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## GEOMETRIC AND PHYSIOLOGICAL ASPECTS OF DEPTH PERCEPTION

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### Introduction

Seeing in depth is such a natural and automatic part of human experience that its basis has remained largely unconscious, taken for granted. Indeed, it took some of the most inventive minds of the Italian Renaissance to overcome the automatic tendency of seeing objects in depth and at their true size. Only after an intense effort did they realize that to paint depth required something much different than painting what was seen, requiring instead an entirely new type of geometry, the geometry of perspective. So it seems that the geometrical study of depth perception has had a very long and interesting history, becoming a highly developed discipline long before the rise of modern science.

More recently (over the past 150 years), there has been a revival of interest in the perception of depth, this time a scientific one. Experiments indicate that in addition to linear perspective, there are a wide variety of different cues to depth, including: interposition, height in the visual field, texture gradients, shading, binocular and monocular parallax, etc. In this paper I shall restrict myself to just two cues to depth: binocular parallax and monocular motion parallax. I restrict myself to these particular cues not because they loom as the most dominant cues for our own perception of depth, for they do not; stereoscopic depth, for example, can lose out when pitted against other familiar monocular cues (Gregory, 1970). Rather, they are chosen because of all the cues to depth, they appear to have a certain biological primacy and have, I think, the best chance of being understood at a fundamental and physiological level.

### Binocular Vision

The importance of two eyes for the perception of depth has been long recognized. Leonardo da Vinci, for example, acknowledged the impossibility of truly imitating nature even by the most skillful painting on a surface, recognizing the necessity of differing views afforded by the two eyes (Gregory, 1970). The importance of this idea became much more appreciated, however, with Wheatstone's invention of the stereoscope. This simple, yet brilliant device demonstrated that the array of different retinal disparities is synthesized by the nervous system to form a perception of solidity. Furthermore, it became clear that differences in horizontal disparities were crucial for the appreciation of depth.

The neuro-anatomical substrate for this synthesis was also recognized rather early, by Newton in 1717 and later by the renowned physiologist, Johannes Müller. Nerve fibers from each eye reach a common area in the cortex by the existence of crossed and uncrossed connections through the optic chiasm. Microscopically, the results are of even greater interest, for it can be shown that nerve connections representing corresponding parts of each retina are not only destined to approximately the same area of the cortex, but they are wired so as to converge onto the same single cell. For example, Hubel and Wiesel (1962) discovered that single cortical neurons receive a very specific input from each eye such that the size and orientation of a bar which optimally stimulates the cell through one eye is the same for the other. Even more spectacular was the later discovery of Barlow, et al. (1967) and Nikara, et al. (1968) showing that each of these cortical cells responsive to properly oriented bars is also sensitive to a preferred retinal disparity. Furthermore, this disparity varies from cell to cell. It should be recognized that an array of such cells could begin the process of coding depth, the brain need only note which cells were active in its computation of disparity. Other work appears to disagree on some important details (Poggio, 1976) confirming, however, the existence of a differential sensitivity to disparity at the single cell level. Although the specifics remain unresolved, the existence of such a class of cells raises the hope that the seemingly higher order sense of depth is in principle understandable in terms of a network of cortical neurons just 2 synapses beyond the eye. Julesz's creation of random dot stereograms (1960) reinforced this hope, affirming that the analysis of depth is likely to be a relatively early process, prior perhaps to higher levels of form processing.

Much remains to be done, however, and there are a number of fundamental issues that await resolution. Not the least of which is the problem of how these cortical disparity detectors can be sure to match up the correct corresponding image fragment of the right eye with that of the left, a problem which seems especially acute when thinking about the analysis required to process random dot stereograms. Spurious matches between points in each eye would seem to be frequent, but the clean percept of depth obtained suggests that they are not. Several solutions to this problem have been proposed, ranging from Julesz's ingenious dipole model (Julesz, 1970) to speculations cast in more neurological terms (Sperling, 1971; Nelson, 1973). These models suggest more complex and cooperative interactions of different elements sensitive to disparity, recognizing the insufficiency of a homogenous array of independent disparity detectors.

My own approach to binocular depth has been slightly different. Instead of addressing the problem of depth directly, by investigating the conditions under which depth is seen and not seen, I have been interested in a more primitive problem, the geometry of binocular correspondence - I pursue this with the hope that by such an investigation, one can develop an alternative, yet complimentary perspective, when dealing with current questions.

### Binocular Correspondence

The problem of binocular correspondence has had a related, yet distinct, history in comparison to the study of stereopsis. The traditional approach to the problem has been the theoretical and empirical delineation of the horopter, the locus in space of points stimulating corresponding retinal points. What is assumed is that these corresponding points give

rise to the perception of the same visual direction, presumably because in some real sense they project to a common brain locus. Except for certain pathological conditions, for example, it has been well established that the fovea centralis of each eye is in correspondence (Hering, 1868); thus, stimulation of each fovea in succession leads to the percept of points originating from the same direction. In addition, for each point off the fovea, there is in theory a point in the other eye which can be considered to be in correspondence, this point being seen in the same direction. It must be emphasized that, in order to determine this correspondence experimentally, one must stimulate each retina successively or with dissimilar images, because it is well known that a simultaneous stimulation of a point over a wide area of one eye (Panum's fusional area) is fused as a single percept when paired with a single point in the other. Thus, one cannot localize the correspondence between the two eyes with any greater precision than Panum's area, an area which grows rapidly in size as one proceeds away from the fovea. When one stimulates successively, however, preventing the opportunity for fusion, one can make a precise determination of correspondence. This procedure, commonly known as the nonius method, is recognized by many to be the most unambiguous method of determining binocular correspondence (Shiple and Rawlings, 1970). Before discussing the experiment measurements of the horopter, however, we need to turn to a discussion of some geometric points, for, without this, the meaning of the experimental findings will remain obscure.

Predictions and Insights from Geometry

Historically, it was initially assumed that each eye could be considered as geometrically congruent with the other; thus, points with the same angular relationship from the fovea in each eye could be considered as corresponding points. Figure 1 from Hering (1862) schematizes this assumption. Although not strictly true (and we shall discuss this later), it provides an important starting point. The most well known consequence of this assumption is the Vieth-Müller circle, the space of locus of points in the horizontal plane which are imaged on corresponding geometric points in each of the two eyes. This circle, dating back to Aguilonius (1613) is valid for the special case when the eye is fixing in the horizontal plane and it follows from the fact that all angles drawn from the nodal points of the two eyes to the circle are equal (see Figure 2).

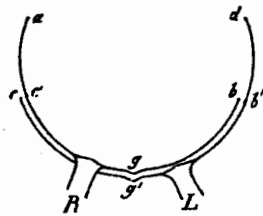


Figure 1

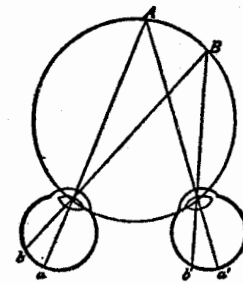


Figure 2

The form of the horopter outside of this horizontal plane, however, has received little attention. Furthermore, there is even wide confusion and misunderstanding regarding its theoretical form, a mathematical point which should be unambiguous. One common misconception is that the theoretical horopter is a curved surface, part of a pinched torus formed by rotating the Vieth-Müller circle around the interpupillary axis. In fact, the theoretical horopter in the vertical dimension is, in general, not a surface, but either a space curve or a line, depending on the exact direction of fixation and torsion of the eye (Helmholtz, 1860, 1910; Hering, 1864). For example, in the case of symmetric convergence in the horizontal plane (and, for simplicity, we restrict ourselves to this case), the vertical dimension of the theoretical horopter is simply a vertical line, passing through the fixation. That there are no other points above and below the horizontal plane can be appreciated by noting that any such points in space will be closer to one eye than the other and will, therefore, be imaged at different elevations above and below the horizontal meridian of each retina. In sum, for the case of symmetric convergence in the horizontal plane, the theoretical horopter is simply the Vieth-Müller circle intersected by the vertical line horopter at the point of fixation (Figure 3).

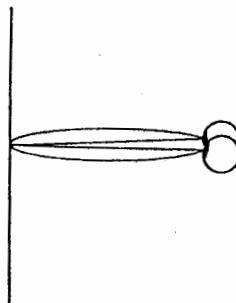


Figure 3

So, in its stark and skeletal form, the horopter provides us with the locus in space of points sharing the common property of having zero angular disparity. Because it provides us with a theoretically determined set of null points which can be verified psychophysically, it is a useful and indispensable concept. It suffers greatly, however, because it neglects the nature of binocular correspondence over the whole binocular field, leaving unspecified the way in which this correspondence might vary from zero disparity away from this horopter line.

More informative would be to provide a more complete and quantitative spatial representation of the nature of binocular correspondence, assigning to each point in space a vector describing the relative angular disparity (both horizontal and vertical) of each point and noting the overall characteristics of this vector field. For example, assuming that the torsion of the eye is determined by Listing's Law (Helmholtz, 1910; Nakayama and Balliet, 1977), one can calculate the relative angular disparity for each point in space for any particular point of fixation. In terms of the special case of symmetric convergence mentioned earlier, I have plotted three such disparity fields (see Figure 4), each associated with points on a frontal parallel plane either in front of, at, or behind the point of fixation. Below each vector disparity plot is a view from above showing the relation of the plane to the point of fixation and the Vieth-Müller circle.

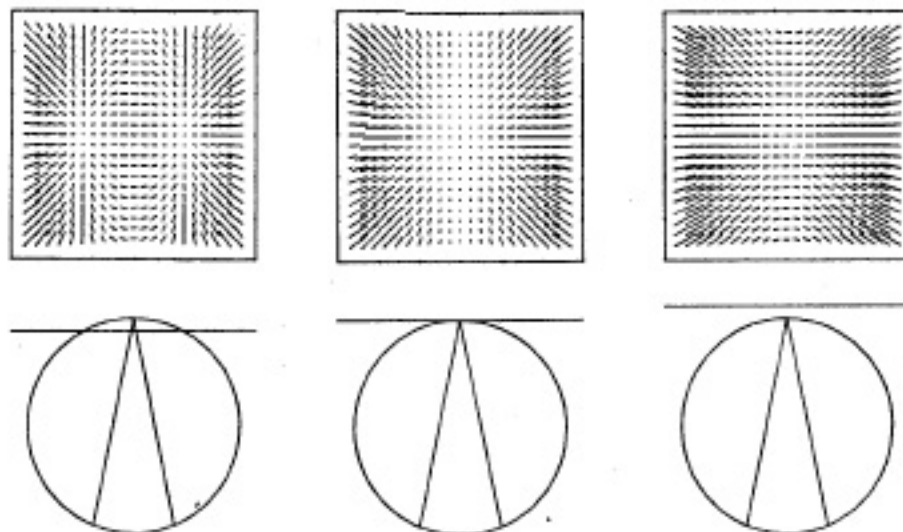


Figure 4

With the plane in front of the fixation (see the left-most field) the disparities are crossed in the middle section of the plane (represented by rightward pointing arrows) and they are uncrossed to the extreme left and right. Only two points in this plane are horopter points. They lie in the horizontal plane to the right and left of the fixation, corresponding to the intersection of the frontal plane with the Vieth-Müller circle and they are plotted as dots. Points above and below these points have a vertical component of disparity. When the plane includes the point of fixation (center), one can observe a vertical column of dots representing the zero disparity locus of the horopter in the vertical dimension, the vertical horopter line. The right-most plot represents the plane behind the fixation. All points on this plane have uncrossed disparity (arrow heads to the left), confirming that no part of the horopter passes through this surface. What is of interest is the rise of the vertical component of angular disparity as we go further away from the median plane. As mentioned previously, this is due to the fact that points off this median plane are closer to one eye than the other, leading to vertical disparities. Although this point is generally ignored in the discussion of stereopsis and binocular vision, it might help explain the wide range of preferred vertical disparities obtained when recording from single neurons in the cat cortex (Joshua and Bishop, 1970).

What is of additional interest is the overall shape of these disparity fields, showing a continuous, yet different, change in disparity for horizontal and vertical components. Julesz's dipole hypothesis suggests that corresponding elements projecting from one eye link up with points in the other. If so, it follows that for a fusional lock without spurious correlations, whole projection areas containing these points will require the equivalent of a highly nonuniform stretching just to view a planar surface. It turns out that this stretching can be handled rather nicely by the spring coupled flexibility of Julesz's model. Since these distortions or stretchings would seem to be required in everyday binocular circumstances with simple surfaces, it gives further credence to the view that the issues raised by this model must be confronted.

Another characteristic of these disparity fields is its very different form as it is moved just slightly in front of or in back of the point of fixation. Clearly, such changes will also occur with changing fixation. Yet, it is our common experience that the apparent depth and slant of a surface remain invariant under such shifts. In order to explain this invariance or constancy, Koenderink and van Doorn (1976) have made what seems to be a brilliant mathematical analysis of these binocular disparity fields. Locally approximating the field on any given surface as the first two terms of a power series, they calculate the gradient of this vector field. The resulting tensor can be decomposed into identifiable components, familiar to those acquainted with the mechanics of deformable materials: a dilation, a rotation and a

deformation. What is noteworthy is that for a given surface, the deformation component remains invariant under a wide variety of conditions, including changes in fixation. Furthermore, the authors propose a neural model of how this deformation could be coded, resembling in many respects the orientation disparity units described by Blakemore, et al. (1972). Although it is an impressive analysis, further work is required to evaluate its validity. What is encouraging is the fact that the relatively well known and highly developed method of tensor analysis is potentially applicable to the problem of perception. Perhaps there are other higher order invariants of the optic array, just waiting to be identified, using similar concepts from applied mathematics or engineering. In the last section I briefly described another possible invariant related to the perception of depth, this one related to the optical velocity field.

In sum, it should be noted that a strictly geometric analysis of binocular correspondence can raise some unique issues, relating to the possible physiological analysis of depth, providing, in addition, a set of expectations from which one can interpret empirical measurements of the horopter.

#### The Empirical Horopter

Actual measurements of the horopter using the criterion of equal visual direction mentioned earlier have been conducted for at least 100 years, concentrating almost exclusively on the horopter in the horizontal plane. Surprisingly, the measured horopter in this plane is not the Vieth-Müller circle, but is a much flatter curve, commonly known as the Hering-Hillebrand deviation. Although space does not permit a detailed exposition of this point, it should be noted that such a deviation is generally interpreted in terms of a slight departure from the principle of geometrical correspondence, relying on the more flexible, yet orderly, anatomical projection of the two hemiretinae onto the common hemicortex, doing so in such a way that the neuroanatomical magnification of the projection of the temporal retina is slightly different than the nasal. Minute differences in this magnification could lead to sizeable differences in the horizontal horopter and this issue has been treated in mathematical detail by Ogle (1964).

Due in part to the confusion regarding its theoretical form, there have been very few measurements of the vertical horopter line. Aside from a lively concern by Helmholtz and his contemporaries, there has been essentially no further interest in this subject. The key 19th century observation was that when each eye was fixing separate and dissimilar vertical targets (a black thread and a blue ribbon, for example), there was an apparent tilt when viewing these targets binocularly, such that the lines had to be extorted with respect to each viewing eye to be seen as parallel (Helmholtz, 1910). Inasmuch as the targets were not fused, this experiment is essentially variation on the nonius method, this time using an orientation criterion. It specifies the horopter not as a series of points, however, but merely as a point at the fixation and a slope. Extrapolating from this single data point at the fixation, Helmholtz argued that the vertical horopter consisted of a straight line tilted away from the observer, being the line passing through the fixation and one's feet! Thus, with increasing distance to fixation, the vertical horopter line is flatter and flatter, becoming horizontal at infinity. Figure 5 shows the different horopter lines calculated for different fixations made in the horizontal plane.

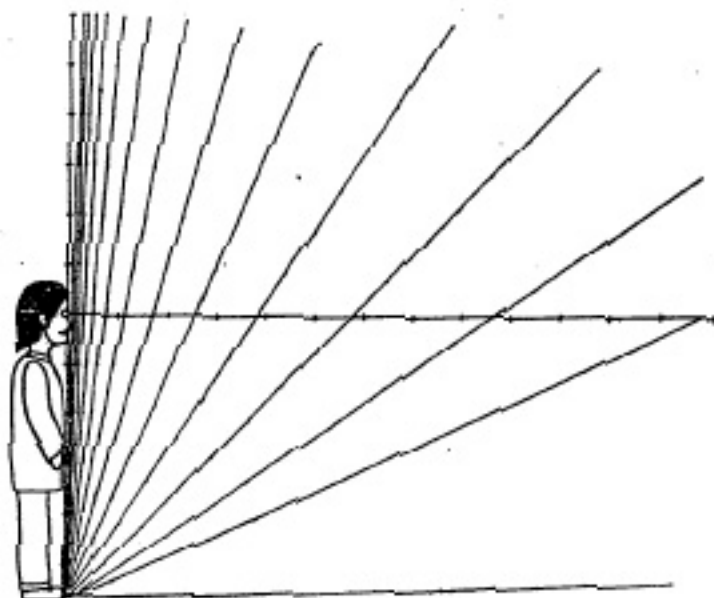


Figure 5

In order to explore this interesting, yet forgotten, subject, we have made more complete measurements of the vertical horopter over a 60-degree range of elevation (Nakayama, Tyler and Appelman, 1977).

Experiment: The Vertical Horopter is Tilted Back

We placed observers in a completely dark room. They saw a binocular fixation cross (labelled B in Figure 6) accompanied by 2 monocular half-images to control for fixation disparities; these are labelled L and R and are immediately above and below this cross. Further away and at various distances we placed two light-emitting diodes, each one which could be seen by only one eye or the other. These were flashed in succession and the task of the observer was to discern the apparent direction of motion as they were alternated. As the experimenter moved the relative horizontal position between the two lights, a point could be found, and reliably so, where there was no apparent movement between the successively presented lights. Thus, at this point, the dots appeared to come from the same visual direction.

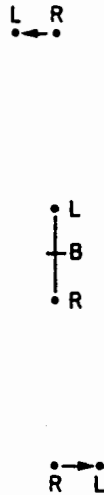


Figure 6

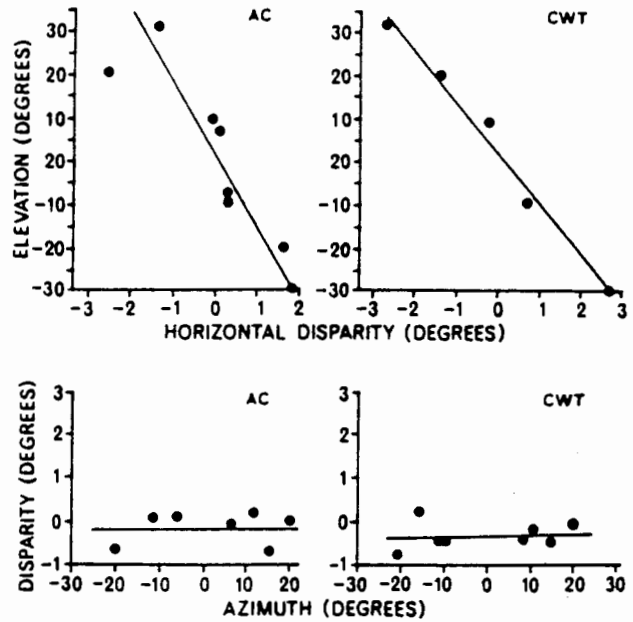


Figure 7

Of great interest was the fact that Helmholtz's supposition was confirmed. Instead of remaining constant, the disparity required to obtain the criterion of equal visual direction varied with elevation above and below the fixation, such that for points further below the fixation, the disparities were more and more crossed, and the opposite was true for points above. The horizontal disparity as a function of elevation is plotted on the upper graphs of Figure 7. Note the steady increase of crossed disparity as one goes from the lowest to the highest elevation, reaching a total range of disparity difference of 4 to 6 degrees. These results indicate that there is indeed a backward tilt to the horopter line and it is a very large one, an even greater tilt than that measured by Helmholtz.

Why are points on oppositely tilted vertical lines in correspondence? The simplest reason, of course, could be the existence of a disjunctive exocyclorotary eye movement about the visual axis. To check this possibility, we conducted one additional experiment. This time, we had the test lights arranged at various distances to the left and right, asking observers to judge whether the alternatively presented lights were up and down with respect to the other (Figure 8), looking for an identity of visual direction as the vertical disparity was varied. If the tilt of the horopter obtained is due solely to eye torsion, there should be a systematic change in vertical disparity as a function of lateral distance away from the fixation. The lower set of two graphs in Figure 7 shows that no such change is apparent. We must conclude, therefore, that the horopter line is indeed tilted and that this tilt is not due to eye torsion, but is due to yet another departure from a strict principle of geometric correspondence. Oppositely tilted vertical lines in each retina contain points which are in correspondence and this is not the case for points along horizontal lines. Thus, there appears to be a shear or skew transformation when considering the relative projection of retinal coordinates to the cortex. It suggests, furthermore, that the boundary of the nasal versus temporal retina, the dividing line between contralateral and ipsilateral projection, is, in fact, not the vertical meridian of the retina, but is one which is tilted in the opposite direction for each eye.

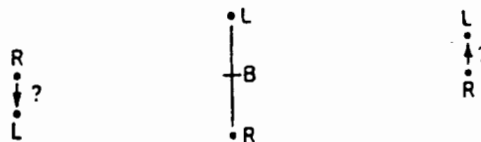


Figure 8



Not only does this slanted line represent the locus of points seen in the same visual direction, but it also appears to be related to the space locus of best stereoscopic vision. For example, Julesz, Breitmeyer and Kropfl (1976) reported an interesting anisotropy associated with stereoscopic vision using random dot stereograms. They found that quickest stereopsis occurs either above and in back of the fixation or below and in front, corresponding closely to the location of the vertical horopter line (see Figure 9), a finding which further validates the horopter concept in relation to stereopsis. The implications of this tilt are of some practical biological interest for they imply that the line locus of maximum correspondence is not a vertical line in front of the two eyes, but one slanted back. Only a moment's reflection is required to recall that this is, indeed, a very typical case in which we use our eyes, either looking at a book slanting backwards from our line of sight or when we are walking along the ground and looking ahead. Whether this tilted line of best correspondence is a result of just these types of experiences (Helmholtz's view) or whether they reflect pre-wiring to adjust for this experience remains, as yet, unresolved.

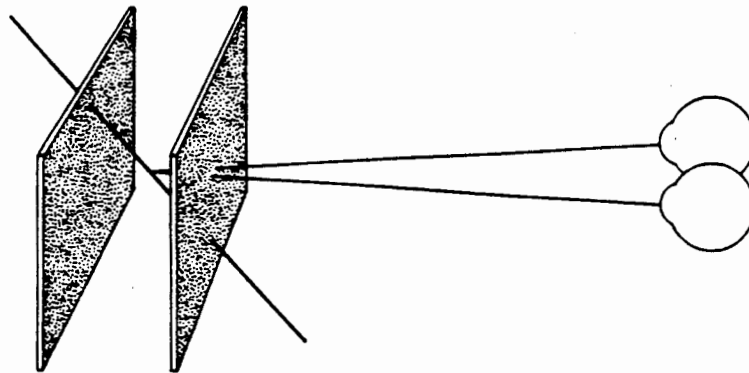


Figure 9

#### Motion Parallax

Although it goes without saying that binocular parallax is a very important cue to depth, it should also be noted that animals with very little in the way of binocular overlap can maneuver skillfully and quickly through complex obstacles. Birds, for example, can fly through thickets and branches, avoiding collision. Infant and newborn animals tested on the ingenious visual cliff (Walk, 1965) show depth discrimination to be an essentially innate capacity with further experimentation demonstrating that much of the ability is monocular, mediated by differential optical motion of near and far surfaces. Such instances emphasize that, in addition to binocular parallax, motion parallax is an especially important cue to depth, suggesting further that, like binocular disparity, it can operate prior to the recognition of patterns.

Thus, it appears that there is something special about motion parallax for it alone appears to provide important monocular information regarding the layout of surfaces in depth, independent of a complex analysis of form. And since there is some evidence that the recognition of form is analyzed separately from the coding of space (Schneider, 1969; Trevarthen, 1967), there is, I believe, good reason to investigate motion parallax as a special spatial sense; not only because it might well be an isolated subsystem amenable to a physiological interpretation, but because it could provide new insights as to how man-made devices could become aware of depth without resorting to an analysis of form.

Starting from the provocative writings of J. J. Gibson (1950), my own contribution, in collaboration with Dr. Jack Loomis, is to further specify the nature of the optical flow pattern in geometric terms, developing from this analysis a plausible way in which fairly low level neural mechanisms could process these velocities to obtain useful depth information. Much of this has been described in detail in a longer paper (Nakayama and Loomis, 1974).

#### Geometric Aspects

First, we need to describe the optical velocity pattern on the retina of an eye moving through a rigid environment, relating particular aspects of this flow pattern to the distances of objects. Under a simple translation of the eye, the resulting flow pattern is very simple, with the angular velocity of each point ( $\omega$ ) being determined solely by the velocity of the eye ( $V$ ), the distance of the object ( $d$ ) and the angle ( $\alpha$ ) between the particular point and the direction of motion:

$$|\omega| = \frac{|V| \sin \alpha}{d} \quad (1)$$

Such a relation indicates that, in theory, all distance values can be reconstructed from other available information. For simultaneous translation and rotation of the eye occurring when the head is translating and the eye is rotating to maintain fixation, or when moving in curvilinear motion, the situation is only slightly more complex. It can be shown that, under these circumstances, there are two and only two optical velocity vector fields, a field associated with translations,  $\vec{\omega}_T(a, \beta)$  where the distances of objects is important and a velocity field due to rotations ( $\vec{\omega}_R(a, \beta)$ ) where the distance of objects is irrelevant. Furthermore, in any local region, the rotational field is nearly uniform. In structure, each individual field is

extremely simple, with the direction of all velocity vectors being determined by only one parameter in each case; the direction of the translation in the former and the instantaneous axis of rotation in the latter. For conditions where the eye is both rotating and translating, the resulting optical flow field is simply the vector sum of these two fields:

$$\vec{\omega}(\alpha, \beta) = \vec{\omega}_R(\alpha, \beta) + \vec{\omega}_T(\alpha, \beta) \quad (2)$$

#### A Possible Physiological Analysis of Optical Flow

Since the optical velocity field under any conceivable type of observer motion has a high degree of redundancy and since the rotational field  $\vec{\omega}_R(\alpha, \beta)$  can be treated as locally uniform, we (Nakayama and Loomis, 1974) proposed that one rather useful way the nervous system could extract information regarding the layout of surfaces would be to take integrated differences in velocity in several component directions over a center and surround region. Figure 10 shows a hypothetical neuron type which, if distributed over the whole visual field, would tend to perform an analysis akin to taking the second spatial derivative with respect to velocity, picking up the nonuniformities in velocity associated with the edges of surfaces at different depths.

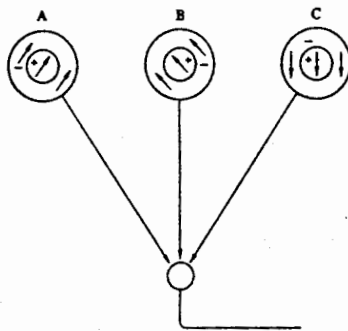
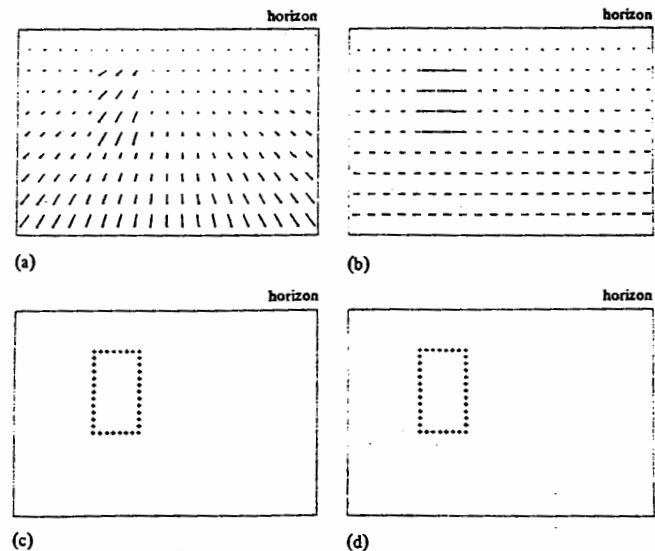


Figure 10



Planar representations of the velocity field of an observer who is (a) approaching a vertical rectangular screen which is off to the side and above the surface plane, and (b) passing a vertical rectangular screen in a direction parallel to the screen; and spatial response profiles (c) and (d) of a layer of the hypothesized 'convexity' cells for the motion in (a) and (b) respectively.

Figure 11

Such a class of cells would pick out these edges, regardless of the direction of the velocity field. For example, in Figure 11, we show two velocity vector fields, one associated with moving straight ahead, the other to the right. Both qualitatively and quantitatively, the fields are different. After an analysis by a mechanism similar to that depicted in Figure 10, however, they share a great similarity in form; in each case, the outline of the object becomes delineated. The general idea gains plausibility, if we consider the ubiquity of special classes of neurons devoted to movement in nearly all animals studied (Grüsser, et al., 1968). Such a process would not only be informative about the relative depth of adjacent surfaces, but could provide information regarding the distinction between figure and ground, an important, yet often overlooked, capacity. Such a scheme is clearly speculative and, although there is some fragmentary evidence that there is a center surround antagonism with respect to velocity (Sterling and Wickelgren, 1969; Loomis and Nakayama, 1973), more direct evidence is needed.

#### Conclusions

Although the issues in each case presented are diverse, it should be clear that there is a definite role for using geometrical concepts, both to frame questions and to provide possible answers regarding the physiological organization of depth perception. What is of especial interest to me is the fact that at this meeting there are scientists with an interest in three-dimensional imaging from many diverse fields; image processing, photogrammetry, etc. - fields which may have great relevance for a physiological understanding of human depth perception. I look forward to a stimulating program and wish to thank the organizers for the invitation to participate in this conference.



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