Information from the World around Us

James E. Cutting

> *A note on the word 'information': In the cognitive sciences use of the word seems . . . equivocating. . . [I]t moves between information-theory references of high-technical color . . . and quite vernacular senses not far from gained or given 'knowledge,' of the world or whatever it may be.*
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> —Baxandall (1995, p. 164)

We perceive *objects* and *events.* Objects are the furniture and clutter in the world around us. They include both artifacts, such as books, chairs, and roads; and natural kinds, such as rocks, trees, and lakes. They can even be nested, including natural objects in artifacts, such as trees in pictures. Events are things that happen over time and, as relevant to perception, they involve either the motion of, or change in, objects over time, or they result from our own movement with respect to objects. On what basis do we perceive objects and events? In psychology, cognitive science, and related fields, the answer in the late 20th century is: We perceive objects and events on the basis of *information.*

It has become difficult to imagine a science of perception or cognition without the concept of information. Information pervades our theories to such a degree that one should wonder how we could do without it. Indeed, the etymology of the term is sufficiently felicitous that no one in our time should pass easily over it: To inform someone means to take a *form* (perhaps of an object) and instill it with*in* something or someone (perhaps even the mind of a perceiver).[1] From such a definition it is a short step to the notion that we perceive the objects and events around us on the basis of information, and that we can act upon and generally know about our world because of information as well. In large part, perception can be said to be the process of *in-forming* the mind.

Nevertheless, our idea of information often baffles scholars in other fields.

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[1] The *Oxford English Dictionary* gives "shape" as the major meaning of the Latinate root *form,* and the first meaning of the prefix *in-* (*in*—pref^2) as "in, within, internal."

Perception and Cognition at Century's End

Indeed, it sometimes appears to them—and sometimes to us—as an unexamined buzzword used perhaps, as Baxandall suggested, in an attempt to bridge the scientific and the everyday. Moreover, we may often forget that information played no role in the theories of James (1890), Titchener (1906), Bartlett (1932), Koffka (1935), Woodworth (1938), Gibson (1950), or any other psychological theorist before the second half of this century. The reason, of course, is straightforward: Information theory was developed in the field of engineering by Shannon and Weaver (1949), and it was their work that gave the term its scientific meaning.

Briefly, within an information-theoretic framework, information is a numerical measurement of the a priori likelihood of an event or occurrence. In particular, it is a transformation (the base-two logarithm) of the number of items in the set to which a particular item of interest belongs assuming equal likelihood of their occurrence. This type of information is measured in *bits,* or the number of binary choices statistically necessary to determine exactly the item under consideration. The usual situation considered is one of transmission; thus, it can to be said that information was *transmitted* in bits. As an example, consider drawing a playing card from a standard deck. If someone draws a single card and announces that it is a spade, that statement implies a set size of four possibilities, and has excluded three of them. It has transmitted the $\log_2(4)$, or 2 bits of information. If one learns instead that it is a jack, one is dealing with a set size of thirteen, and has excluded twelve. Thus, the $\log_2(13)$, of 3.7 bits of information have been transmitted. In this manner, being told the card is a jack provides more information than being told it is a spade.[2] Notice that traditionally one speaks only about the amount of information; in this view information by itself has neither content nor meaning (but see MacKay, 1969).

At midcentury, information theory had rapid impact on our discipline. It was quickly applied to language, memory, perception, and action (Attneave, 1954; Broadbent, 1958; Cherry, 1957; Garner, 1962; Miller, 1951; Quastler, 1955). But, too useful to be confined to a particular calculation, the meanings for the term speciated. For example, frustrated with its lack of attention to meaning, Gibson (1966) discussed the bases of perception in terms of "information about," specifically eschewing information theory. More importantly, however, the information-processing approach to cognitive psychology was born (e.g., Haber, 1969; Lindsay & Norman, 1972; Neisser, 1967), where the time course of the perception of something (typically briefly presented letters or text) was analyzed and plotted, but sel-

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[2] Despite the powerful applications of information theory to electronics and computer technology, there are problems in its application to psychology. One concerns a priori knowledge; one may not know about cards or games. Garner (1962) solved this through the notion of uncertainty, information should be measured against a knowledge base. Thus, if one knows it is a jack and is told it is a jack, there is no information transmission. With respect to perception, major problems include the fact that the objects of the world do not often come in set sizes of known number (a dog comes from a set of how many animals), and that they often belong to multiple sets (a dog is both an animal and a pet, and there are more kinds of the former than the latter); and that the source of information may be lying (the card is really a deuce, not a jack). See Cutting (1986) for further discussion.

dom was the information itself measured in any particular way. The proliferation of meanings for the term information has continued and at the end of the 20th century our current notions of it often have little to do with the original ideas of Shannon and Weaver (see also Cutting, 1987, for a review).

I take the flowering of the term information as evidence, not necessarily of loose thinking among psychologists, but of scientific necessity. That is, the implications of the term information have been so important that it was appropriated by our discipline in new ways as an attempt to solve the critical problems in perception and cognition. Why is the term information so indispensable? What are its historical antecedents? Where exactly is it located? These are the questions this chapter will attempt to address.

At base, I claim we use the term information to solve a certain aspect of a central problem in the history of philosophy—the mind–body problem. More precisely, we wish to account for transformation from the physical stuff of the world into neural, and particularly mental, stuff within the perceiver and knower. Quite literally, we assume that information is the medium that allows an object or event to be registered by the senses and, as a product of exploration and attention, registered in the mind of the perceiver.

I will also claim that, historically, psychology in general, and visual perception in particular, has broached three frameworks in which this transformation is accomplished—through appeals to personal experience with the world, to mathematical constraints that may structure the world, and to biological expediency as creatures evolved in the world. There is no inherent reason why an assembly of all three should not serve perceivers (as well as researchers), but they begin with different assumptions and are thus partly incompatible. I will present them exclusively, and as they were broached. My approach will also condense several otherwise historically separable lines of thought, and this process will necessarily make some strange bedfellows along the way. Nonetheless, I think its result can best represent the kinds of thought the psychology of this century has had about the concept of information. As would be expected, part of it also bears relatively close relation to the exposition by Proffitt and Kaiser (chap. 7, this volume) on internalization of external constraints; Information is external to the perceiver and brings evidence of the outside world into the mind of the perceiver.

I. FRAMEWORK 1: EXPERIENCE IN AN UNRULY WORLD

> We see, and cannot help seeing, what we have learnt to infer. (J. S. Mill, 1889, p. 226)

North American psychology inherited much from the British philosophical tradition of empiricism from the 17th through the 19th centuries. More particularly, from John Mill (1829), John Stuart Mill (1848), and their antecedents (see, for example, Pastore, 1971), we received the idea that the laws of association, based on the law of contiguity, govern all of what we now call perception and cognition. That is, as individuals we are exposed to many co-occurrences of objects and events around us; from this exposure we covertly built up a large store of them; and we use the covariance matrix to guide our percepts, thoughts, and actions. Thus, the information in this context can be generally associated with the idea of "knowledge" as Baxandall (1995) noted above; the physical aspects of the objects and events themselves are typically only vague, referential ghosts.

This experiential build-up process is thought to be generally reflexive and unconscious; and, as implied by the quote of J. S. Mill above, it leads to percepts that we would now call automatic (Shiffrin & Schneider, 1977) and cognitively impenetrable (Pylyshyn, 1989). In this view, habits tie the world together and information lies in mere and shear frequency; it is tallied, as in Morton's (1969) logogen model of word recognition, with each occurrence and co-occurrence of things we perceive.

Throughout the historical period including Hume and Berkeley, the Mills and Russell, and then in this century Brunswik, the psychology of mind developed the idea that through the associations collected over the long haul of personal experience we build up the skill to interpret the world around us. In this view, for example, each of us generally sees and understands the world in the same way because we share an overwhelming number of similar experiences with it; someone raised in a completely different environment would likely perceive our world in quite a different way (Helmholtz, 1878/1971). The central problem that associationism tried to face and solve, at least with respect to perception, was the initially near-hopeless, "blooming, buzzing confusion" (James, 1890, Vol. 1, p. 488) of the world around us. How are we to make sense of the world? The associationistic answer came through the power of experience and memory within the organism. The frequency information presented by the world itself was a tangle of probability and, thus, was incompletely untrustworthy.

A. From Local Signs to Cues

From a German tradition, and particularly from Lotze (e.g., Boring, 1942; Pastore, 1971), we inherited the idea of local signs, small bits of clusters or arrangements of experienced pattern that lie in what we now call the visual array and help knit it together so we can infer what is to be seen. This idea is rather far from our idea of information but it is antecedent to another, more closely related term—*cue.* Faithful to its 16th-century etymology representing marginal notes in theater documentation (*q,* for *quando,* Latin meaning "when"), a cue was a prompt for action provided to a knowledgeable actor.[3] That is, a cue could be effective only if one already knew the play to be acted. Both James (1890) and Titchener (1906) used the term cue in this way, as a prompt for action. Later, Woodworth (1938) and oth-

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[3] *The Shorter Oxford English Dictionary* gives this as the etymology of the word "cue;" the *Oxford English Dictionary* gives it as well, but suggests further that it is unproved.

ers changed its meaning and applied it to perception. Thus, cue was now a prompt for how to perceive. Cues were applied most particularly to the perception of depth and what we now might call layout. Indeed, lists of "cues to depth" can be found in most contemporary textbooks in perception and in introductory psychology, and they are a legacy of associationism from the early part of this century.

Meanwhile, outside of many important aspects of this tradition, Koffka (1935) provided a new perceptual framework—that of proximal and distal stimuli—which entered into common discourse. This distinction helped psychologists locate the place of these cues (see also Hochberg, chap. 1, this volume). With respect to visual perception it could then be said that we perceive distal objects and events (those that generally lay beyond arm's reach) on the basis of proximal cues, aspects of those objects and events that we would now say are projected to the eye of the observer. Thus, cues would now begin to have a status different from the objects and events to which they were related, yet also exist in the world, external to the observer.

Finally, with Brunswik (1956), cues came to have their most articulated definition. A cue was a visual pattern or set of visual relations about which we have accumulated much experience. When dealing with a set of objects, that personal history suggests to each of us that each proximal depth cue is associated with a particular distal arrangement of objects. Moreover, that association occurs with some probability, called *cue validity,* which perceivers have registered over their lifetime. In this view, for mathematical reasons if not experiential ones, that probability is always greater than zero and always less than unity; cue validity, then, dictates the surety with which, for example, the layout of the objects in depth can be discerned. The work of Massaro (1987) is the clearest contemporary extension of this idea, and the central aspects of his program have been couched in terms of Bayes theorem (Massaro & Freedman, 1990).

B. An Assessment and a Metatheory

The two great strengths of an experiential approach are that it is open (a) to all cognitive and perceptual experience, and (b) through all sensory modalities. Moreover, applications in music (Krumhansl, 1990), auditory perception (Saffran, Aslin, & Newport, 1996), word perception (Morton, 1969), and letter perception (Estes, 1976) have shown it to have considerable merit. Nevertheless, as with any approach, it has its weaknesses. For example, more narrowly in any Bayesian approach, if an individual is to perceive a particular object or event he or she must have a reasonably good prior assessment of its possible occurrence.[4] More broadly in any experiential approach if the perceiver is to make any sense of the world, he or she must similarly draw on previous experiences.

[4] It is not by accident that a priori knowledge plagues both an information-theoretic approach and a Bayesian approach to perception. Both try to solve the problem of information through probability, and probability cannot be assessed without some fore-knowledge of what will occur and when.

Leaving aside the problems of initial knowledge (Chomsky, 1959) and the contextualization of the covariance matrix of cue validities (Hochberg, 1965), the Bayesian approach in particular, and the associationistic approach in general, also make it difficult to account for learning to perceive new objects. In Piagetian terms (e.g., Piaget, 1978) the theory handles assimilation well—of fitting new exemplars of objects into old categories—but it does not handle accommodation well—the comprehension and establishment of new categories of objects and events based on what we see (see also Medin & Coley, chap 13, this volume). The Bayesian/cue-validity approach also makes for potential evolutionary mischief. To quote the title of Gibson's (1957) critique of Brunswik (1956), one would then seem to face "survival in a world of probable objects." Probabilities too far from unity could lead to death.

It should be little surprise that this general framework, as applied to perception, is most generally associated with the metatheoretical view *indirect perception* (Ayer, 1956; Gibson, 1979), although not all who would espouse this metatheory would also rely so heavily on either associationism or Bayes's theorem. Nevertheless, this framework and this metatheory both rely as little as possible on discussions of stimulus properties. In this view, external information is relatively weak and nonspecific; the mapping of sources of information back to the events and objects that generated them is many-to-many, a tangle of context-dependent relations. Since the sense data from the stimuli in the world are thus viewed as incompletely trustworthy, the approach relies heavily on the computational power of a knowledgeable perceiver. At the end of the 20th century one might also state that proponents of this view emphasize top-down processes.

II. FRAMEWORK 2: MATHEMATICS AND NATURAL LAW IN A WELL-ORDERED WORLD

> [O]rdinary sense perception could . . . not fulfill its task—that of building up an objective world—if it were not able to comprehend the isolated sense data under certain group concepts and . . . the "invariants" in reference to this group. (Cassirer, 1945, p. 288)

The second framework is quite different, and stems from Galileo's *mathesis universalis* (e.g., Pylyshyn, 1972). Galileo, and scores of philosophers and scientists since, believed that the book of nature was written in the language of mathematics. In particular, twentieth-century mathematicians (Kline, 1959, 1980) and physicists (Einstein, 1921; Feynman, 1965; Wigner, 1959) have often expressed awe and pride in the fact that mathematics seems to be such an appropriate tool to measure and describe nature. From accurate measurement and description, it is assumed, comes understanding and theory. Not surprisingly, then, many theorists have attempted to use math to ply their way into understanding human nature and the mind. Results are not always successful (see admonitions by Uttal, 1990), but there are many sustaining ideas in this notion that make it a central pillar among approaches to perception.

The basic assumption of this framework is quite different than that of associationism. The world is not seen to be chaotic; instead the world, and particularly the visual world, is well ordered, and that order is reflected in the mathematics applied to it. The basic task of the researcher is to follow the appropriate natural law (e.g., Kugler & Turvey, 1987) and discover the appropriate mathematics, and then to apply them usefully to perceptual and cognitive issues. The problem for the perceiver is much less difficult; natural law is followed because there is no alternative, and mathematics is used because that is the way perceptual systems work. The natural law and mathematics are deeply ingrained in the nervous system, and their rules constrain and guide perception and cognition. Thus, information from the world presents itself in a language of mathematics, and the perceptual system uses that language to discern properties and identities of the objects and events. Perceivers, then, generally perceive the same sorts of things, not because they share the same history, but because they all follow the same natural laws, expressible in mathematical relations.

A. Geometry

Historically, the first type of mathematics applied to perception was geometry. Literally meaning "earth-measure," geometry is the basis of surveying and has been used for more than two millennia to describe, and impose structure on, the layout of the world around us. Euclid's Elements are more often studied, but his Optics (Burton, 1945) is more pertinent to vision and cognitive science. Having laid out geometry in his Elements, his Optics is a set of theorems and proofs about vision and about how we perceive the layout of the world. Classical optics then developed slowly over many centuries, and scrutiny of original works in translation and of analyses from different disciplines yields the same result: The optics of Alhazen (Lindberg, 1976), Grosseteste (Ronchi, 1957), Descartes (1637/1971), Leonardo (Richter, 1883), and Smith (1738), followed the pattern of Euclid. Thus, despite the claims of Gibson (1966, 1979) and others, this tradition embraces the view that optics is about the visual perception of layout (Ronchi, 1970). To be sure, the geometry of Euclid, and later of projective geometry (e.g., Nicod, 1930), is largely one of transparency where objects do not appear to occlude other objects. Nonetheless, the beginning of a perceptual theory can be found in Euclid.

As an informal proof of the centrality of visual perception to optics consider the following sketch of an analysis. In the Burton (1945) translation of his optics, Euclid presents more than 60 proofs about physical relations and phenomena in the world with respect to vision. His proofs contain 58 diagrams, and in 55 of them one point within the diagram is the eye of the perceiver, and angles are measured with respect to this point. Similarly, Richter's (1883) compilation of Leonardo's notebooks on linear perspective (which includes several of Euclid's proofs) includes 53 drawings, 46 of which include the eye or a point that could represent the eye. So too, most of optics texts from the medieval period to Smith (1738) equate optics and vision, and use diagrams similar to those of Euclid and Leonardo. Only with Newton

(1730/1952; Dover edition) was the centrality of vision to optics offset. In only 9 of his 57 diagrams does the eye appear, and in these often only gratuitously. Thus, Newton removed the eye from optics, and perhaps with it mathematical approaches to vision from the mainstream scientific thought.[5]

B. Projective Geometry

Euclid's Optics (Burton, 1945) is about how geometrical shapes project to the eye of the perceiver. As a mathematical discipline, however, projective geometry did not mature until the 19th century (e.g., Kline, 1959). Nonetheless, aspects of projections dominated practical applications of mathematics in mapmaking (e.g., Snyder, 1993), in Renaissance painting and architecture (see La Gournerie, 1859; Olmer, 1943). The appeal of projective geometry to the study of vision, if not to the other sensory modalities, is straightforward. One of the classic entrées into the study of visual perception is the conundrum of ambiguity in a two-dimensional image (retinal or pictorial) as it represents a particular three-dimensional object. That is, although the projection from the 3D object to the 2D image is well ordered and mathematically certain, the attempt at reverse projection (sometimes called *inverse optics*) from the 2D image back to the 3D object is not. More information or more restrictions are needed. For example, if the object were in motion and one assumes that it is known to be rigid, then multiple images of it or its moving image would dictate the presence of a single, unambiguous object, and inverse optics can be carried out. This fact became the basis of the enterprise called structure-from-motion (e.g., Ullman, 1979).

Fortunately, visual perception appears to follow some aspects of projective geometry. Perhaps the clearest proponent of this view has been Johansson (e.g., Johansson, von Hofsten, & Jansson, 1980) who, with Gibson (1950, p. 153n), proposed that a particular theorem from projective geometry—that of the cross-ratio—would be useful to perceivers. There then accrued evidence for its occasional, but not universal use (Cutting, 1986; Niall, 1992; Niall & Macnamara, 1990; Simpson, 1986). A serious problem with this approach emerged at about the same time as its initial corroborations: The assumption of rigidity is often invalid. Perceivers often see things as nonrigid when they are rigid even when a rigid interpretation is possible (Braunstein & Andersen, 1984; Hochberg, 1987; Norman & Todd, 1993; see also Hochberg, chap. 9, this volume). This renders the perceptual achievement of structure-from-motion much more difficult to understand.

C. Group Theory and Invariance

In a French tradition—from Poincaré (1905) through Casirer (1944, 1945) to Piaget (1970)—a differently styled approach to perception and cognition began, based in

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[5] Newton's text should have been called *Dioptrics,* rather than *Optics,* because it deals largely with lenses.

group theory and the systematization of geometries in Felix Klein's Erlanger Program (e.g., Klein, 1908). In North America psychologists were slow to appreciate the power of this approach, but Gibson (1950, 1960) began it with a discussion of *invariants.* Later, he (Gibson, 1965, 1979; see also Michaels & Carello, 1981; Wagemans, Van Gool, & Lamote, 1996) would embrace invariants as they are revealed through *transformations,* thus opening a door to group theory that he would never step through.

Group theory, invariants, and transformations go together roughly like this: The shape of rigid objects remains invariant (unchanging) under at least six transformations (ways of invoking a change). Three of these transformations are translations of that object in space (in Cartesian coordinates along x,y,z) and the other three are rotations (again in x,y,z). These six transformations and their combinations form a mathematical group (see also Proffitt & Kaiser, chap, 7, this volume). Groups of transformations exist only when the members follow particular set of rules: closure, association, identity, and inversion (e.g., Bell, 1945). Any transformation of an object along one or more of these six dimensions, often called the Galilean group, leaves the object unchanged in shape.

With some elaboration, such as allowing for transformations under changes in illumination, Gibson tried to make this approach into theory of visual perception. From outside his particular perspective, years of study of structure-from-motion began (see Braunstein, 1976, and Ullman, 1983, for reviews). Other psychologists, also outside of Gibson's direct influence, began to consider not the invariants, but the groups of transformations themselves (e.g., Carlton & Shepard, 1990; Garner, 1970; Hoffman, 1966; Leyton, 1992; Palmer, 1991) as keys to understanding perception.

D. An Assessment and a Metatheory

The great strengths of any mathematical approach are its clarity, its precision, and its power through the use of deductive inference. The Piagetian idea of assimilation is little problem since the mathematics of one set of stimuli or one task will be quite different than another; and accommodation would likely to driven by different mathematical solutions in the presence of different stimuli. To be sure, the issue of similarity (e.g., Goodman, 1972; Medin & Coley, chap. 13, this volume) plagues the mathematical approach to the same degree as the associationistic approach.

One of the major drawbacks of most mathematical approaches to perception is that their utility seems almost exclusively confined to vision. Projective geometry has essentially no application elsewhere; geometry, although it might play some role in taste through stereochemistry (Amoore, 1970; but see Schiffman, 1974), seems largely visual; and even group theory, the most abstract of mathematics, has its clearest application in vision (but see Balzano, 1980).[6]

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[6] There are many other approaches to perception which might be called mathematical. Many of these have their bases in statistics (see Cutting, 1987), particularly the statistics of form. These include those by Field (1987), Julesz and Bergen (1983), Lord and Wilson (1984), Pentland (1983), Uttal (1983, 1985), and Zusne (1970). These do not fit neatly into the three approaches discussed here.

Although it does not exhaust the metatheoretical possibilities in a mathematical framework for perception, Gibson's version of a basis for perception came to be known as *direct perception* (Gibson, 1979; Michaels & Carello, 1981). Gibson (1979) rejected the central idea of cues from associationism—that the world presents itself in a confused, disorganized manner. Instead, without direct appeal to group theory, Gibson was convinced that invariants revealed themselves under object motion, observer movements, and change of illumination. A small army of researchers then set out to find invariants and other higher-order relations; many were found, but it now appears that invariants of the kind that Gibson proposed are too few for perception to proceed on their basis alone (see Cutting, 1993). Although the basis of direct perception is debated (Michaels & Beek, 1996; Oudejans, 1991; Pittenger, 1990; Stoffregen, 1990), several agree (Burton & Turvey, 1990; Cutting, 1986, 1991), that the theory generally proceeds on the assumption that there is a one-to-one mapping between a source of information in the world (typically an invariant) and the object associated with it. In the late 20th century one would generally say that almost all such mathematical approaches to perception are based on bottom-up processes.

III. FRAMEWORK 3: BIOLOGY IN AN EXPEDIENT WORLD

> One could argue that . . . the visual system often *cheats,* i.e., uses rules of thumb, short-cuts, and clever sleights-of-hand that were acquired by trial and error through millions of years of natural selection. (Ramachandran, 1985, p. 101)

A third major framework for the notion of information in perception is nascent, and at the end of the 20th century it remains relatively ill formed. The central idea is both a theoretical one and a methodological one: Perception has evolved to solve particular tasks at particular times. To study each task separately is the ideal, and when one does so it is sometimes said—rather oddly—that one has a *computational theory* (after Marr, 1982). More precisely, this means that one has some idea of what is important to the organism, some idea of how which situations and tasks are important to it, and some faith that this task can be meaningfully studied separately from other tasks.

More deeply, the idea is that, over the long haul of evolution, biology has been both adventitious and conservative. To meet the requirements of new species radiating out into different niches, evolution has molded new tissues and functions out of old ones, but also changed them minimally as needed. Thus, just as the bones of the inner ear were molded out of material from the jaw (e.g., Gould, 1983); neurological tissue devoted to one task may have been modified and incorporated into use for another. Such a process would not make a well-designed machine, but it would emphatically make a well-adapted one. Moreover, if perceivers generally perceive the same sorts of things, it is not because of personal history or natural law, but because they share the same biological underpinnings. This approach generally proceeds on two fronts—through appeals to ontegeny, or comparisons across the development of individuals (see Spelke, chap. 11, this volume), and through appeals to phylogeny, or comparisons across species. It is the latter that I will focus on.

A. Tricks and Modules

The most extreme form of this biological approach was given by Ramachandran (1985) as suggested above—that perception proceeds merely from a "bag of tricks." Unfortunately, to promote this idea is to promote only half the story; one must also attempt to understand why the "tricks" are as we find them. The idea fosters first the suggestion of *modules* (Fodor, 1983; Marr, 1982), isolable subsystems within the brain that act more or less independently; and second, a piecemeal modularity of visual systems on a large scale such that every perceptual task may be different, involving different and generally noninteracting neural tissue. An indefinitely large number of relatively isolated visual modules may turn out to be the case, but at present I regard this as unlikely.

A more parsimonious approach is to start globally, and to limit the number of modules to a small number until converging evidence can be found that firmly segregates each, both in terms of perceptual phenomena and neurological locus. One such approach suggests there are at least two visual systems, one for perceptual tasks involved with action, and the other for those involved with cognition and categorization (see Milner & Goodale, 1995).[7] The future truth of the degree of modularity of the visual system seems likely to lie somewhere between two systems proposed by Milner and Goodale (1995), and the very large number as would be suggested by Ramachandran (1985).

If perception and cognition have followed the route of biological expediency, then major claims of the other two frameworks are weakened: Neither the force of personal experience nor the cleanliness of a single type of mathematics seem likely to rule all of perception and cognition. On one hand, the time scale of personal experience will pale in the face of the time scale of evolution and, on the other, mathematics may be too structured and rigorous in the face of a rubric for change no more constraining than utility. At best, then, personal experience and mathematics would have different, more particular, and separable roles to play within each task and within each module. Thus, from the point of view of biological expediency, information could be measured in terms of frequency, of geometric relations, or of any other form that a sensory system could capitalize upon (chemical valences, spectral profiles, temperature, spatiotemporal patterning, and so forth). From my point of view, aspects of projective geometry still seems likely to work best for vision, but again, what these aspects may turn out to be is as yet undetermined.

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[7] The recent history of neuroscience can be painted as one of opposing pairs of proposed systems. For two influential predecessors to Milner and Goodale, see Schneider (1969) and Ungerleider and Mishkin (1982).

In addition, in a biological approach human beings become very much part of the fabric of all life, complex and simple. By extension, one might expect that neither the many-to-many nor the one-to-one relations between information and objects proposed by indirect and direct perception, respectively, would generally hold. On the one hand, the computational power needed to untangle the many-to-many relations between information and objects seems daunting. Species with simpler nervous systems might not be able to survive. Since we evolved from simpler species, many-to-many relations are not likely to have been those with which we started, and thus perhaps they do not hold for us now. On the other hand, the rigid uniformity of one-to-one relations between information and objects would seem to inhibit evolution. Over the course of evolution, newly redesigned sensory systems might find it difficult to exploit the complex of regularities to be found in the world, if there were not different ways to perceive the same objects and events. Moreover, since newly redesigned systems often retain older capabilities, it would then be surprising if different information were not used in different tasks with the same objects and events (see Hochberg, chap. 9, this volume, for further discussion).

B. An Assessment and a Metatheory

The great strength of the biological approach lies in its pragmatics; necessity, contingency, and happenstance—rather than logic or math—drive the evolution of cognitive and perceptual processes. Even associations, which are largely context blind, are less pragmatic; what works in this framework is what rules. Piagetian notions of assimilation and accommodation are accomplished by whatever means necessary, and thus loom less important in this approach. The great weakness of this approach, however, is the inverse of pragmatics. One must worry about Kiplingesque just-so stories as explanations for the states of affairs that one finds in perception and cognition; pure teleology is unhelpful.

Although not exhaustive of the possibilities, one metatheoretical solution to this problem, which I have called *directed perception* (Cutting, 1986, 1991, 1992; see also Cutting & Massironi, chap. 6, this volume), is to suppose that the relationship between information and objects/events is many-to-one. Because each source of information is proposed to map back to a single object/event or its property, each source of information can specify to some degree what is to be perceived; however, because more than a single source of information may be associated with each object/event, species are free to move from reliance on one to a reliance on another; and if many information sources are used different individuals within a species are free to weight their use of various sources to different degrees. Finally, a process could be viewed as both bottom-up and top-down; see Proffitt (1993) for an elaboration of a biological approach to perception that embraces such constraints in both directions.

IV. MULTIPLE SOURCES OF INFORMATION AND THE PROBLEMS THEY PRESENT

> The education of our space-perception consists largely of two processes—reducing the various sense-feelings to a common measure and adding them together into the single all-including space of the real world. (James, 1890, Vol. 2., pp. 268–269)

A. On the Abundance of Information

Regardless of which of these three frameworks one follows, or which of the three metatheories loosely allied to them one espouses, any perceptual theorist must face several issues: First, does he or she acknowledge the existence of multiple sources of information in the world for a given object or event? Those influenced by an experiential framework or by indirect perception on the one hand, and those influenced by a biological framework or by directed perception on the other, will all generally embrace such multiplicity. Although those influenced by group-theoretic frameworks may be relatively neutral to this idea, those influenced by direct perception do not typically embrace the idea of multiple sources of information (but see Michaels & Beek, 1996; Oudejans, 1991).

The latter road, espousing a one-to-one relation between information and the object or event to which it refers, may be a difficult one to follow. Following Gibson (1979) perceptual variables are often parsed in terms of those that are lower order and higher order. On the one hand, lower-order variables are ones typically closer to traditional psychophysics—wavelength, extent, intensity—and acknowledged by all researchers to be manifold. On the other, higher-order variables thought to be used by the perceptual system are certain efficacious combinations of the lower-order variables. The problem is that in the face of potential multiplicity of lower-order information sources, each of which seem correlated with certain perceptions, one must search for a higher-order combination that, by itself, is both sufficient to sustain perception and is not overly correlated with the lower-order variables (Burton & Turvey, 1990; Michaels & de Vries, 1998).[8] Unfortunately, the potential combinatorics of adding, multiplying, or dividing even a modest number of lower-order variables can make the search difficult. Moreover, as noted above when discussing invariants, the search for higher-order variables that are demonstrably used by the perceiver has been slow and laborious. This search has turned up some important examples. However, if Gibson were correct in his insistence the perception used these alone, one might have thought they would have been easier to find (Cutting, 1993).

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[8] There are other distinctions in the ecological community besides higher- and lower-order information. One is the extrinsic–intrinsic distinction proposed by Warren (1984). Extrinsic information is measured in standard physical units (time, mass, extent); intrinsic information converts these measures relevant to the organism. Measures of objects in the world in terms of the eye-height of the observer is one standard for intrinsic measurement.

B. On the Use of Abundant Information

Accepting the potential for the existence of multiple sources of information for any given perceptual situation, the second issue is, How do perceptual systems deal with this multiplicity? Various schemes of integration and selection have been proposed. To be concrete so that these schemes can be easily discussed, consider the situation depicted in the upper part of Figure 1. Imagine that this is not a picture, but a real display seen with one eye.

Here, somewhat ironically since this example is taken from Gibson (1950, 1979), two traditional sources of information are provided for judgments of the relative depth, or the layout with respect to the observer, of the two vertically oriented panels: Relative size and height in the visual field (sometimes called height in the picture plane, or angular elevation). Both sources appear to work in concert to make Panel A appear closer than Panel B. That is, because both panels are depicted to have the same shape one might assume that, in the depicted world, they are objects of the same physical size; that is, since the projection of Panel A is larger than that of Panel B, Panel A must be closer. In addition, because the base of Panel A is lower in the picture than that of Panel B, again it must be the closer.

How might these two sources contribute to the perception of layout? In an

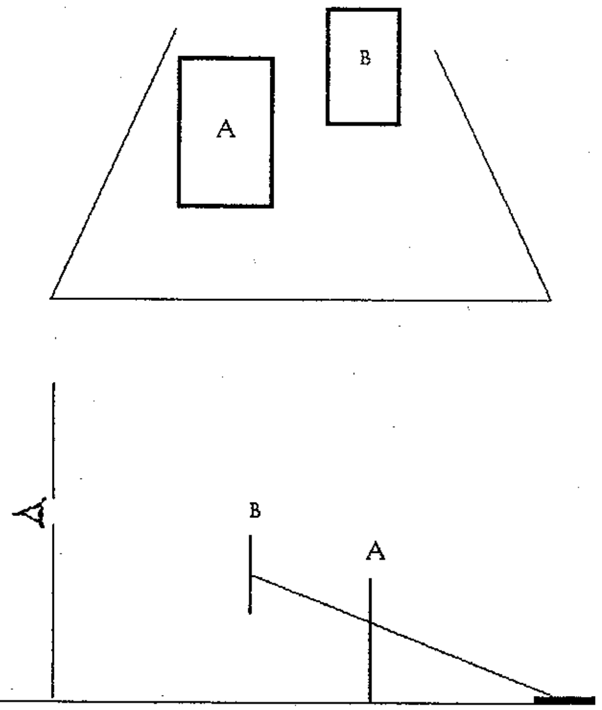

FIGURE 1 A "cue-conflict" situation adapted from Gibson (1950, p. 179; Gibson, 1979, p. 158). In the upper part of the figure, (A) appears to be closer to the reader than (B) because of differences in relative size and height in the visual field. But the lower part of the figure shows that this is not true, as would be revealed with the addition of binocular disparities.

experiment using these two and other sources, both in isolation and in combination, Künnapas (1968) found that judgments of distance were greater and less variable the more sources of information that were present in the stimulus. That is, as it might be in this case, the more sources that are present the greater and more consistent the judged distance between the panels. Both effects are important, the former contributing to the impression of greater perceived extent in the world and the latter contributing to the stability of that percept.

How should we understand these effects? There are several possibilities, and the scheme I will promote here is an elaboration of those of Bülthoff and Mallot (1988) and Massaro (1987). In general two classes of information use exist, which I will call selection and integration (see also Cutting, 1986; Cutting, Bruno, Brady, & Moore, 1992).

C. Styles of Selection

1. Satisficing

The most pragmatic style of selection can be called *satisficing,* a decision-making term from Simon (1955). That is, an observer can simply search for adequate information in the stimulus, stop when it is found, and thus ignore any other source that may be present. Satisficing, from "satisfies," is generally quick and meets the demands of a search task—information is found and acted upon. It contrasts with *optimizing,* which is a slow search process and, in this context, would entail exhaustive search for all sources of information and the subsequent use of all of them. In using a satisficing strategy, one may find different sources of information on different trials but performance is always about the same and adequate to the demands of the task. No particular commitments to the roles of consciousness and attention are made here; consciousness and attention could either be present or absent. In the case shown in the upper part of Figure 1, satisficing would occur if observers sometimes used height in the visual field to judge which panel were further away, sometimes used relative size, but never used both.

Cutting, Flückiger, Baumberger, and Gerndt (1996) presented evidence for a satisficing strategy in a wayfinding task, where observers judged the direction of their heading with respect to their gaze in a situation of simulated pursuit fixation during forward locomotion. Three sources of information were manipulated factorially. These were the displacement direction of the largest object in the field of view, the inward displacement of any object toward the fovea, and the outward deceleration of any object. Performance was the same (about 80%) when one, two, or three sources were present—regardless of which ones they were—and performance was at chance (50%) when no information was present.

2. Suppression

A second selection strategy is similar, but more consistent than satisficing. Given the presence of two sources of information, the observer might consistently select one source and base his or her judgment on that source alone, suppressing the other. Again, no commitment to consciousness or attention is made. In the context of the upper part of Figure 1, a suppressive result would occur if observers always based a relative-distance judgment on relative size when both size and height were present, but they used height when it was present alone.

Evidence for suppressive selection, like satisficing, can occur when the judgment for the two sources combined is no different than for one of them in isolation. It can also occur in other psychophysical situations where the two sources are manipulated orthogonally, and performance is found to vary only with one. For example, Cutting (1986, Experiments 7 & 8) showed that, in a task where observers judged the rigidity of moving objects, subjects used the cross-ratio (an invariant from projective geometry, discussed earlier) when that object rotated, but used a yoked set of flow vectors when it translated. In that latter case, the cross-ratio was present and could have been used during every trial, but observers' results suggested that they suppressed the cross-ratio in favor of the yoked flow vectors.

The stimulus arrangement shown in upper part of Figure 1 two sources of information are present and both yield the same depth order. Within traditional terminology, this might be called a *cue-consistent* display. Other stimulus arrangements might have both, or more, sources present, but with each or a combination yielding different depth orders. Such have been called *cue-conflict* displays (see Woodworth, 1938).

3. Veto

A particularly vigorous example of selection occurs when one source of information simply overrules another in a cue-conflict situation, which Bülthoff and Mallot (1988) called veto. An example of this is suggested in the lower part of Figure 1, also from Gibson (1950, 1979). The juxtaposition of the two sections of the figure suggests that the base of the smaller-appearing, higher panel in fact does not abut the surface of support but, by an unseen system of support, is levitated above it. Most importantly, if a third source of information, binocular disparities, is added by allowing the viewer to see the display with two eyes then the disparity information will veto the effectiveness of height in the visual field and relative size. Why? How?

In one account (Cutting & Vishton, 1995), disparities will reveal that the base of Panel B is not at the same depth as the portion of the surface of support projected just beneath it. Thus, one of the assumptions of height in the visual field—gravity, or that the bases of both objects lay on the surface of support (see Cutting & Vishton, 1995)—is proven incorrect and, thus, the source is invalidated. Disparities will then also be likely to show that Panel B is in fact closer than Panel A, and that an assumption underlying the use of relative size, that the depicted objects are the same physical size, is also invalidated. In this manner, veto is an example of selection working at the level of the assumptions underlying each information source. Other examples have been found in the literature, with binocular disparity information vetoing relative motion (Turner, Braunstein, & Andersen, 1997).

D. Styles of Integration

1. Accumulation

The alternative to selection is integration, where the perceiver uses two or more information sources in concert. The most straightforward type of integration is accumulation, of which there are several types. Here, and most easily, judgments for the two-source stimulus must be greater than those for stimuli with either source alone. Accumulations of information can be additive, as suggested by the quote of James above, or subadditive—although much depends on assumptions about the nature of the underlying scale that observers use (Cutting et al., 1992; Massaro & Cohen, 1993).

If, in the presence of two consistent sources of information, the relative-depth judgment is equal to the sum of the judgments of each source separately, then additivity can be said to occur; if, on the other hand, relative depth judgments are less for the combined-source case, the subadditivity can be said to occur. Cutting et al. (1992) found that in judgments of exocentric depth, relative size and height in the visual field were combined subadditively, but that pairwise combinations of relative size and occlusion, relative size and motion parallax, and occlusion and motion parallax, were all combined additively (see also Wanger, Ferwerda, & Greenberg, 1992). In situations of conflicting ordinal information, evidence of integration—additive or subadditive—would be that the two-source stimulus yields judgments less than the absolute value of the largest of the two one-source stimuli.

2. Cooperation

Another type of integration occurs when the combination of two consistent sources yields a judgment greater than either one-source stimulus alone. This may be called superadditivity or, more likely, cooperation. The latter term is sometimes used much more broadly to indicate many more possible interactions, and even additivity.

Perhaps the best example of cooperation was demonstrated by Tittle, Perotti, and Norman (1997); they found that the combination of stereo and motion information supported depth judgments better than the summation of the separate probabilities from stereo and motion information alone. It is particularly interesting that stereo information seems to veto motion information in source-conflicted situations (Turner, Braunstein, & Andersen, 1997) but cooperate with it in source-consistent situations; the former result supports the idea of the modularity of the two systems, whereas the latter result supports some degree of their integrality.

3. Disambiguation

Finally, a third type of integration occurs with the disambiguation of one source of information by another. The best developed presentation of this idea can be found in the work of Landy, Maloney, Johnston, and Young (1995). These authors claim that the kinetic depth information (Wallach & O'Connell, 1953; see also, Proffitt, Rock, Hecht, & Schubert, 1992) yields information about local ordinal depth but without information about the sign of depth. Thus, one might know that three parts of an object occur at egocentric distances in either the orders A, B, C, or C, B, A; but rejecting other possibilities. The back projection from a relatively distant point-light source of a bent coat hanger on a rotating turntable, for example, will reveal the hanger's 3D structure up to the possibility of reflection (this despite the fact that only one of the possibilities will be a completely rigid interpretation). The addition of stereo information, however, will disambiguate the sign of depth order, and only one of the interpretations will generally be seen.[9] Once the information has been disambiguated, then processes of accumulation or cooperation can come into play.

V. INFORMATION AND WHAT IT REPRESENTS

> [T]urns of the head are also registered by vision. They are specified by what I have called the *sweeping* of the field of view over the ambient array. (Gibson, 1979, p. 118)

As suggested in the introduction, I claim that we use the term information to help solve one aspect of the Cartesian problem of two worlds, the physical and the mental. If the concept of information is to do any theoretical work it must help us bridge this gap: Information presents to the perceiver a "digestible" form of the object or event that it represents. How do we suppose it does this?

From a general associationistic framework and from one of indirect perception, information can only *suggest* what object or event might be present; the observer must do some work (usually "mental" work, often called "computation") to discern what is to be perceived, and even then can never be quite sure. From most mathematical frameworks and from direct perception, information is said to *specify* the object or event that is present. Many biological approaches make no particular commitment here, but directed perception chooses the idea of specification over suggestion. Much mischief can be involved in the idea of specification (see Oudejans, 1991; Massaro & Cohen, 1993; Schwartz, 1996), but in many cases the specification of a percept by information can be written as a deductive syllogism (Cutting, 1991; see also Richards, Rubin, & Hoffman, 1982). That is, given certain assumptions (axioms), a definitive conclusion can be drawn.

Consider again the example shown in the upper part of Figure 1, with two sources of information—height in the visual field and relative size—and consider height first. Given the assumptions outlined by Cutting and Vishton (1995) that (a) the panels and the ground plane are opague; that (b) gravity is present, allowing the bases of the upright panels to lie on the ground (and no "accidental," hidden supports are present); that (c) the observer's eye is above the surface of support; and that

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[9] One can also argue that the kinetic depth effect does not yield information about depth but instead yields information about shape (Cutting & Vishton, 1995; Cutting, 1997).

(d) the panels are not too distant with respect to eye height, it can be deductively concluded that Panel A is in front of Panel B. The amount of distance between the panels is not specified; thus, the deduction is valid only as an ordinal judgment. Nonetheless, under these assumptions, height in the visual field *specifies* ordinal depth, which panel is in front of the other.[10]

Consider next relative size. Assuming that (a) the two panels represent objects of the same physical size, and that (b) they are not too near, one could proceed by noticing that Panel A is about 1.5 times bigger than Panel B. One could then deduce that Panel B is about 1.5 times farther away than Panel A. In this manner, relative size can *specify* (at least within measurement error) the ratio of relative distances of the panels from the observer. Notice first that this is not absolute information—the panels could be 1 and 1.5 m away, or 20 and 30 m away—but the information has the potential of specifying depth relations beyond mere ordinality.

Whether the visual system uses information beyond ordinality is unclear. On the one hand, Landy et al. (1995) have assumed that sources of information using different scales are used by the visual system—ordinal, ratio, absolute, and even the unsigned depth of the kinetic depth effect. On the other hand, Cutting and Vishton (1995; Cutting, 1997) have assumed that all sources degenerate to ordinal scales. The former approach has the advantage of coming closer to a metric representation of space; the latter has the advantage of scale convergence (Birnbaum, 1983)—"reducing the various sense-feelings to a common measure" as suggested above by James (1890, pp. 268–269)—where different information can be more easily integrated. Through multiple constraints within ordinality, one can also begin to build up a near metric representation of depth. Cutting and Vishton (1995) have discussed this in an analogy to nonmetric multidimensional scaling (e.g., Shepard, 1980).

VI. SUMMARY: WORKING AMONG THREE FRAMEWORKS

As suggested in the introduction, there is no particular reason why information could not serve the perceiver from the points of view of all three frameworks. Nonetheless, research cannot easily proceed considering all three simultaneously. One must be wary of simple amalgams of approaches with different underlying assumptions (Henle, 1957); such admixtures tend not to be principled, and thus they lose logical and theoretical force.

Consider some antinomies that inhibit simple concatenation of frameworks. The associationistic approach generally assumes that cues are probabilistically related to the objects they represent (with the probability greater than 0.0 and less than 1.0); aspects of the mathematical and biological approaches generally assume

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[10] It should escape no one that writing the process of perception as a deduction seems quite close to the notion of unconscious inference (e.g., Helmholtz, 1878). There are differences, however, between inductive inference (which is basically guesswork) and deductive inference (which is sure and upon which mathematics is based; see Skyrms, 1975). The issue, then, is where the premises from the inference come from (see Cutting, 1991).

that information specifies what it represents (with the probability 1.0). The associationistic approach is generally unconcerned with assumptions, and can be modeled by inductive inference; mathematical and biological approaches, when pushed, generally lay out assumptions and follow a line of deductive inference from them. Associationistic and mathematical approaches, on the other hand, are rarely modular and rarely interested in neurophysiology; biological approaches are almost always modular and always look to actual or plausible neural structures. And the associationistic and biological approaches have ample room for individual differences; a mathematical approach usually does not. Yet despite these differences, there is much to recommend each approach.

The strength of an associationistic approach is that personal history and all sensory modalities are considered. Such approaches are also quite sympathetic with the recent development of simulated neural networks (e.g., Anderson, 1995), and they play most sympathetically with cognition and perception as they might work together. On the other hand, the general weakness of the approach is that it fails to take seriously the structure of the stimulus. Both mathematical and biological approaches tend to do this.

The strength of any mathematical approach is its deductive rigor, and the ease with which it can apply to vision and a few other domains, such as music. This rigor affords a power of deductive inference generally unavailable in associationistic or biological approaches. Mathematical approaches typically make little commitment to modularity, personal history, or evolutionary history, but their great potential weakness was foreshadowed by Cassirer (1944, p. 11): "The precision of mathematical concepts rests upon their being confined to a definite sphere. They cannot, without logical prejudice, be extended beyond that sphere into other domains." In other words, mathematical approaches are likely to retain their power only in relatively narrow domains.

The strength of a biological approach is in its pragmatics, and its emphases on task specificity, evolutionary continuity, and the radiation of species into new niches requiring new developments in perceptual systems. It makes little commitment to personal history (except as it can emphasize flexibility), and its emphasis on contingency is distinctly noncausal. The weakness of the approach lies in its difficulty in dealing, in an instructive way, with uniquely human faculties—such as language and reading—and in knowing when one has pushed it too far. The biological approach can account for adaptation and findings structures and phenomena as we see them; it also allows for neutral evolution, where genetic drift and truly random factors may be at the root of structures and phenomena.

What is most gratifying about all three approaches to perception, however, is that—at least to some degree or another—they all appear to work. Advances in our understanding can be gained through pursuit of any of the three. Thus, as the sciences of perception and cognition continue to mature into the next century, we are likely to find ourselves fascinated, coerced, and even cajoled by developments made within each.

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Julian Hochberg

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