PERCEPTION AND INFORMATION

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How, then, is it that we receive accurate information, by the eye, of size, and shape, and distance?'

James Mill (1829, p 95)
INTRODUCTION

What is the nature of information, what enables it to inform our perceptual systems? Psychology, particularly in its study of information processing, aspires to an answer, but since perception researchers measure information in different ways, this answer is not definitive. By its focus on processing, psychology has long taken information for granted, usually assuming it to be like text or speech, but if information were actually so constrained, I contend, the bulk of perception would be uninformed. The world rarely presents itself language-like to our senses.

In this review I consider various types of information assumed by perceptual researchers. Assumptions about information constrain our ideas about the relations between perception and cognition. They shape the emerging field of cognitive science. They also form the backdrop to the issue of bottom-up versus top-down processing—the latter a time-worn but far from weary idea, formal syntheses of these two positions are emerging (e.g., McClelland 1985, McClelland & Elman 1986), but here I focus on bottom-up issues.

Historical Roots

Among English writers, Shakespeare may have had priority in linking perception and information in a single statement “It is the bloody business,” says Macbeth, “which informs thus to mine eyes” [Macbeth (II, i)]. But Mill, as quoted above, was among the first philosophers of mind to conjoin the two. Indeed, perception and information are a natural pair. Both of Latin origin, they appeared in English literature in the 14th and 15th centuries. Information, the older term, signified communication of knowledge, a notion with which modern treatments are still in tune (Machlup & Mansfield 1983). Etymologically, to inform means “to instill a form within.” and it is a modest step to consider perception as instilling the forms of external objects in the mind of a perceiver.

“Perception” has a more curious etymology. In feudal economics it meant the collection of rents. Its present meaning retains an aspect of its heritage if we recognize perception as the collection of information about the world. For Locke (1690) and Berkeley (1709) perception was broadly associated with thinking. Reid (1785) distinguished it from sensation, yet, to use Hamilton’s (1859) terminology, how does one separate presentation by the senses from re-presentation by the mind? One approach is to study the mapping entailed between proximal information and distal objects and events.

Mapping, Inference, Structure, and Measurement

Proximal-distal mappings are central to the discussion of perceptual information. Their consideration began in earnest with Koffka (1935), but roots can
be found in the causal theory of perception (e.g. Russell 1927). The typical course of perception for a readied organism proceeds 1 from real-world object or event, 2 through a medium, 3 to sensory surfaces and receptors, and then 4 to the central nervous system. One can study information at stage 2. If the mapping from stage 3 back to stage 1 is ruly, then perception can be relatively straightforward, if not, additional elements must be added. Doubts about the completeness of these four steps caused many to add 5 a stage of conceptual elaboration and re-presentation (e.g. Descartes 1649, Locke 1690). Berkeley (1733) waffled, but J. S. Mill (1843) finally christened stage 5 with the name inference. Helmholtz (1866) then toyed with the term unconscious inference but gave it up (Helmholtz 1878) because Schopenhauer had used this term to denote a different concept. Regardless, the idea of unconscious inference remains with us today (e.g. Rock 1983, 1985).

But inferences come in two kinds. They can be deductively valid or inductively strong (e.g. Skyrms 1975). Perception could be deductive if all premises came from stimulus information and from design features of a perceptual system. Bottom-up processing is almost by necessity deductive. If the mapping from proximal stimulus back to distal object is assured, then no probabilistic associations need be added, no cognition is required. Richards et al. (1982) employed mathematical proof to determine when information is sufficient and deductive perception possible. This is a type of inference with which Gibson (1979) for one, could be happy. If, however, perception is inductive, some premises come from memory and cognition, perception must have top-down components with no recourse but to concepts of probabilism and cue-validity. Many modern thinkers have espoused such ideas (Brunswik 1956, Gregory 1974, Neisser 1967, Kolers 1983).

In broad form, however, this view seems on the wane. Part of the reason is an upturn of interest in the work of James Gibson and his ecological approach, an interest registered both by psychologists (Bruce & Green 1985, Shepard 1984, Turvey et al 1981, Warren & Shaw 1984b, Wilcox & Edwards 1982) and philosophers (Fodor & Pylyshyn 1981). Some have tried to improve on Gibson (Bickhard & Richie 1983, Heil 1983, Michaels & Carello 1981, Natsoulas 1984), others have pointed out problems with the ecological approach (Ullman 1980, Cutting 1982a), and still others have broached these problems for all theories of perception (Hochberg 1982, 1984, Cutting 1986).

New support for the idea of bottom-up processing has come from the field of machine vision. Through Marr (1982), Ullman (1979), the work that theirs has fostered (e.g. Brady 1981, Grimson 1981, Pentland 1986, Pinker 1984), and the work from somewhat different traditions (e.g. Ballard & Brown 1982, Binford 1981, McArthur 1982), machine vision has outraced the early lead of the ecological approach in its search for specifiable information on which
percepts might be based. An emerging synthesis of methodologies in psychology (Cutting 1986, Proffitt & Bertenthal 1986, Todd 1982, Todd & Mingolla 1983, Warren 1984) and machine vision (Hildreth 1984, Stevens 1981, 1983b, Ullman 1979) has brought a new style of research. Two steps are entailed: 1) mathematical proof of the consistency of information and 2) demonstration that it is perceptually useful.

Approaches to information are many. One could, following Aristotle, Kulpe (1895), and Kubovy (1981), look for stimulus dimensions that carry information—extent, time, frequency, and intensity. While such a neat beginning may be suitable for taste, olfaction, kinesthesis, and touch, it is much less so for audition and vision. Instead, another tradition has it that information is in structure (Garner 1962, 1974). Following this lead, I have divided approaches to information into five groups according to potential origins of structure—experience, constraints, statistics, analysis, and geometry. The crux of any information is its measure. How it is measured determines what is deemed important to a perceptual system. Each type assumes that perception, typically vision, is informed by measures of the stimulus, and that perception is, in part, information measurement (Lappin 1984).

STRUCTURE FROM EXPERIENCE

For James Mill, information existed in association networks and in what twentieth century analytic philosophy calls sense-data. This is the oldest form of information discussed in psychology.

Information in Frequency of Occurrence

The idea that information exists in the number of times something happens was at the base of Morton’s (1969, Gordon & Caramazza 1985) logogen model, which counted occurrences of words for later recognition, it also has a place in cognitive learning (Estes 1976), in concept formation (Mervis & Rosch 1981), and in memory [Hasher & Zacks 1979, although not in all contexts (Kahneman et al. 1982)]. In music perception, Krumhansl (1985) has found that probe tone ratings given by listeners to notes and chords as they fit into a diatonic scale are highly correlated with their frequency of occurrence in pieces of classical music. Such results complement her continued interest in the density of events in space and time (Krumhansl 1978, 1982).

PROBLEMS WITH FREQUENCY

Despite its utility to perception, frequency information is not perceptual, it must be cognitive. It can only be useful to an organism after large amounts of processing, or many logogen ticks, have occurred. It is not information about a current stimulus, it is about similar previous stimuli. Thus, frequency information leaves as a mystery how a
stimulus informs for the first time, or how similarity with previous stimuli is determined

STRUCTURE FROM CONSTRAINTS

A second general approach to information considers constraints. Rather than concentrating on what a stimulus is, this approach focuses on what it is not, considering potential false targets and weeding out alternative percepts.

*Information from Bits to Simplicity*

Perhaps the most familiar style of information measure comes from electrical engineering and information theory (Shannon & Weaver 1949)—bitwise assessment through logarithmic counts of alternatives. According to this approach, *information exists in the set size to which an object or event belongs*. Early applications to perception include those of Attneave (1954) and Garner (1962). Currently, this approach is not so popular in perception as in cognitive science more generally (Dretske 1981, Machlup & Mansfield 1983), but two threads remain. Bits-measure plays a practical role in electronic transmission of images, and it has fostered continuing interest in perceptual economy.

Sperling (1980, Sperling et al. 1985a) described techniques for the transmission of American Sign Language (ASL) over telephone lines. Since telephone transmission typically uses a bandwidth about 1/300 that of television, serious compression of the visual signal is necessary. Using many different coding schemes, the most successful entailing reduction and adaptive coding of pixels (picture elements) and reduction of frames transmitted, Sperling et al found it possible to transmit acceptable ASL at near-telephone line capacity. The practical import of these findings is patent, their theoretical implications are discussed below.

The second thread of interest in bits-measure involves the Gestalt concept of simplicity. The importance of design simplicity, or minimalism of physical solutions to structural problems in nature, was emphasized by Mach (1886) and later by Kohler (Koffka 1935, Attneave 1982). In perception, good figures, the Gestaltists argued, should also be simple. The task of quantifying minimalism began with Hochberg & McAlister (1953) and has been renewed by Hemenway & Palmer (1978) and by Butler (1982). It has also received philosophical attention from Sober (1975) and from Hatfield & Epstein (1985). The natural descendent of the study of perceptual simplicity is the work of Leeuwenberg (1971, Buffart et al. 1981, 1983) and what is now called structural information theory. In vision and audition, stimuli are parsed into primitive elements. These are then combined, counted, and demonstrated to predict perceived forms over certain nonperceived forms, which have less parsimonious combinatorics. In the visual perception of motion, Restle

PROBLEMS WITH BITS AND SIMPLICITY Among the assumptions in almost any application of information theory to perception is that perceptual objects come in fixed, homogeneous, nonoverlapping sets of known size. Unfortunately, the world around us is not populated with such things. And as with frequency, bits-measure is information only for an organism with substantial personal history.

Sperling’s work with ASL sequences suggests further difficulties. Bitwise assessment of images and its assumed psychological relevance rest on two deeper assumptions about aliasing, the distortions found in any quantized signal. That spatial aliasing [or discreteness effects due to receptor packing in the retina (Williams & Collier 1983)] constrains all perception of form and that temporal aliasing [or discreteness effects in stroboscopic motion due to low temporal resolution in the signal (Burr 1981)] constrains all perception of motion. Although both are important to perception and to discussion of high-quality images, neither has psychological preemminence. Multiplying pixels by gray scale by frame rates, seems an inadequate way to measure perceptual information.

The problems with approaches to simplicity are two. First, and appreciated by Goodman (1972) and Sober (1975), is justification of primitives or the stimulus “atoms” underlying percepts. One must have an a priori rationale for their choice, otherwise one’s proofs rest only upon shrewd guesses. Restle (1979), in selecting primitives from the mechanics of motions, seems to have justified this approach best. Second, Hochberg (1981, 1982), the originator of this approach, has shown that perceptual economy is easily overridden by other stimulus factors, thus robbing it of central importance.

Information from Group Theory

Where information theory and bitwise assessment left off, interest in mathematical groups picked up. The switch was led by Garner (1970) and his analysis of symmetry. If good patterns have few alternatives, there might be information in counting members of a symmetry group. The idea here is a plea for formalism—information is constrained through groups of transformations on a stimulus that follow postulates of closure, association, identity, and inversion. The roots of this idea can be traced to Cassirer (1944), Poincare (1907), and Helmholtz. Promoting what is now known as the “group of displacements,” Helmholtz (1894, p 504) suggested “Being acquainted with the material form of an object, we are able to represent clearly in our minds all the perspective images we expect to see when we look at it from
different sides, and we are startled if an image we actually see does not correspond to our expectations. The group of Euclidean translations (along $x$, $y$, and $z$ axes) and rotations (around orthogonal axes oriented in $x$, $y$, and $z$) consists of six dimensions of continuous transformations that leave an object's shape invariant (Lévy-Leblond 1971).


PROBLEMS WITH GROUPS  Eddington (1939, p. 148) stated that "The starting point of physical science is knowledge of the group-structure of a set of sensations in a consciousness." Group theory has much promise in perception, but there are nagging problems (Cutting 1986). For example, although groups can describe perceptual phenomena, their capacity to explain them is less clear. Consider a parallel from another branch of mathematics. Although catastrophe theory (e.g., Zeeman 1976) models equally well the hysteresis effects in stereopsis and in binge/purge eating disorders, it explains neither. So too group theory may model but not explain perception. At the very least, group theory suggests interesting questions about perception.

STRUCTURE FROM STATISTICS

A third approach to information is statistical, and in vision research it roughly divides two ways. The first considers statistics of textures that varicolor a surface, the second considers whole forms and has its roots in signal detection theory. In both, information is in spatial distribution.

Information in Texture Shape

Julesz has developed a theory of textons, or statistical primitives for the visual system (Julesz & Bergen 1983), where information is measured by the shape of a texture element. Julesz (1975) began by discussing the probability of two-dimensional (2-D) placement of dots, dipoles (oriented needles), and sequential gray scale (a kind of shading pattern) as first-, second-, and third-order statistics, respectively. His original conjecture was that textures identical in dot and dipole statistics but differing in gray scale could not be
discriminated. Interesting variations and counterexamples were found (Diaconis & Freedman 1981, Julesz 1981). Statistical order has faded from central importance, and the universe of textons is now tripartite, comprising elongated blobs, terminators, and the crossing of line segments. Any one of these can be located easily and rapidly on a surface of differing textons. Beck (1982b, 1983, Beck et al. 1983b) has followed in this vein. Julesz has continued (Sagi & Julesz 1985), and Caelli (1981, 1985) and Foster (1984) have promoted related schemes.

Perhaps the most important work on texture is that of Treisman (1982, 1985, Treisman & Paterson 1984, Treisman & Souther 1985, see also Prinzmetal 1981). Eschewing statistics, Treisman has proposed a feature-integration theory of perception, where focal attention is necessary to merge separate attributes of a stimulus. As in Julesz's work, empirical results determine features in an experimental task of visual search. Treisman demonstrated that search time is very long for a target among distractors that possess its component features. She found emergent features and search-time asymmetries that are further diagnostics for visual primitives. Her current list includes color, lines, terminators, and closure. Matching Julesz's list (and Marr's) rather well.

Other statistical attributes of form are treated by Zusne (1970) and Lord & Wilson (1984). In addition, Pentland (1983) has suggested that fractals may have psychological correlates. Fractals are graphical objects (technically curves) that fill space through recursion (self-similarity at different scales), can have noninteger dimensionality, and can have stochastic character (Mandelbrot 1983).

**PROBLEMS WITH TEXTONS AND FEATURES** Texton theory neatly bypasses one problem of structural information theory by basing its selection of primitives upon empirical results. But other difficulties arise. First, texton studies are. In essence, the study of wallpaper. A quick look around an environment without walls reveals that most common textures overlap, interleave, grade, and are differentially shaded. This may not pose insufferable difficulties because textons can be slanted without changing character (Kanade & Kender 1983, but see Beck 1982b). Second and more important, because it studies rapid perception texton theory bears only on static images. Reaction-time and tachistoscopic measures of perception apply primarily to information detectable at a single moment. But much information is revealed to vision through motion, and there is conflicting evidence as to whether form and motion are processed independently (Cutting 1982a, Krumhansl 1984). And third, texton studies do not consider natural textures.

Careful study of Brodatz's (1966) work on such textures will repay anyone.
Information in Dotted Forms

Another statistical approach concerns signal detection, proposing that information derives from probabilistic relations among signal elements and noise. In psychology, this style of research began as part of an engineering approach to speech perception (Miller et al 1951). In vision, such studies began at the dawn of the application of computer technology to perception. Researchers represented stimuli and noise by means of computer controlled dots. Stimulus dots were placed on the surface or within the form of primary interest. Dots have several physical properties that make them good tools of inquiry (Sperling 1971), and they are also easy to generate. This type of study has been sustained in three areas: 1) stereopsis, most notably studied by Julesz (1971; see also Prazdny 1985a), 2) the microtexture of form, and 3) the perception of motion. Only the latter two areas concern us here, and I discuss the last in a later section.

Glass (1969) discovered that by rotating identical sheets of speckled transparencies, with respect to one another, one will see remarkable, global swirling patterns, now known as Glass patterns. Their interest is in what they can tell us about local determinants of global patterns. Recently, Prazdny (1984, 1985b) has shown that spatial distributions of energy rather than of symbolic codes are responsible for the effect, and Zucker (1984, 1985, Zucker et al 1983, see also Stevens 1983a) used such patterns to discriminate two types of form: one of edge detection and the other of global patterning.

Uttal (1983, 1985) has continued his study of dotted forms. Among recent findings he noted two in conflict. In two-dimensional figures the most important attribute for detectability of dotted lines is evenness of spacing, but in three dimensions the detection of a curved surface peppered with dots is better when dots are randomly rather than regularly distributed. Uttal suggested that the latter finding is due to effects of spatial aliasing, the biases that emerge from regular sampling. Under conditions of three points with no noise, however, Lappin & Fuqua (1983) found remarkable sensitivity for even spacing of three dots rotating on a line slanted in depth.

Problems with Dotted Figures. Like textons and features, Glass patterns suggest fundamental processes early in the sequence of visual processing. But how do such processes work in the perception of everyday scenes? Zucker (1985) analyzes this issue, but his distinction relegates all normal perception to global-pattern processes. More importantly, dotted forms were initially used in studies of visual perception for the pragmatic reason that they were easy to generate and easy to control. With the development of better and cheaper computer graphics capabilities, which allow generation of increasingly naturalistic scenes, it is not clear what future role dotted-form
research should have in our field. Control is no longer sacrificed in complex displays.

STRUCTURE FROM NEURAL ANALYSIS

One aspect of simplicity and texton/featural approaches to perception is their focus on primitives—decomposition of scenes into discrete building blocks. When confronted with complex stimuli, such approaches cannot always guarantee straightforward decomposition. Some stimulus attributes, for example, may be both bloblike and terminatorlike. Two forms of analysis, however, guarantee complete decomposition. In one, currently called the neural dynamics approach (Cohen & Grossberg 1984, Grossberg & Mingolla 1985a,b), various perceptual phenomena are considered and neural networks proposed to model them (see also Anderson 1983). In the other and more traditional approach, stimuli are decomposed by Fourier analysis.

Information in Fourier Components

Fourier analysis of visual stimuli has burgeoned in the last 20 years. Borrowed from auditory research, this approach assumes that information lies in distribution, amplitude, and phase of sine wave components of a visual image. Yellott et al. (1984) recently reviewed this work.

Four threads can be traced within the recent literature. First, interesting new data are available on Fourier-like components that pervade underwater environments (MacFarland & Loew 1983). Second, the relation between Fourier channels and attention continues to be explored (Banks et al. 1985, Graham 1985, Yager et al. 1984), third, new spatiotemporal analyses have been performed (Nakayama & Silverman 1985, van Santen & Sperling 1984, 1985, Sekuler et al. 1984, Stromeyer et al. 1984), some including Gabor functions (Watson et al. 1983), and fourth, parsimonious image analysis and regeneration is now possible through pyramid schemes that provide excellent Fourier approximation (Burt & Adelson 1983a, 1983b).

PROBLEMS WITH SINE WAVES

There is great power in Fourier analysis, and that is its problem. Joseph Fourier guaranteed that any signal could be analyzed into sine waves. Thus, Fourier analysis (or the multilevel zero-crossing analysis of Marr 1982) is unselective. Everything in the stimulus is transformed, not merely the most meaningful or important parts. And except in work with faces (e.g. Harmon 1973), Fourier analysis is generally used to look inward at predispositions of the nervous system, rather than outward at the objects and events of the surrounding world. It simply cannot be that our visual system finds informative everything at 8 cycles/degree.
STRUCTURE FROM GEOMETRY

The idea that geometry is the foundation of vision has a long history—from Euclid through Alhazen, Kepler, and Descartes. We have generally ignored those roots, but Euclid (Burton 1945) was much interested in size, the horizon, occlusions, induced motion, and motion parallax. Euclid’s Optics, an extension of his Elements (the foundation of geometry), deals entirely with physical constraints on perception.

Although admonished otherwise, we can fit Gibson (1979) into the Euclidean tradition of classical optics. Information is geometrized “in the light,” measured in visual angles. For nearly a century the geometry thought relevant to vision has been projective (Russell 1897, Poincaré 1905, Johansson et al. 1980). But projections vary [see Carlbom & Paciorek (1978) for an overview of planar projection techniques and Sedgwick (1983) for their application to perception].

Information, Geometry, and Static Form

Geometric information concerns both the static and the moving form. Research on static projections has advanced in three areas: 1. relations of object parts to objects, 2. use of textures on surfaces to derive surface shape, without recourse to textons or features, and 3. use of shading to recover surface shape.

First, consider object recognition and the interpretation of junctions of line segments in recovery of object shape. Ballard & Brown (1982), McArthur (1982), and S. Lee et al. (1985) have reviewed work since Guzman’s (1969) analysis of intersections—forks, arrows, and tees—and Perkins (1983), Shepard (1981), and Barnard (1985) have considered constraints on the perception of rectangular solids. One basic assumption here—that solids are made up of edges that intersect at right angles—is clearly false for most natural objects.

The most important recent advance in figure-ground segregation is in the study of nonrectilinear contours. Koenderink & van Doorn (1982) and Koenderink (1984b) noted constraints on ending contours of smooth objects, and Hoffman & Richards (1984, Richards & Hoffman 1985) have suggested that six codons, or arrangements of maximal and minimal curvature in line segments, can be used to break up objects into parts on the basis of self-occluding contour, or silhouette profile. Codons map onto geons [or generalized cones (Binford 1981)] for object recognition. Biederman (1985) estimated that 36 geons can describe 2 million different objects. Nonrigid objects with rigid parts, like animals and people, might be categorized and recognized by such a scheme. Webb & Aggarwal (1982) Implementation of object recognition by such a scheme is probably far into the future, but the idea seems promising.
Second, consider surfaces. Discussion of surface geometry began with Gibson's (1950) analysis of information in texture relations. But after Gibson for a period of 30 years the issue of recovering surface shape from textures was bypassed for discussion of absolute surface slant and texture density, neither of which is an important psychological variable. Slant research continues (Epstein & Lovitts 1985), applied most notably to the practical problem of landing aircraft (Perrone 1984).

Owing to more recent interest in machine vision, the recovery of surface shape from texture geometry has recaptured attention. Orthogonally specifiable measures of textures on surfaces number at least three: density, scaling (or perspective), and foreshortening (or compression). Information about flatness is contained in the scaling measure and that about curvature in foreshortening (Cutting & Millard 1984, Stevens 1984, Todd & Mingolla 1984). Recent work in machine vision (Besl & Jain 1986, Brady et al 1985, Crimson 1983, Kanatani 1984, Ullman & Richards 1984) has concentrated on complex surface shape. But textures, like textons, are too sensitive to spacing considerations to play more than a minor role in the perception of natural surfaces.

Third, and most important, is shading. Studies of illumination have received recent psychological attention (Bergstrom et al 1984, Flock & Nusinowitz 1984, Gilchrist & Jacobsen 1984, Granrud et al 1985). Assisted by computers, psychological (Todd & Mingolla 1983, Mingolla & Todd 1986) and machine-vision (Pentland 1982, Woodham 1984, Lee & Rosenfeld 1985) studies of shaded surfaces are paving the way for a new kind of psychophysics, impossible even a few years ago, in which complex variables of lighting, reflectance, shading, and color can be minutely controlled.

**Information, Geometry, and Motion**

Ullman (1983) outlined three geometric approaches for the recovery of structure from “unrestricted” motion, which assumes nothing but rigidity (see also Webb & Aggarwal 1981). Rephrased slightly, they are 1) discrete points and views, 2) discrete points and displacements, and 3) displacement fields. The first two, and often the third, are related to the statistics of dotted forms discussed earlier, but here motion and geometry are paramount.

**Discrete Points and Views** The first approach considers planar projections of a rigid 3-D array of points at particular times. The projection locations are then used to derive 3-D structure. Following Ternus (1926), Ullman (1979) explored the correspondences among projections of points across different stimulus frames. More recently, Ullman (1984a) and Williams & Sekuler (1984) explored spatial and statistical constraints, respectively. Various stroboscopic effects have also been explored (Petersik 1979).
placed dots within a sphere and Lappin et al (1980), Lappin & Kottas (1981), and Doner et al (1984) placed them on its surface in the study of object coherence. Results show a remarkable ability of the human visual system to solve correspondences, considerable susceptibility to noise interference, and increased resistance to disruption with increased numbers of frames presented. Continuing studies of apparent motion also fit into this scheme (e.g. Ramachandran 1985, see also Allik & Dzhafarov 1984, Bregman & Mills 1982, Sperling et al 1985b).

A PROBLEM WITH POINTS AND VIEWS The drawback of points-and-views analysis is that it sets up a correspondence problem—negotiating which points map onto themselves across frames—that occurs only in phenomena of apparent motion, not in real motion. Todd (1984a, 1985), for example, has argued against points analysis in vision and has shown that correspondence is not necessary for the perception of a moving object.

DISCRETE POINTS AND DISPLACEMENTS The second approach to motion uses point locations and vectors (lines of particular length, direction, and sometimes curl) to represent relative velocities through 3-D space. This approach started with Johansson (1950) and Wallach & O'Connell (1953), but Green (1961) and Braunstein (1962) paved the way with studies of computer-generated motion. Johansson et al (1980) reviewed much of this work from the 1970s. More recently, Gogel (1978) and Goldberg & Pomerantz (1982) looked at proximity interactions among points of light. Rogers & Graham (1979) and Carpenter & Dugan (1983) studied motion parallax. Mori (1984) explored velocity effects in vector analysis. Shum & Wolford (1983), Wallach et al (1985), and Wallach & O'Leary (1985) decomposed vectors in various ways that Johansson (1985) claimed were consistent with his theory. Petzner (1983) has used the technique to explore information in ASL. Proffitt et al (1983) extended the vector analyses of points to those of shaded areas, and in a related development, Kaiser et al (1985) showed that the intuitive-physics results of McCloskey (1983) are due, in part, to differences between static line drawings and actual presentations of moving objects.

Within this framework an orthogonal issue has developed. Is information about motion merely kinematic or is it dynamic—i.e., are forces perceived and used? Several different lines of research suggest that forces are derivable from kinematic displays. Todd & Warren (1982) and Kaiser & Proffitt (1984) have shown that the ballistic motions of objects can be correctly determined. Runeson & Frykholm (1983) have shown that point-light displays of human actions reveal information about objects, otherwise unseen, that they interact with, and Freyd (1983), Freyd & Finke (1984), and Finke et al (1986) have shown dynamic effects for static and stroboscopically presented forms.
In the study of machine vision, vector analysis is used to recover object shape. Ballard & Kimball (1983) explored the perception of objects in motion, and Horn & Schunck (1981), Prazdny (1981, 1983a,b), Rieger & Lawton (1985), and Rieger & Toet (1985) have used such analysis in the study of optic flow for a moving observer, a topic I treat below.

PROBLEMS WITH POINTS AND DISPLACEMENTS This approach continues to have the problem of points, which Hildreth (1984, 1985), for one, circumvented by dealing with the motion of boundary edges and sorting out the possible vector fields generated. There is, however, a more pressing problem with the study of unrestricted object motion. Embedded in Gibson's (1979) invariance, in Johansson's (1978) decoding principles, and in most machine-vision research (but see Bennett & Hoffman 1985) is a rigidity assumption. Only in the domain of growth (Todd et al. 1980, Pittenger & Todd 1983) has rigidity been relaxed. But viewers do not always see rigid objects even when such objects are possible interpretations of the stimuli (Braunstein & Andersen 1984a, Hochberg 1986, Schwartz & Sperling 1983, Todd 1984b). Ullman (1984b) suggested that before rejecting the rigidity principle one should be sure 1 that no 3-D structure is perceived in a static display and 2 that motion is not misperceived. But this replaces a reasonable assumption about rigidity with a less reasonable one about veridical measurement and interpretation of motion. Research is needed on the boundary conditions of perceived nonrigidity over rigidity.

DISPLACEMENT FIELDS AND WAYFINDING A third approach to motion perception involves analysis of fields of vectors. Braunstein & Andersen (1981, 1984b) and Graham & Rogers (1982) explored depth effects through motion parallax in displacement fields, and Nakayama et al. (1985) and Ball & Sekuler (1982) explored motion discrimination effects that occur in viewing fields of moving dots. But most researchers have used this approach in attempts to characterize the information available about one's direction of movement during locomotion, a task I call wayfinding. Gibson (1950) and Calvert (1950) characterized the resultant motion of objects, often called optic flow in this context, as a set of vectors (flow lines of position, direction, and length) that point away from a focus of expansion. The location of this focus, they argued, provided the information for wayfinding.

1971, Johnston et al 1973) Regan & Beverley (1982) pointed out a reason. In certain environments there is always a focus of expansion where one looks, regardless of where one is going. This focus is due to vector cancellations resulting from eye rotations (Longuet-Higgins & Prazdny 1980, Koenderink & van Doorn 1981). Although Regan & Beverley’s analysis has problems (Priest & Cutting 1985), it is unlikely that the focus of expansion can be salvaged. Instead, Cutting (1986) proposed that certain properties of motion parallax and of serial fixations in optokinetic nystagmus can be used for wayfinding accuracy within one degree of visual angle, approximately that needed for running through a cluttered environment.

**A PROBLEM FOR FIELDS** It seems likely that the human visual system does analyze displacement fields, employing massively parallel neural systems (Ballard et al 1983). But research that only considers unnatural displacements across a projection surface, probing what the visual system sees (Regan & Beverley 1982, Nakayama et al 1985), deals only with unrepresentative manipulations of a perceptual system and may not apply to real perceptual problems.

**Information for Perception and Action**

Perception subserves activity. It is a major disappointment of modern psychology that studies of perception and action are rarely linked. The field analyses discussed above are a promise of linkage.

Visual perception tells us where we are within our surrounds, information we can use in changing our location and to get needed feedback. Among the few studies relevant to this area, Thomson (1983) and Elliott (1986) found conflicting results on the necessity of monitoring visual information during locomotion. D. Lee et al (1982, 1983) measured the use of visual information during long jumps and when hitting an accelerating ball. Lee & Reddish (1981) looked at visual information for plummeting gannets, and Warren et al (1986) found that, when moving over irregular ground, an observer adjusted the vertical component of gait, leaving velocity unchanged. The latter result means that information about time to contact (Lee 1980) with objects along the path is generally unchanged by terrain. Recent explorations of sensory-motor adaptations are also relevant to perception and action (Lackner 1985, Shebilske 1981, Shebilske et al 1983).

**Information, Topology, and the "Geometry of the Visibles"**

Two sideights on geometry and perception should be considered. One concerns topology, the only kind of geometric information not ultimately couched as visual angles. Koenderink (1984a), Lappin (1984), and particular-
ly Chen (1982, 1985) proposed that the visual system is quite sensitive to the
topology of form, segregating those objects with bounded external contour
from those that have holes. But Rubin & Kanwisher (1985) suggest that much
of Chen’s effect may be due to luminance differences in stimuli.

The second sideline concerns non-Euclidean geometry. Measurement of
visual angles in Euclidean systems depends on straight rays of light, or
projectors. But following from Reid’s (1764) “geometry of the visibles,”
Helmholtz’s (1866) discussion of curved visual space, and Luneburg’s (1947)
analyses of binocularity, a series of inquiries into Riemannian curvature has
ensued, some philosophical (Daniels 1974, Hopkins 1973, Suppes 1977);
Psychological efforts have focused on binocularity (Blank 1978) and the alley
problem (Indow 1982, Indow & Watanabe 1984), or on illusions (Watson
1978). The major issue was raised by Grunbaum (1973). How do these
non-Euclidean models of perceptual data map back onto the Euclidean experi-
ence we have of our normal surrounds? A possible resolution lies in whether
curvatures measured are within the tolerances of our visual system.

INFORMATION AND ICONIC MEMORY

A series of topics do not readily fit into the structure of my overview but are
important to any discussion of information and perception. Iconic memory
research is one, and it is in a state of transition. Thorough reviews of an
immense literature (Coltheart 1980, Long 1980) have given way less to
increased knowledge about the role of persistence in vision than to the mantra
of ecological validity (Haber 1983). Rather than synthesizing anything new,
let me point out several trends pertinent to my topic.

has shown that holistic information is retained better upon a single glance at a
photograph, that featural information is retained better upon multiple glances,
that visual persistence is worth about 110 ms of extra stimulus presentation,
and that luminance reduces both information available and information ex-
traction rate. Long & Wurst (1984) have shown that complexity in perimeters
and areas of figures affects the duration of visible persistence, but in reversed
fashion depending on whether the form is filled or not. Di Lollo (1984) and Di
Lollo & Hogben (1985) have studied the duration and suppression of persist-
ence, which others have studied in both stroboscopic (Burr 1981, Farrell
1984, Pomerantz 1983b) and apparent (Hogben & Di Lollo 1985) motion. In
this connection, the role of abrupt onsets continues to receive attention
(Kowler & Sperling 1983, Yantis & Jonides 1984), as do partial report
procedures (Bundeson et al 1984, Yeomans & Irwin 1985). In addition,
Weichselgartner & Sperling (1985) developed a continuous measure of visual
persistence.
INFORMATION IN NONVISUAL MODALITIES

Vision may be the least representative of our senses. Thus, a review of information and perception would ideally devote much effort and space to other modalities. Unfortunately, comparatively few studies on these other modalities are available.

Outside of work in auditory psychophysics and an occasional foray into ecological acoustics (Jenkins 1984, Warren & Verbrugge 1984), work in audition is focused on speech and music. In speech research a 30-year debate continues on whether information for speech is in the acoustic signal (Blumstein & Stevens 1980) or in the match of gestures to that signal (Liberman & Mattingly 1985). Longstanding interest continues in categorical perception (Massaro & Cohen 1983a, Repp 1984) and in selective adaptation (Samuel 1986). In music research, a livelier and more tractable endeavor, investigators study information with respect to tonality (Krumhansl 1985), sequence and contour (Wright & Bregman 1986, Boltz & Jones 1986, Deutsch & Fere 1981, Dowling 1978, Massaro et al 1980), and rhythm (Handel & Todd 1981, Povel 1981).

For touch and haptic perception Klatsky et al (1985) found, in keeping with Gibson (1966), that exploration and object recognition can be both rapid and accurate. Anstis & Tassinary (1983), Oldfield & Phillips (1983), and Benedetti (1985) explored tactile illusions. In olfaction and taste, soluble chemical compounds inform the perceiver, but we know remarkably little about how these modalities work (Carterette & Friedman 1978, Engen 1982). Natural conditions of tasting (licks, sips, and gulps) and smelling (sniffs) yield optimal conditions (Halpern 1983, Lang 1983), taste is not as sluggish as once thought (Kelling & Halpen 1983), entropy can be measured during adaptation (Norwich 1984), and there is a tight relation between chemosensation and cognition (Rabin & Cain 1984).

INFORMATION USE

Individual sources of information—whether experiential, statistical, or geometric—rarely stand by themselves. Unless all the information needed for a percept is contained in one prepackaged source (unlikely in everyday situations), perceptual information must exist in several forms. The perceiver must choose among or combine these forms.

Equivalence, Cognitive Penetrability, and Choice

Equivalent information has most often been discussed in the contexts of speech perception (Liberman 1982, Repp 1982) and visual perception of
objects in depth (Gogel 1984) In both, one "cue"—or physical source of information—can trade off against another, and perception remain unperturbed In speech and vision, trading relations might be taken as evidence for modularity of perceptual system Modular systems (Fodor 1983) are thought to be "cognitively impenetrable" (Pylyshyn 1984), data driven from the bottom up The perception of different stem lengths in the Muller-Lyer figure, for example, is not altered by knowing that they are identical Information specifying the percept is thought to be "encapsulated," and that knowledge cannot descend into the guts of the perceptual process Although the broad strokes of this example are compelling, careful analysis (Peterson & Hochberg 1983, Peterson 1986) of ambiguous line drawings and stereographic displays can show the role of intention on what otherwise might seem to be low-level visual processes Moreover, some percept-percept couplings (Hochberg 1974, Epstein 1982) demonstrate that higher-level assumptions and interactions may invade a module to determine perceptual outcomes But perhaps none of the assumptions made for perception need be cognitively based Johansson (1970) felt that they were hard-wired Gibson (1970) objected to Johansson’s decoding principles because they seemed to imply insufficient information in the stimulus But Cutting (1986) has suggested the opposite When more than one information source is available, a perceptual system must choose between (or combine) them In two viewing situations, entailing judgments of planar rigidity and of wayfinding as discussed above, different invariants equally specified a perceptual outcome, but the visual system most often chose only one

*Additivity, Integration, and Multimodal Perception*

When information is combined, additive models often fit best (Cutting & Millard 1984, Dosher et al 1986) Such additivity, however, is confined only to certain stimulus dimensions Garner (1974, Lasaga & Garner 1983), Pomerantz (1981. 1983a), and Kemler Nelson (Foard & Kemler Nelson 1984. L. Smith & Kemler 1978, J. Smith & Kemler Nelson 1984) have explored the nature of stimulus dimensions and their interaction in various tasks Some dimensions are often separable and allow for additivity, others are integral and do not Garner (1986) now regards integrality as a mandatory, and separability as an optional, secondary process Children often start out classifying stimuli in integral terms and later, as a result of developmental changes, move to strategies of separability But whereas it is relatively easy to see how integrality might work within a sensory modality, it is more difficult to anticipate such effects across them (but see Algol et al 1986) And more generally,
Ashby & Townsend (1986) provide an overview of the kinds of perceptual independence that provide a backdrop for discussions of stimulus additivity. Hornbostel (1927, p. 210) suggested that "it matters little through which sense I realize that in the dark I have blundered into a pigsty." This may be true for a folk phenomenologist, but to a psychologist it should matter quite a lot how such a conclusion might be reached, particularly since a single modality is not likely to provide all the information needed for pigsty perception. Marks (1978) gave us a thorough history of views on the unity of the senses, and research has been done on how information from the different senses might fashion unified percepts.

Two modalities are usually considered at a time, and one is almost always vision. The interrelation of vision and kinesthesia has been investigated by Lackner & Taublieb (1984) and Lackner & Shenker (1985), B. Jones & O'Neil (1985) explored bimodal and unimodal responses to texture, finding that visual and haptic information seemed to be additive. The interrelation of vision and audition in speech perception has received much attention since the discovery by McGurk & MacDonald (1976) that simultaneous presentation of an auditory /ba/ and a visual image of the lips forming /ga/ yields a compelling percept of /da/. Summerfield (1979) and Massaro & Cohen (1983b) replicated and extended the result. Dodd (1979) and Kuhl & Meltzoff (1984) explored it with infants, and Green & Miller (1985) looked at the influence of visual rate on the combined percept. The perception by infants of more general visual-auditory combinations has been explored by Spelke (1976, Spelke et al. 1983), and discussed by E. Gibson (1984).

**Informative Displays**

Finally, information in stimuli is important not only in terms of the perceiver but also in practical situations for the researcher. Given the increase in use of computer displays, it is good to see that some attention has been given to how they are perceived (Haber & Wilkinson 1982). Tufte (1983) provides new insights into how we might most effectively present scientific information in graphs and charts.

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