessary for his perfection of the sewing machine; Louis Agassiz found a way to extract a fossil, undamaged, from a slab of stone; James Watt came up with a simpler method of manufacturing lead shot; H. V. Hilprecht realized how to fit certain archaeological fragments together, enabling him subsequently to decipher their cuneiform inscriptions; Friedrich Kekulé solved the outstanding problem of the molecular structure of benzene; Otto Loewi devised the experiment that led to his 1936 Nobel Prize for the discovery of the chemical basis of neural transmission; and (in the related hypnopompic state) I myself conceived of the experimental study of mental rotation. (See Shepard, 1978b; Shepard & Cooper, 1982, chap. 1 & 2, for fuller documentation and sources.) And every waking day, by thought alone, physicists, stereochemists, mechanical engineers, inventors, architects, carpenters, interior decorators, and just plain folks successfully anticipate the consequences of carrying out complex physical manipulations and rearrangements of objects in the three-dimensional world.

"An observer can orient his head and eyes to some component of an optic array. . . . But [not] to an afterimage or a memory image" (J. Gibson, 1970, p. 426). Yet in a dream, one can orient one's (dream) head and eyes to one's (dream) environment or even, in a hallucination, orient one's (real) head and eyes to a hallucinated object in one's (real) environment, and, in both cases, one experiences the appropriate perceptual consequences. See particularly the description of just such a hallucinatory experience by the 19th-century astronomer and chemist Sir John Herschel (1867; quoted in Shepard & Cooper, 1982, p. 5). Apparently, internal loops can mimic the feedback furnished by external loops. Foreshadowing the commutative diagram that I much later proposed (Shepard, 1981b, p. 294), Heinrich Hertz succinctly stated that "the consequents of the images must be the images of the consequents" (Hertz, 1894/1956, p. 2).

Gibson is correct in insisting that an observer cannot literally "*scan,* or *inspect* or *examine* a subjective image" (J. Gibson, 1970, p. 426; also see J. Gibson, 1979, pp. 256ff.). Nevertheless, following Kubovy's (1983) proposed rewording, we are able to *imagine* scanning a spatially extended object, map, or scene, or to *imagine* approaching it for closer (mental) examination of its parts (as has been extensively demonstrated by Kosslyn, 1980). We are also able to *imagine* inspecting a three-dimensional object in different orientations, as was noted long ago by Helmholtz (1894; as translated in Warren & Warren, 1968, pp. 252–254, and quoted in Shepard & Cooper, 1982, p. 1) and as is now chronometrically investigated in the psychological laboratory (Shepard & Cooper, 1982; Shepard & Metzler, 1971). Moreover, the experimental results for such mental scanning, approaching, and manipulating of imagined objects are all quite parallel to those for the corresponding scanning, approaching, and manipulating of real objects (Finke & Shepard, in press; Kosslyn, 1980; Shepard & Cooper, 1982).

Our ability to take account of events with which we are not in physical interaction provides the strongest motivation for a concept of internal representation. Two kinds of such events are those that have happened already and those that have happened not yet. In seeking to eliminate the need for the concept of internal representation, Gibson therefore had to depart most radically from prevailing psychological theories in his treatment of temporal notions, particularly, the notion of the present. He came to the conclusions that "resonance to information has nothing to do with the present" (J. Gibson, 1966, p. 276) and that "what we see *now* refers to the *self,* not the environment" (J. Gibson, 1979, p. 254). Gibson held that the enduring invariants in an individual's environment are available to be picked up (over time) by the exploring individual. Thus, as we move about an object, we pick up its layout as seen from many points of view or, equivalently, from no particular point of view (J. Gibson, 1974; also see J. Gibson, 1966, pp. 275 ff.). Such considerations led Gibson to a novel characterization of visualization: "We see formless and timeless invariants when we perform visual thinking" (J. Gibson, 1974, p. 42).

Although I share with Gibson the idea that visualization reflects invariants in the world, I believe that the invariants that are most deeply internalized are those that constrain the possible transformations of all possible objects relative to the observer and not those that characterize a particular object or layout. As theoretical justification, I have argued that the objects that have been important to us over evolutionary history have been informationally complex (requiring vast numbers of degrees of freedom for their characterization) and, furthermore, have changed over the eons. In contrast, the rigid displacements of those objects have been constrained for all time to the same six degrees of freedom (Shepard, 1981b, p. 327). As empirical justification, I have cited the results of the experiments that my associates and I have reported on mental rotation, which clearly indicate that an object, despite having been repeatedly seen in many orientations or from many points of view, is still visualized or imagined in only one of these ways at a time (Cooper, 1975, 1976; Shepard & Metzler, 1971; see especially Metzler & Shepard, 1974, p. 196). If an individual could directly visualize the inherent structure of an object without regard to point of view, then that observer could immediately "see" whether two objects were of the same shape regardless of their respective orientations. Such seeing is not immediate, however; the time to determine such sameness increases markedly with differences in presented orientation (Figure 8).

Although our visualizations of objects and their transformations may be schematic, they are nevertheless concrete in the sense that the objects are represented in a particular orientation and their transformations are represented over a particular path (Shepard & Cooper, 1982). What is internalized at the deepest and most abstract level is not any particular object or transformation (which are arbitrary with respect to orientation and path) but the set of constraints that in three-dimensional Euclidean space govern the possible projections and transformations of an object (Shepard, 1981b). Although we do more fully pick up the structure of an object when we are able to view it in different orientations, we still only visualize that structure fully from one viewpoint at a time; to visualize it in a different orientation requires additional time that increases with the difference in orientation. Moreover, different views can effectively be related to each other only if they fall within an appropriate integration time. An individual can pick up the layout of an environment and then visualize that environment as it would successively appear from the station points that are traversed as the individual walks about blindfolded. But, at any one moment, the representation is always from a particular station point and, in the absence of a further look, decays in about 8 s (Thomson, 1983).

Gibson's focus on the external loop led him to suggest that performance in a tachistoscopic experiment (in which brief exposure is used "to prevent the occurrence of exploratory eye movement" and, hence, to block "completion of . . . [the] external loop") is "a mere laboratory curiosity, unrepresentative of day-to-day activity" (J. Gibson, 1970, pp. 426–427). However, the most direct way to find out whether internal mechanisms, or internal loops, have incorporated external constraints is to block the external loop. Thus, by establishing an ecologically invalid environment in which the diurnal cycle of light and darkness was eliminated, animal behaviorists discovered that animals have internalized the invariant period of the earth's rotation. And by presenting ecologically invalid displays in which the physical motion between two positions of an object is deleted, we are beginning to discover that humans have internalized the invariant principles of kinematic geometry.

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