T-175

TRANSFORMATIONAL REALISM: THE OPTIC ARRAY, THE OPTICAL IMAGE AND THE RETINAL PROCESS

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ABSTRACT

It is ordinarily assumed that through 3D, visual perception is constructed by virtue of a series of brain mechanisms not as yet thoroughly understood. There is now, however, an alternative formulation based on the quantum properties of retinal processing. This formulation states that the sensory mechanism allows a 3, 4, or even greater dimensionality in processing, right from the beginning. Holography is an instance of such processing. A holomic perceptual theory based on holographic quantum considerations will be described and some of its ramifications demonstrated.

Configural Aspects

> Objects are not fleeting and fugitive appearances [images] because they are not only groups of sensations, but groups cemented by a constant bond. It is this bond alone, which is the object in itself, and this bond is a relation.
> (Poincare, 1905b)

Transformational Realism: The Optic Array, The Optical Image and the Retinal Process

> Instead of postulating that the brain constructs information from the input of a sensory nerve, we can suppose that the centers of the nervous system, including the brain, resonate to information. (Gibson, p. 267).

Introduction: The What of Perceptual Processing

This paper concerns the initial sensory mechanism, which in the eye consists of the optics of pupil and lens and the receptor processes of the retina. In vision, I hope to show that making a distinction between the optic array, optical image, and retinal process (and specifying the transformations involved), resolves several hitherto intractable issues. These issues are: (a) the grain problem, that is, determining the origins of sensory configurations; (b) the existence or nonexistence of a retinal image; and (c) the dimensionality of the initial sensory process.

within a week everything was once more experienced as right side up, demonstrated this beyond doubt. The experiments by Richard Held (1968) and Ivo Kohler (1964) showed that moving about was critical to this adaptation of phenomenal experience.

Given that relations are basic to what is being processed, the next questions becomes, "Relations among what?" Mach concluded, on the basis of his observations (see review by Ratliff, 1965) that what is being processed are the spatial and temporal relations among the magnitudes of infinitesimally small points of radiant electromagnetic energy, the spatial and temporal derivatives of luminance. As described later in this lecture, a more comprehensive but related formulation of this approach has been used by Sejnowsky and Lehky (1987) to compute configuration using "the second derivative of the tangent vector to the surface along a line" (p. 18).

The Optic Array

What must be taken into account when describing the initial stages of processing can be illustrated by examples taken from research on visual perception. An ecological view of perception was developed by James Gibson on the basis of his extensive research, which clearly showed that visual form perception is initially three-dimensional (or even four, that is, space and time dimensional) and not composed of elementary lines and two-dimensional planes. This led Gibson to view perception as direct or immediate rather than constructional (with the exception of the cognitive influences on perception).

Although the holonomic brain theory supports Gibson's intuitions, the tenets of theory were not acceptable to Gibson. Both he and his colleagues (as well as many others) suspected that its constructional aspects implied construction from elements (elementarism). These suspicions become groundless once it is understood that the initial perceptual processes are transformational and not elementaristic. In accord with Gibson's view, the constructional aspects of perception are top-down selective cognitive operations, such as those involved in learning and remembering, for example, the progressive differentiation of the sensory input (see e.g., Gibson & Gibson, 1955).

Some philosophers (e.g., Putnam, 1973) and scientists, such as Gibson and Turvey, are puzzled by the fact that whereas "perceivers are primarily sensitive to higher order variables of stimulation, light which lacks macroscopic structure provides no information to a visual system." (Fowler and Turvey, 1982). As noted earlier, this is known in philosophy as "the grain problem." The choice must clearly be made for a perceptual system responsive to higher order variables. These are, in fact, provided by reflected and refracted patterns of radiant energy. Gibson and Turvey as well as most scientists fail to distinguish between radiant energy and "light" that is produced when patterns of such energy stimulate appropriate receptors. Nor do Gibson or Turvey realize that reflected radiant energy provides produced by reflected from objects.

A simple demonstration suggested by C.A. Taylor (1978) in a small volume on Imaging, prepared for instruction at the 6th form level in England, illustrates what is involved. Taylor placed a slide in a slide projector and projected it after removing the lens. "Technically the pattern on the screen with no lens in the projector is called a hologram. ...the term simply means that each point on the screen...is receiving information from <u>every</u> point on the object". (p. 2).

Taylor went on to demonstrate that indeed each section of the screen receives information from every point on the object (the slide) by performing the following experiment: The projector is placed a few feet from the screen and then a converging (magnifying) lens is used to form a reduced image of the slide on the screen. The reduced image of the whole slide can be produced with the lens at any position within the patch of light, demonstrating that all sections of the illuminated screen contain information about all points on the slide.

This demonstration makes clear that incident radiation becomes "scattered" by an object -- scatter being defined as an organized bouncing of incident radiation off the object so that the organization of the radiation becomes distributed. It takes a lens to transform this organized scatter into what we are able to recognize as a (space time) image. Taylor rightly pointed out that "the simple ray diagrams of geometrical optics hide a great deal of the complexity of this operation" (p. 3). In short, image formation depends on the recombination of incident radiation "scattered" by reflection and refraction from surface and objects.

Thus, the dilemma posed by ecological optics is not really a dilemma after all. With respect to vision, reflected patterns of radiant energy that enter the pupil appear to lack macroscopic structure, but appearances are deceiving: The structure is hidden because it becomes enfolded and spread, distributed, into a form displaying "nonlocality." Just as in a hologram, or in the placement of a radio receiver tuned to a broadcast, every location contains the essential information necessary to reconstruct the macroscopic structure. Pupil and lens then unfold this potential into a recognizable optical image that interfaces with the retinal process.

As with Gabor's insights that led to the invention of optical information-processing systems such as holography, the holonomic brain theory holds that ambient patterns of energy that appear as "scatter" actually enfold and distribute macroscopic structure into a new order or organization. (Fourier transforms entail sets of operations called "point spread functions"). This order serves as a potential to be transformed into a space-time image by the optics of the eye. Configurations hidden by the distributed nonlocal reordering of the input (as in a hologram) can be unfolded by the pupil and lens performing an inverse transformation.

The Optical Image and Optical Flow:

How do these arguments regarding a retinal image hold up in the light of a transformational realism? Gibson (1979) claimed that no such representation of the object world need be involved in the perceptual process. The holonomic brain theory on the other hand, because it necessarily incorporates all the stages of processing as performed by the organism, begins with the observation that, in the stationary eye, the optics do in fact create recognizable images of objects. The fact that this is so tells us something about the system and cannot just be dismissed.

There is a sense in which even Gibson would admit such images:

> If we could think of an image in the derived sense as a complex of relations, as the invariant structure of an arrangement, in short as information, there would be no great harm in extending the original meaning of the term. But this is hard to do, for it carries too much weight of history. It is better not to cry. It would surely be false to say that there is a phonograph record in the ear, and the same error tempts us when we say that there is an image in the eye.

Thus, in ecological optics, the optic array, the optical image (or flow), and the retinal process become confounded. Gibson argued rightly that the retinal process differs from a photograph and that the optic array external to the eye conveys the complexity necessary for perception to occur. However, he ignored the transformational steps that characterize the optics of the eye and the distinction between the resulting optical image and the retinal process.

A realist stance toward both the momentary optical (moving, informative) image and the optic array identifies their difference. Thus, as noted, the optic array is considered to consist of a spectral manifold (an enfolded, distributed form of electromagnetic energy), which is a transform of the patterns defining objects. The optic array thus resembles a holographic film -- or a cross section of the waves carrying radio and television programs that have been broadcast (cast-broadly). By contrast the optical image is a three or more dimensional flow in the unfolded, space time sense. To an observer of an excised eye it appears much as does a photograph taken by a camera; under natural conditions, flow patterns constitute an occulocentric space.

A further argument has been made to the effect that although the eye is a camera that focuses an image on the retina, it is we, with our visual apparatus who "see" that image, that we cannot know the actual design that the optical apparatus projects onto the retina. But the same considerations hold for a photographic print. Are we to deny the reality of the photograph as we perceive it to be? The holonomic brain theory considers optical flow and image as such but distinguishes them clearly from the retinal process that transduces that flow by virtue of its neurochemical and neuroelectric properties.

The medium that operates on (records) the optical flow is different from that which records a photograph. The photographic medium is sensitive only to the intensities (amplitudes) of energy at any given point. By contrast, as Selig Hecht (1934) and others (Sakitt, 1972) have shown, retinal receptors are sensitive to single quanta of electromagnetic energy. Therefore, the quantal aspects of incident radiation must be considered in any representation of the receptor process. Mathematically, the holonomic brain theory therefore represents the receptor process not only by a real number representing the amplitude of the energy at a particular location but by a complex number that takes into account the phase of the quantum, that is, a number with direction. This sensitivity to polarization indicates that the retinal receptor processing of the optical flow is sufficiently multidimensional to allow visual experience to be three and even four or more dimensional.

There is an interpretation of the function of the pupil/lens system, presented in several texts on physiological optics (e.g., Hecht & Zajac, 1974) that differs completely from either Gibson's or the position taken here. Although the transformational description of the aperture/lens system is the same in this approach as in that taken in the holonomic brain theory, what differs is the interpretation of what is being transformed. In most interpretations other than those used in ecological optics or formalized by the holonomic brain theory, the events occurring on both sides of the aperture/lens system are described in complementary fashion, that is, in either space time or spectral terms depending on which description is the most convenient. Such approaches do, of course, distinguish between holograms (a spectral representation) and ordinary photographs (a space-time image), but only with respect to how each is formed and not in relation to stages of perceptual processing. Complementarity in psychophysics is akin to complementarity in quantum physics (the Copenhagen solution to the Heisenberg duality). "Meaning," interpretation, are eschewed.

Complementarity in description sounds sophisticated and is appealing to many scientists who do not want to become enmeshed in philosophical issues. However, careful consideration of the complementarity stance strongly suggests that it leads to something akin to solipsism. At best such an approach yields "many worlds" (many different explanations are equally valid) at worst an "any worlds" (any explanation will do) interpretation. This approach unnecessarily complicates explanation -- especially in studies of perception (take a look at most texts in this field).

By contrast, the remaining sections of this paper describes the functions of sensory and various systems in terms of a hierarchy -- better termed a "lowerarchy" -- of nested subroutines (control processes). These subroutines often operate (in the case of brain function, often in parallel, see e.g., Sperling, 1984) on the sensory process. This top-down operation by subroutines avoids "the insoluble paradox of an infinite regress" of superordinate little men in the brain that so troubled Gibson. All that is necessary is a system of allocation, initiated either by the sensory input per se, or by ongoing physiological stimulations. (See e.g., Chap. 4 in Plans and the Structure of Behavior by Miller, Galanter, & Pribam, 1960). When these are inadequate, an "executive," decides on the basis of prior experience which subroutine is to operate when. The role of the frontal cortex of the forebrain in executive processing has been reviewed extensively (Pribam 1961b, 1973, 1987a).

Retinal Receptor Processes

The disassociation of optical image and flow from retinal receptor processing clarifies a considerable number of points that have been raised by those interested in the perceptual process. First, as noted, Gibson's intuitive mistrust of the notion of a two-dimensional picture-like image can be taken into account without denying the existence of a moving optical image or flow. Second, the optical and retinal processes are, therefore, not constrained to two dimensions. Third, the details of the retinal process become accessible to interpretation as modulations of the spontaneous activity of this structure by both the full richness of a four-dimensional spatio-temporal optic array and optical flow and central control processes.

Cutting (1986), with several penetrating descriptions, reviewed the types of relations that, at a minimum, must be entered into computations of the retinal process. To begin, the retinal surface is curved, conforming nearly to a section of s sphere. Thus the interface of the optical image with the retina must be curved and the type of geometry used to describe this interface must be spherical rather than plane, a distinction first made by Leonardo da Vinci. As a consequence, the processing units established with reference to the optical image are lines across curved surfaces, that is, arc. Such arc can become grouped into cones, and measured in terms of solid visual angles (and tangents to such arcs). Cutting provides "rules of thumb and fist": The width of one's thumb at arm's length is about 2^o degrees whereas that of the fist (without thumb) is about 10^o.

Second, the eyes move in their sockets in such a way that the retinal surface moves with respect to the optical array to cause transformations in the retinal coordinates. The relationship between such transformations and the dimensionality of the optical array is expressed in terms of occulocentric concentric torroids (Cutting, 1986, p. 195).

As an example, Cutting analyzes motion parallax, which provides a plausible means for determining one's direction of movement. As noted, occulocentric concentric torroids are observer-related descriptions of potential optic motions. Thus,

> Any object or texture in three dimensional space can be assigned an optic vector with one assumption and three variables. The assumption is that the objects in the world are not moving, and the variables are the object's instantaneous distance and direction from the observer and the observer's trajectory through the environment. These specify all flow. (p. 218)

Here, it is sufficient to note that computations regarding parallax (as well as other related phenomena such as the Doppler effect) come naturally and simply when the spectral domain as well as the space time domain are addressed in the computations.

This type of analysis of relationships among surfaces constitutes projective geometry. Johansson (Johansson, Van Hofsten, & Jansson, 1980, p.31) emphasizes the relational nature of projective geometry: In "projective geometry metrics has no meaning. Instead certain relations, the so called projective properties, which remain invariant under perspective transformations of a figure, are abstracted. One example [of] such invariance under form change is the cross ratio."

Cutting details how computing cross-ratios can account for the rigidity and flatness of perceived figures. When extended to such related techniques as density indices, all four space time coordinates are handled, giving rise to three-dimensional images. As already indicated, in the holonomic brain theory the optical image is already three- or more dimensional as is retinal processing. Furthermore, it is the optical image that veridically represents the properties of surfaces and objects in space time, not the optic array. Thus, the value of Cutting's approach, which is based on prior work by both Johansson and Gibson, is not as Cutting conceives it, to show how a two-dimensional retinal image can be processed into a three-dimensional experience, but to show how two-dimensional pictures and displays on an oscilloscope screen become experientially perceived as three- or more dimensional. The two-dimensional display can be thought of as similar to the experiment in mechanics where a ball rolling down an inclined plane is used to determine the basic laws that govern bodies in motion.

The cross ratio is, in most computations, the polar projection of four colinear points. However, the cross ratio has limitations: It "is confined to colinear or coplanar points ... [and] is confined to four and only four elements" (p. 115). Cutting indicated that these limitations are overcome by generalizing the cross ratio technique to a distance-density model as proposed by Krumhansel (1978).

Cutting shows that in order to perceive flat rigid surfaces rotating in space -- what in these lectures are considered to be images -- the distance-density model specifies the invariance processed by the perceptual system. For situations in which the organism approaches or recedes from such surfaces, distance-density models fail and flow vectors specify the invariant.

Here the distance-density model for image processing is more relevant. Cutting utilized several forms of the model and found that, when he used an exponential form, an infinitely dense array of points yields a density distribution that is uniform throughout -- in other words, the density distribution is little different from the perceived shape of the image.

Cutting (1986) cautions, however:

> I do not contend that index 4 [the exponential form] is a computational algorithm used by the visual system. I suggest only that it captures constraints on the information used for making perceptual judgments. I assume that the visual system performs some structure-through-motion analysis, perhaps along the lines proposed by Ullman (1979). I assume further that densities at various points in space around and on the object correspond to the sensitivities of the algorithms for determining a unique three-dimensional interpretation. In regions of high density the algorithm -- whatever form it takes -- should be sensitive to any point not in rigid relation to others, and in regions of low density it should be less sensitive. In other words, density measures predict the

> tolerance of the human visual system for small perturbations in the registration of the locations of particular points in the array. (p.120)

Two possibilities for understanding brain function in perception result from this assessment: (a) The fit of the exponential form of the model reflects the logarithmic form of the retinal configuration: "retinal fovea to periphery" in the cortical representation, and (b) the requirements of the human perceptual system can be expressed in terms of spatial frequency as well as density -- high density equals high spatial frequency, low density equals low spatial frequency.

The How of Perceptual Processing

Note that Cutting sharply distinguishes between the constraints used by the visual system, the "what is being processed" from the "how of processing." The question therefore arises as to whether the distance-density model has any relevance to neural processing in vision. If the approach taken in these lectures is correct, the answer is yes. What needs to be found is the set of transformations between the description of the invariants constraining the perceptual process and those constraining the description of the neural process.

When our interest lies in how processing takes place, we must look from the world of what is being processed as would an outside observer. Helmholtz (1863) stated the issue clearly:

> Let me first remind the reader that if all the linear dimensions of other bodies, and our own, at the same time were diminished or increased in like proportion, as for instance to half or double their size, we should with our means of space-perception be utterly unaware of the change. This would also be the case if the distension or contraction were different in different directions, provided that our own body changed in the same manner.
>
> Think of the image of the world in a convex mirror. The common silvered globes set up in gardens give the essential features, only distorted by some optical irregularities. A well-made convex mirror of moderate aperture represents the objects in front of it as apparently solid and in fixed positions behind its surface. But the images of the distant horizon and of the sun in the sky lie behind the mirror at a limited distance, equal to its focal length. Between these and the surface of the mirror are found the images of all the other objects before it, but the images are diminished and flattened in proportion to the distance of their objects from the mirror. The flattening, or decrease in the third dimension, is relatively greater than the decrease of the surface-dimensions. Yet every straight line or every plane in the outer world is represented by a straight line or a plane in the image. The image of a man measuring with a rule a straight line from the mirror would contract more and more the farther he went, but with his shrunken rule the man in the image would count out exactly the same number of centimeters as the real man. And, in general, all geometrical measurements of lines or angles made with regularly varying images of real instruments would yield exactly the same Euclidean results as in the outer world, all congruent bodies would coincide on being applied to one another in the mirror as in the outer world, all lines of sight in the outer world would be represented by straight lines of sight in the mirror. In short I do not see how men in the mirror are to discover that their bodies are not rigid solids

> and their experiences not good examples of the correctness of Euclid's axioms. But if they could look out upon our world as we can look into theirs, without overstepping the boundary, they must declare it to be a picture in a spherical mirror, and would speak of us just as we speak of them; and if two inhabitants of the different worlds could communicate with one another, neither, so far as I can see, would be able to convince the other that he had the true, the other the distorted relations.

Helmholtz's observation is relevant to the thesis of this paper: He notes that when two inhabitants of different worlds, in our case the worlds of psychophysics and neuroscience, try to communicate with one another, each would have difficulty in convincing the other that he had the undistorted view. Communication can only occur when both frames of reference, both worlds are acknowledged by discovering the transformations (e.g., the convexity of the mirror in Helmholtz's example) that connect them.

Movement is critical to the determination of the transformations that characterize the relationship between psychophysics and neuroscience. But more than movement is involved. Visual processing is ordinarily (see e.g., Hubel & Wiesel, 1962; Marr, 1982) assumed to result in images by way of a procedure similar to that proposed by Euclid: that is, the formation of lines or contours from points, the formation of two-dimensional surfaces from contours, and the formation of three-dimensional object-forms from surfaces. This assumption is fed by recourse to experiments in which two-dimensional pictures of three-dimensional forms are used -- and the illusions resulting from such use. The assumption also follows from the erroneous belief that a two-dimensional "retinal image" is formed by the optics of the eye. As noted, the optical image is a flow composed of at least three-dimensions, the retinal receptor surface is curved, and nystagnoid movement continuously changes the relationship of the optical flow to that which is being imaged. How then do the retinal receptors process the optical flow? Rock, (1983), suggests that because of movement,

> each stimulated retinal point signifies a distinct direction. Therefore one can interpret the outcome even of the typical conditions of form perception in terms of the collectively perceived occulocentric directions of the parts of a figure. This would already be a departure from the current emphasis on contour detectors. But we can take a step further. In humans and other species that move their eyes, the perceived direction of a point with respect to ourselves (referred to as egocentric or radial direction) is some joint function of retinal locus and eye position.
>
> We performed the following simple experiment (Rock & Halper, 1969). Condition 1: The observer fixates one luminous point while another moves around in a particular path in a dark room. Since the latter point traces an extended path over the retina, we can safely predict that its path will be discerned. However, the speed of the point is relatively slow, so that we should not expect a simultaneous iconic image of the entire path. Observers have little difficulty in perceiving the path in this condition. They are able to draw an accurate picture of it. Condition 2: The observer tracks a single luminous point as it moves along the same path as in condition 1 with no other point visible. Here no image is spread over the retina. Only a small region of the fovea is stimulated. However, by taking account of changing eye position, the perceptual system is able to detect the changing egocentric directions of the point. The result is that observers perceive the path of the moving point as well in this condition as in the first. Condition 3: The observer tracks the moving

> luminous point but tries to note the path of a second stationary point. The stationary point here produces an image that is successively spread over the retina. But the observer is unable to use this information and has no impression whatsoever of a path traversed by the stationary point. Position constancy obtains, which means that path perception is governed not by changing local sign but by changing egocentric direction. The stationary point does not change its egocentric direction.
>
> Therefore, no motion path is seen.
>
> A simple method of performing this kink of experiment is to move a narrow slit in an opaque surface over a luminous figure seen in the dark. Then only s single point of the figure will be visible at any time. This method is essentially one that has been referred to as the "anorthoscopic" procedure. (p. 46)

The results of this type of experiment contradict the common assumption that form perception follows the rules of Euclidean Geometry where points compose lines, lines compose planes, and planes compose solids. The primitives of form perception are not points or contours but relations between changes in oculocentric and egocentric direction. The occurrence of these directionalities implies the existence of oculocentric and egocentric frames of reference, that is, "spaces", which must be constituted in a top-down fashion. To repeat: Lines and edges are not the primitives that configure the perceptual process; lines and edges result from the perceptual process, they do not determine it.

A Computational Model

A similar conclusion was reached by Sejnowski and Lehky (1987), who devised a most ingenious computational model that takes advantage of the full richness of the optical image:

> One of the primary properties of a surface is its [three dimensional] curvature. ... The curvature of a surface along a line through the surface can be computed by measuring the second derivative of the tangent vector to the surface along the line. The principal curvatures at a point on the surface are defined as the maximum and minimum curvature, and these are always along lines that meet at right angles. The principal curvatures are parameters that provide information about the shape of a surface, and they have the additional advantage of being independent of the local coordinate system. Hence it would be helpful to have a way of estimating principle curvatures directly from the shading information in an image. (p. 9)

After reviewing the failure of other attempts to compute the shape of a surface from its shading, Sejnowski and Lehky decided to base their computation on the known properties of receptive fields of neurons in the ganglion cell layer of the retina. An input layer was constituted to consist of two superimposed hexagonal arrays of units, one array being made up of "on" and other of "off" units. Thus each point of the image is sampled by both on and off units. The response characteristic of the receptive field of each unit is the Laplacian of a two-dimensional Gaussian, in other words, the typical center-surround organization of receptive fields recorded from the optic nerve. Responses of these input units to an image were determined by convolving the image with the units' receptive fields. This procedure was used by Rodieck (1965) to describe the functions of the retina on the basis of actual recordings (Rodieck & Stone, 1965) and formed one of the cornerstones of holographic theory (Pribram, Nuwer, & Baron, 1974).

Simulation of these procedures in a computational model adds considerably to our ability to portray just how the sensory process operates: "Besides being biologically plausible, choosing these particular input receptive fields was advantageous from a computational view...: the responses of these center-surround receptive fields, acting as second derivative operators, tended to compensate for changes in appearance in the object [illuminated] from different directions" (Sejnowski, 1976). I am sure Ernst Mach (see e.g., Ratliff, 1965) would be especially pleased to see this aspect of the model in operation.

The model programs the receptive fields of the output layer in terms of graded responses, which are a function of both the value of the principal curvatures as well as their orientations: in short, the phenomenological descriptors of the image. This accords with the assumption made in the initial lecture that phenomenal experience is coordinate with the junctional dendritic microprocess, which is composed of graded polarizations.

However, a problem emerged in that the signal from each unit is ambiguous: There are an infinite number of combinations of curvature and orientation that give rise to anidentical response. "The way to [re]solve this ambiguity is to have the desired value represented in a distributed fashion, by the joint activity of a population of such broadly tuned units have overlapping receptive fields in the relevant parameter space (in this case curvature and orientation)" (Sejnowski, 1976).

This kind of distributed representation is found in color vision. The responses of any one of the three broadly tuned color receptors is ambiguous, but the relative activities of all three allow one to precisely discriminate a very large range of colors. Sejnowski and Lehky (1980) noted the economy of coding such an arrangement: "It is possible to form fine discriminations with only a very small number of coarsely-tuned units, as opposed to requiring a large number of narrowly-tuned, nonoverlapping units".

From the neurophysiological viewpoint the most interesting aspect of the model is the development of receptive field configurations in the middle, hidden, layer of the model. Recall that only the first layer of the model was programmed according to physiological constraints, that is, those that configure the ganglion cell layer of the retina. The configurations of the unprogrammed middle layer come to show a remarkable resemblance to those in the primary visual receiving region (the striate visual cortex). Many of these units had oriented receptive fields. Two classes of such fields were identified on the basis of their connections with output units: those that discriminated for the direction (vertical columns), and those that discriminated the magnitudes of the principal curvatures (horizontal rows). The "receptive field" of a point operator is a 2 or more dimensional Gaussian envelope. By receptive field is meant the geometric differentiation of the point. In this manner a bilocal entity such as direction encoded as a vector has as its "receptive field" an edge finder and its second derivative maps into a "bar detector". Koendrik has shown that the range of receptive fields mapped in the primate visual cortex can be described within the first four order of differential geometry. The layers of the computational network, artificial and natural, appear to be performing operations of this sort.

From the standpoint of understanding the neurophysiology of perception, there is a critical conclusion to be drawn from the experiment: "The network model provides an alternative interpretation of these properties [of cortical neurons which are ordinarily conceived as line or edge detectors], that they can be used to detect shape from shading rather than edges."

Shading is spatially four-dimensional because it varies over height, width, depth, and time with movement. Retinal processing, if shadings (and textures that can be conceived as microshadings) are to be utilized, must be more than two-dimensional. As noted, retinal receptivity is in the range of photons, quanta of radiant electromagnetic energy, and therefore sensitive to phase--that is, direction. This gives the process sufficient degrees of freedom to allow the type of multidimensional processing espoused by Senjowsky and Lehky (1987). As they reported, the model must still overcome some remaining difficulties: "In the curvature domain, unlike the orientation domain, we have a set of non-overlapping tuning curves, and therefore curvature is not well represented in the model in its present state." The curvature domain should be sampled more densely. This is certainly the case in the actual retina and the quantal approach of the holonomic brain theory directly addresses this issue; the issue of grain that was the theme of the early parts of this paper.

Summary

The facts of optical processing by lens and pupil are agreed upon and therefore make a good starting point for an examination of the perceptual process. Distinguishing between processing performed by the optics of the eye from that performed by the retina allows for the occurrence of a moving optical image or flow. This flow is not two-dimensional, however, but richly multidimensional. The multidimensionality is complemented by the richness of the retinal receptor process. A computational approach to modelling the retinal process is not only feasible but has been begun with results that lead to the simulation of the receptive field properties of cortical neurons in the visual system. The computations are based, not on the construction of two-dimensional stick figures from lines and edges, but on shadings of curved (and colored) three-dimensional images as they are experienced.

This rich multidimensionality of the optic array and the optical flow that is preserved and complemented by retinal processing resolves "the grain problem" but poses an additional hurdle for direct perception. As Cutting (1986) pointed out, Gibson's program of identifying invariants leads to a plethora of dimensions potentially useful in perception. This means that selection must occur at the various processing stages. Selection can be passive, as by filtering, or active and directed by the accumulation of the results of prior selections. According to the evidence that makes up the foundations of the holonomic brain theory, sensory, driven, essentially passive selection characterizes the configural aspects of perception. On the other hand, because of the amount of memory storage involved, cumulative, directed selection characterizes the cognitive aspects. As noted in the previous lectures and brought out more fully in those to come, the results of prior selections become stored not only in the primary projection systems but also in neural systems separate from these primary systems. These "higher order" systems are triggered by current sensory input to initiate directive procedures that operate back on the sensory driven processes by way of top-down neural connectivity: Thus directive and selective neural processes interpenetrate. Perception results from the transformational character of these interpenetrations.

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