Chapter 10
VISUAL SPACE PERCEPTION

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1. EGOCENTRIC COORDINATES

The three-dimensional environment around us provides a Euclidean framework for our own perception of spatial relations. The external Euclidean cues to these relations may be broadly categorized as static, if the observer is stationary, or dynamic, as when he locomotes or when objects move with respect to one another in the same neighborhood. Within these two broad categories, all the physical cues to spatial relations can be itemized as in the first column of Table 1. Of course, having identified these available cues says very little about visual space perception, for we have not demonstrated that the human observer is, in fact, able to use these cues.

Although object relations in the environment can be described in terms of a Euclidean coordinate system, it is not clear that such a coordinate system offers the best framework for describing human space perception. Other obvious possibilities include cylindrical, polar, or spherical coordinate systems. Even though any one of these coordinate systems is just a transformation of the others, it is desirable that the coordinates we choose be close to those which the observer uses, for then we can see more directly how he is handling spatial information.

TABLE I
CUES TO SPATIAL LOCALIZATION

Physical cue	Notations	Neurophysiological basis	Physiological Response
1. *Principal Axes*			
A. Primary (fore-aft body movement)	$d\theta/dt = d\phi/dt=0$	No flow	Orientating, fixation
B. Secondary (gravity)	$\phi = \pm90°$	Vestibular	Righting
C. Left-right	$\theta = \pm90°$	Hemisphere	Turning
2. *Monocular*			
A. Static			
(*i*) Direction	θ, ϕ	Direction columns	Saccade
(*ii*) Size	$\Delta\theta, \Delta\phi$	Unknown	
(*iii*) Gradient	$d\theta/\theta,$ $d\phi/\phi$	Orientation columns, Spatial frequency channels	
(*iv*) Intersections	"T"	Hypercomplex units	
B. Dynamic			
(*i*) Mean movement	$d\theta/dt,\ d\phi/dt$	Motion detector	Pursuit
(*ii*)Self-induced parallax	$d\theta/dt$	Unknown	
(*iii*)	$\Delta(d\theta/dt)$	Unknown	
3. *Binocular*			
A. Static			
(*i*) Absolute distance	R	Unknown	Accommodation
(*ii*) Relative distance	ΔR	Disparity columns	Vergence
(*iii*) Gradients	dR/R	Unknown	
B. Dynamic			
(*i*) Flow	$dR/dt, dR/R \bullet dt$	Unknown	
(*ii*) Binocular shear	$\Delta(dR/dt)$	Unknown	Vergence tracking

    The coordinate system we have chosen as the most informative is a spherical system centered on the observer (Fig. 1). This is an egocentric coordinate system. In such a system, two primary directions must be defined to represent the axes of the framework, as well as a unit of radial distance. The first obvious reference axis is "straight ahead." When the observer is moving, the straight ahead axis is defined unambiguously by the direction of his motion vector. When stationary, this reference axis is ambiguous, but is generally taken as the direction of forward movement. When the body is in motion the axis is particularly unique, because it corresponds to the direction of the

vanishing point of the flow patterns induced by the forward motion through an environment, as shown in Fig. 2. We define this direction as the primary direction. Orthogonal to this direction is a second axis naturally defined for the earthbound observer: the gravity axis. This axis may be determined in part by vestibular sensations but is primarily specified by the visual cues of the environment which are subject to gravity constraints, such as the verticality of trees and buildings as well as the horizon itself (Gibson, 1950).

Together, these two coordinates permit a specification of any visual direction in terms of the horizontal angle θ with respect to the primary visual direction $\theta = 0$ and the vertical elevation ϕ, with $\phi = 0$ in the horizontal plane and $\phi = 180$ in the vertical as determined by the gravity cue. Given a visual direction specified by θ and ϕ, a radial distance R must then be specified. We will arbitrarily chose as a unit for R the height of the observer's eyes above the ground. (This unit has the advantage of being correlated with interpupil distance, and, hence, tends to make the relation between radial distance and disparity invariant with the age of the observer.)

For a proper understanding of visual space perception, it is important to recognize that the two primary axes for the egocentric coordinate system
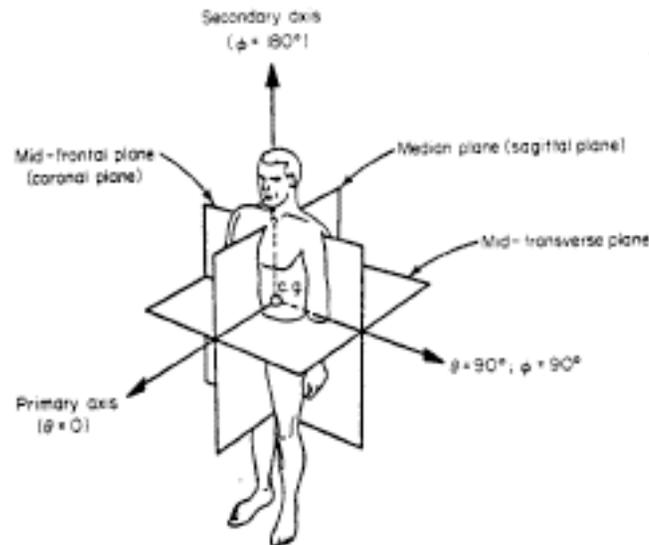

Fig 1. Body-centered coordinate system. The primary axis points in the direction of forward motion. The secondary axis corresponds to the gravity axis. Angles a and 0 are taken, respectively, in the transverse and sagittal planes. [Adapted from Howard & Templeton (1966).]

are not necessarily absolute and fixed but instead are set to some degree by the observer himself based upon information available to him. For example, although the gravity sense provides an absolute reference for the vertical meridian, it is not necessary for the observer to have his own gravity detector. Because gravity acts upon everything in the environment, it is only necessary to know that trees are vertical and buildings have vertical edges and that the horizon is horizontal, With this knowledge, even if you tilt your head and had no vestibular sensations you could still deduce the secondary direction. In fact, these components of the visual scene may override the vestibular cues when an internal egocentric frame is constructed (Dichgans, Held, Young, & Brandt, 1972).

The primary direction is likewise indicated solely by relative information available to the observer through the visual input, regardless of head or body position. The primary direction is constrained only by the direction of locomotion of the whole body, regardless of where the observer fixates.

For example, if the observer is fixating off to one side away from his direction of movement, the asymmetric flow patterns on the retina will indicate that fixation is not in the primary direction. As shown in Fig. 3, asymmetric flow patterns will result whenever the fixation point does not correspond to the vanishing point of flow set up by the body motion. Thus the primary
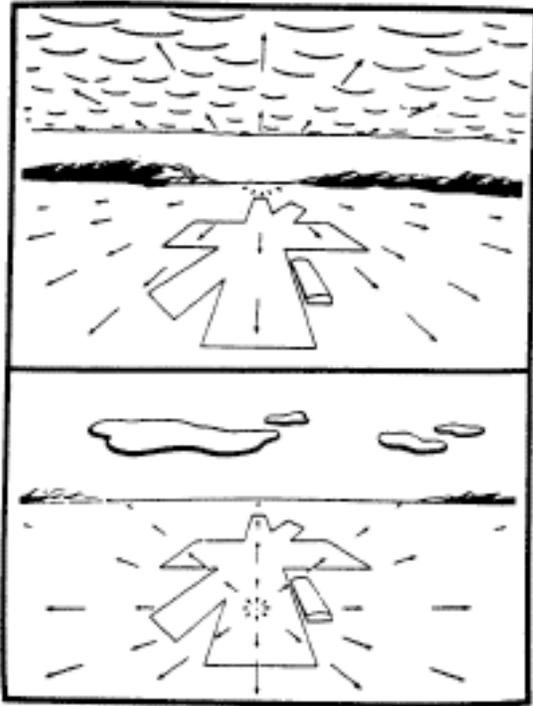

FIG. 2. Flow patterns induced by motion through an environment, in this case by a pilot during level flight (top) or during landing (bottom). The primary axis points toward the source of the flow. [From J. J. Gibson, *The Perception of the Visual World,* Boston: Houghton Mifflin, 1950. Reproduced by permission.]
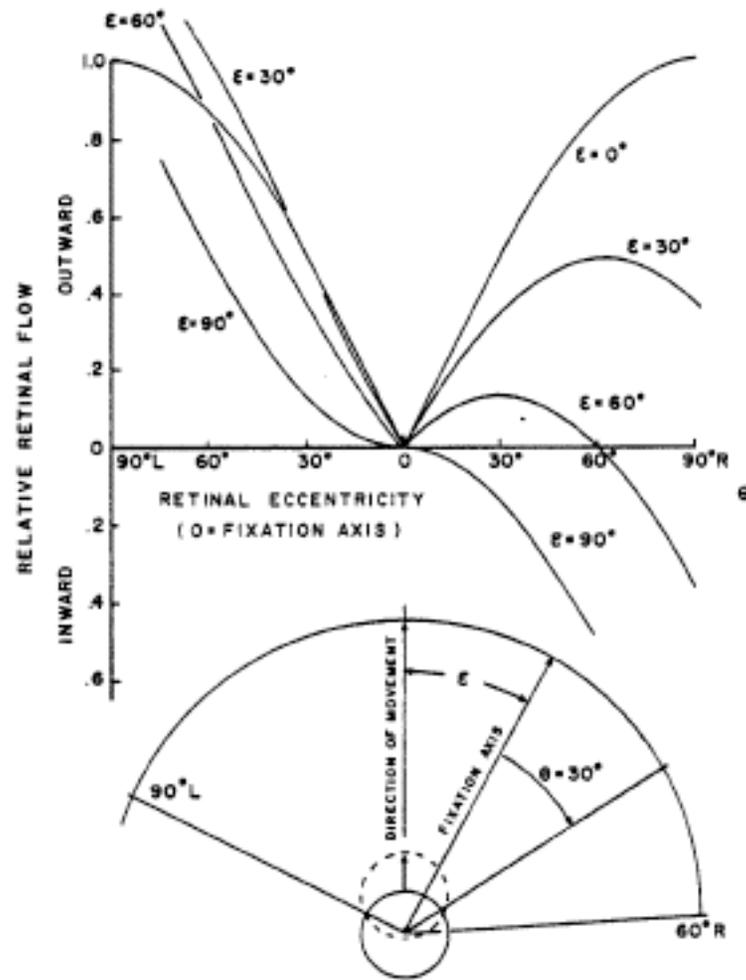
FIG. 3. Upper graph shows idealized horizontal retinal flow at any retinal angle from the fovea (θ) for several eccentricities of fixation (ε) relative to the direction of body (head) motion. When the fixation axis coincides with the direction of body movement, then the retinal flow pattern is symmetric on each side of the fovea (ε = 0° As the angle between the direction of body movement and fixation increases, the flow on each side of the fovea becomes more and more asymmetric (ε = 30, 60, 90°).

visual direction can be determined by the relative visual information alone. The observer needs no visual information other than the visual flow pattern. In order to adjust his egocentric frame to proper orientation, the observer merely has to refixate so that the flow patterns are symmetrical on each half of the retina.

Although not yet studied in man, an excellent model for orienting may be drawn from studies of orienting by the fly (Reichardt, 1973; Poggio & Reichardt, 1973). Of particular interest is the orienting tendency produced by a moving stimulus located at various retinal eccentricities. To measure this tendency, these authors placed the fly in the middle of a cylinder the white inner wall of which had a single black stripe which could be positioned at any angular eccentricity in the fly's visual field. With the fly held rigid by a thin arm of a torque-compensator, the torque generated by the fly's attempt to orient to the oscillating bar may be measured for any eccentricity of the bar. Once

such a stimulus strength versus eccentricity function had been determined, this function could in principle be applied to the flow rates of Fig. 3 to determine the orienting tendency for complex flow patterns. For the fly, this weighting function is given in Fig. 4. The abscissa of this figure shows the eccentricity of the stimulus presented to the fly, with the primary direction ($\theta = 0$) taken as the sagittal direction through the body. The abscissa is the torque that a moving bar will generate as the fly tries to orient toward the stimulus. The torque curve is S-shaped because, in one case, the fly attempts to turn counterclockwise, whereas when the stimulus is presented to the opposite side, there is a clockwise turning tendency. The curve in Fig. 4 is therefore a weighting function, which indicates how effective the stimulus is when it is off the primary axis. Because the curve is symmetrical about the primary direction, it is obvious that any asymmetric flow presented to the fly (as in Fig. 3) will cause it to orient toward a more stable position. The potential well in the lower part of the figure indicates the stable condition more clearly.

The same kind of weighting function can be applied to orienting (saccadic fixation) behavior in man. However, instead of using the two optic lobes as the fly, the presumed correlate will be the difference in stimulation between the two hemispheres. As we shall see later, a similar model may also be used to interpret vergence fixation along the primary axis.

The important conclusion to draw from Figs. 3 and 4 is that there is behavioral evidence demonstrating the ability of an animal to localize the straight ahead solely by relative visual information, without reference to any absolutes such as provided by vestibular sensations. Egocentric coordinates defined by such relative information are not necessarily very precise. But we must remember that the intent to orient to the primary direction need not be precision, but rather may be to provide a global orientation which will enable the organism to conduct a finer processing of information in a more limited region of visual space (Trevarthen, 1968; Schneider, 1967; Ingle, 1973). Such a refined processing of visual information in the neighborhood of the primary direction is not conducted in isolation, however, but rather must still be interpreted with reference to the entire visual scene. The global egocentric framework is thus not merely a basis for providing a semireflexive orienting mechanism. Instead, it may be vital to an interpretation of spatial relations in the neighborhood of fixation where acuity is high. Perhaps the strongest evidence supporting the dependence of detailed spatial analysis upon the global egocentric framework is provided by Hein and Diamond (1972); although antecedents appear earlier (Held, 1968). Hein has found that the development of sensory-motor coordination of guided reaching in kittens required the development first of an egocentric framework that relates the position of the body to its environment.

A. Translations of Coordinates

The Euclidean space around us is still. But if we operate in terms of an egocentric coordinate system, then whenever we twist, turn, or reorient, our egocentric coordinates have undergone some translation. Nevertheless, it is clear that when we move our egocentric reference frame we do not
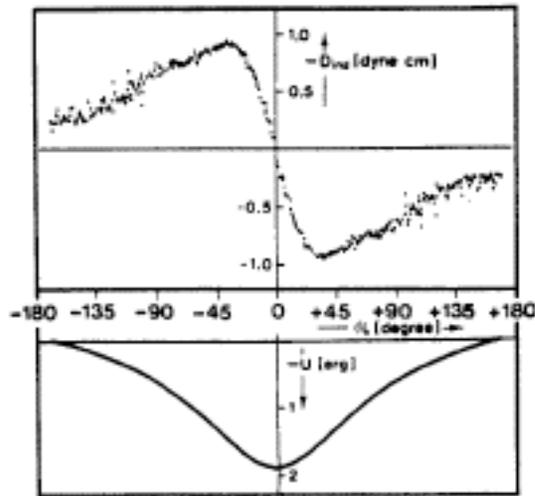
Fig. 4. The orienting torque of the fly induced by a stripe placed at various angular eccentricities, ψ_Ω off the primary direction. The lower figure is the potential well calculated from the torque measurements and shows the stable orientation is at $\psi = 0$. [From Poggio & Reichardt (1973).]

want to infer that the whole world has moved. Therefore, our specification for the coordinate system must be such that any transformation we are likely to make should leave the spatial relations within the coordinate system invariant. If the relations that our own brain is attempting to interpret remain invariant under translations of our coordinate system, then we will have a stable world.

Although many scientists have considered and studied this problem since Helmholtz, most current explanations for the stability of the world under active, self-produced movements still follow Helmholtz's original proposals. For example, it is possible that when a self-produced movement is initiated, there is an internal compensatory signal that in some way cancels or modifies the afferent change (Sperry, 1950; von Holst & Mittelstaedt, 1950; MacKay, 1956; Teuber, 1960). The extensive work on adaptation to prismatic distortions, whereby compensation proceeds much more rapidly with active, self-produced movements is strong evidence suggesting an internal readjustment tied to the egocentric coordinate system (Kohler, 1962; Held, 1965; Held & Freedman, 1963; Harris, 1965; Howard, 1973). However, one striking property of these adaptation effects is that following adaptation to a large shift in the frame (such as a 20° lateral displacement) there is only a small orienting error immediately after the subject is returned to the preadaptation condition. Because the error following adaptation is much smaller than the induced displacement of the frame, it is possible that the frame itself was invariant under translation and instead the observer adapted only to the local (prismatic) distortions in the flow or gradient patterns that now slightly redefine the axes of the coordinate system. Such an interpretation implies that the coordinate system itself is invariant under angular translation.[1]

Luneburg (1950) was the first to formalize precisely a coordinate system that would be invariant under changes in head and eye positions. This system was shortly followed by others cast along similar lines (Hardy, Rand, Rittler, Blank, & Boeder, 1953; Blank, 1957, 1958). One of the more recent formalisms of Luneburg's position is by Leibovic, Balslev, and Mathieson (1971), who derived a set of (eisekonic) coordinates[2] whose distance elements remain invariant under changes in fixation position (with head rigid). One such pair is represented by loci equidistant from the observer (the equidistant horopter) and radii emanating from a cyclopean eye (an approximation to the Hillebrand hyperbolas). In essence, this is a polar coordinate system in the horizontal plane

through the eyes, and, thus, a special case of our chosen egocentric coordinate system. Clearly, translations of fixation position along any arc will leave the remaining equidistant arcs invariant in that they will continue to excite the same neural populations. Similarly, changes in fixation along the radial loci (Hillebrand hyperbolas) will leave the remaining rays invariant. Leibovic notes that such a coordinate system fits nicely with Blakemore's (1970a) proposal that columns in the visual cortex of the cat appear distributed either as depth columns, whereby all cortical units in the column respond to a line at a particular orientation and locus of constant distance; or as direction columns, where all cortical units in the column respond to a line of a given orientation lying along a locus of constant visual direction.[3]

Perhaps the strongest evidence supporting the notion that distance and direction are encoded separately is the behavior of eye movements. Referring to Fig. 5, when fixation is altered from *A* to *B*, a saccade is first made to orient both eyes to the direction of *B*(i.e., to *A'*) and then a vergence
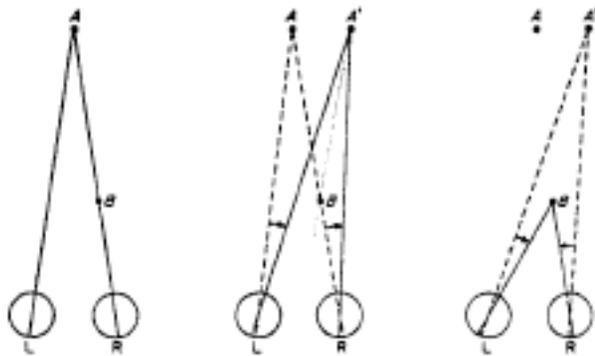

FIG. 5. Schematic diagrams illustrating sequence of movement in changing fixation from A to B. *(1)* Binocular fixation of A. *(2)* Conjugate lateral movement without change of convergence to A', so that bisector of angle of convergence passes through B. *(3)* Convergence movement from A to B. Steps *(2)* and *(3)* are to some extent superimposed; but in view of their time characteristics, they are easily distinguished. [From G. Westheimer & A. M. Mitchell, Eye movement responses to convergence and stimuli. *Archives of Ophthalmology. New York,* 1956, 55, 848-856. Copyright 1956, American Medical Association.]

movement is initiated causing the eyes to slide down the new visual axis to the point *B* (Westheimer & Mitchell, 1956; Yarbus, 1967). The independence of these two sequential movements implies a separation of mechanisms, which has also been shown to have entirely different dynamics (Rashbass & Westheimer, 1961). Further support for the independence of visual direction and distance is provided by Foley (1972), on a more conceptual level. Curiously, when an observer is required to set up spatial configurations according to a preset Euclidean pattern, he will make size and distance judgments that may be in direct conflict with his separate judgments of visual angle. This suggests that angular judgments are encoded independently of size-distance judgments. Thus, there is strong support for a coordinate system based upon θ, ϕ, and R, with θ, ϕ, and R encoded by separate mechanisms or pathways.

However, it is still not clear why linear transformations of the egocentric system should leave object positions invariant, although von Schelling (1956) has shown that a metric invariant under such transformations can be found. One metric that is particularly appropriate is based upon ratios of distances. For example, consider the changes in object relations as the observer moves forward through his environment. As distant objects are approached, they become not only larger, but also move toward the periphery of the visual field. A possible mechanism for keeping object size invariant under such a translation would be one that compresses the apparent peripheral angles and

expands the spatial representation of objects falling upon the central foveal region. The mapping of the retina onto the cortex is ideal in this respect, for the central fovea has a large representation at the expense of a smaller peripheral representation. Because the retino-cortical transformation is roughly a logarithmic function of retinal eccentricity (Fischer, 1973), ratios of spatial relations cast upon the fovea would remain invariant under forward translation by the observer. Thus, the cortical magnification factor could be an economy of neurons that yields high foveal acuity, while at the same time serving as a mechanism for leaving angular distances invariant under translations of egocentric coordinates (Cowan, 1974; Richards & Cowan, 1975).

More difficult to interpret is the stability of the visual environment under saccadic or vergence changes in fixation. The notion that such self-produced movements may generate "corollary discharges" that suppress or modify afferent input during this coordinate change has already been mentioned. Rather than invoking elaborate compensatory mechanisms, however, the brain may operate on a much simpler principle: namely, to assume that the world is stable unless afferent information proves otherwise (MacKay, 1970). Considering that the definition of the egocentric coordinate system is heavily dependent upon flow patterns and movement, so long as no apparent motion of the environment is observed, stability could be inferred. Suppression of visual input during saccades would facilitate such an inference (Latour, 1962; Zuber & Stark, 1966; Volkman, Schick, & Riggs, 1968; Richards, 1969). However, such suppression may not be necessary, for the retinal flow during the saccade, which may reach 100 deg/sec, greatly exceeds the optimal velocities for stimulating movement detectors, which respond in the neighborhood of 1-10 deg/sec. (Sekuler & Ganz, 1963; Barlow, Hill, & Levick, 1964; Sekuler, Chap. 11 of this volume). Movement suppression would therefore be more important during pursuit tracking (Richards & Steinbach, 1972) and vergence fixation, both of which are slower movements that yield flow patterns moving in the velocity range of the motion detectors.[4] Both of these latter types of movements, however, could invoke simple compensatory signals. For example, to compensate for the unidirectional lateral flow encountered during a pursuit movement, the brain only needs to suppress the hemispheric imbalance that would normally trigger a saccade (see Fig. 3). For vergence movements, the flow patterns to the hemispheres are symmetrical anyway, and the cancellation could occur directly at least in the frontal plane.

Such a model for visual stability of the environment also places a constraint upon the eye movement systems themselves. In order that no afferent information be available to the egocentric coordinate system during eye movements, it is critical that the eye positions themselves not be consciously sensed by this system (Merton, 1964; Hay, 1971). Thus, all major afferent signals for the primary visual directions that define the egocentric coordinates should come from the visual flow patterns alone and must not be perturbed by a proprioceptive sense of eye position. Instead, the sense or perception of eye position should be closely linked to the central eye movement command center (Skavenski, Haddad, & Steinman, 1972), whose primary coordinates would then be reset when necessary solely by retinal input (i.e., the flow pattern). By analogy, other egocentric coordinate systems defined for other sensory modalities should also not rely upon proprioceptive input for their definition of coordinates. Such multiple coordinate systems which are then only loosely coupled to one another should provide a stable framework for visual space under a variety of transformations of sensory input.

II. STEREOPSIS

With a global egocentric coordinate system that is stable and invariant under translation, this system may then be centered on particular regions in the visual field that may be subject to closer scrutiny. The objective will be to perform an analysis of objects in three-dimensional space in the neighborhood of the fixation point. The cues that can be used to analyze information in this smaller region will be the same as those put forth in Table 1. However, rather than processing the more global θ, ϕ, and R values, it may be more efficient to examine the increments in these values: $\Delta\theta$, $\Delta\phi$, ΔR, and their various spatial-temporal derivatives. A first step in this direction is to consider how a three-dimensional space is constructed in the region of the fixation point. This is the problem of stereopsis.

Crucial to an understanding of stereopsis is recognition of the significance of the overlap in the nasal and temporal portions of the retina of each eye. Consider the upper part of Fig. 6. The portion of the visual field indicated by horizontal cross-hatching goes to the left hemisphere, the vertical cross-hatching goes to the right hemisphere. Now, in the pieshaped sector below the fixation point, stimuli will go to the left hemisphere via the left eye but to the right hemisphere via the right eye. The opposite is true for the sector above the fixation point. Thus, nearer and farther from the fixation point there is an hourglass shape which does not have representation in the same hemisphere and hence the binocular correlations needed for stereopsis become impossible. Yet if objects are to be analyzed in three-dimensional space about the fixation point, stereopsis is necessary. The brain solves this problem as indicated in the lower portion of the figure. Instead of having complete decussation through the fovea there is an overlap in the projections of the visual field that allows visual information to be correlated in the same hemisphere on one or the other side of fixation (Stone, 1966; Blakemore, 1969; Sanderson & Sherman, 1971). In each eye, this overlap will appear as an encroachment of nasal retina upon temporal retina and vice versa and is hence designated as the nasaltemporal overlap. This nasal-temporal overlap plays a major role in stereopsis.

With binocular information available to each hemisphere in the neighborhood of the fixation point as indicated in Fig. 6 stereoscopic information may be extracted from the three-dimensional space surrounding fixation. The manner in which this is done is still not clear. Proposals for the basis of stereopsis fall into two categories: (1) Those based upon a Keplerian model requiring disparity detectors and (2) those based upon global correlations and "disparity pools."

A. The Keplerian Model

The Keplerian model for stereopsis is merely an internal reflection of the external geometry of binocular parallax. As rays emanate from the nodal points of each eye, they cross and create a grid, as shown in Fig. 7. With the two focal axes F_L and F_R taken as reference, the distance of any object may be read off the grid in terms of its angular position in each eye. The difference in the angular position in each eye is retinal disparity, δ, which is zero at the intersection of the foveal projections as well as along the arc indicated by the heavy line. The object distance relative to the distance of the fixation point can thus be determined-if retinal disparity can be sensed. The first demonstration that this is possible was by Wheatstone (1838), using his now famous stereoscope. More recently,
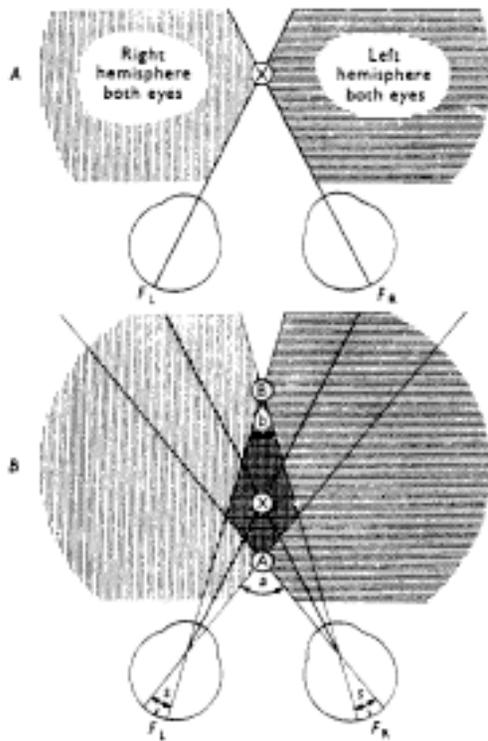
Fig. 6. (a) Assuming that partial decussation exactly divides the retinas through the foveas, F_L and F_R the region of space shaded with vertical lines is entirely represented in the right hemisphere, since it projects upon nasal retina in the left eye and temporal in the right. The horizontally striped area is likewise represented in the left hemisphere. The areas of space nearer than the fixation point, X, and beyond it should project to separate hemispheres through the two eyes. (b) Now, if a central vertical strip of retina of angular width s is represented in *both* hemispheres, the striped regions of Fig. 6a are expanded to include the area around the fixation point, which projects to both hemispheres through both eyes. The precise location of the point X between A and B depends on the relative contribution of nasal and temporal retina to the region of double representation, which is determined by the exact position of each fovea within the strip s. The point x might, in fact, lie anywhere between A and B. [From Blakemore (1969).]

"disparity detectors" have been found in the visual cortex of the cat (Barlow, Blakemore, & Pettigrew, 1967; Pettigrew, Nikara, & Bishop, 1968; Joshua & Bishop, 1970) and monkey (Hubel & Wiesel, 1970) and have been inferred from psychophysical adaptation studies in man (Blakemore & Julesz, 1971; Blakemore & Hague, 1972; Felton, Richards, & Smith, 1972; Ronchi & Mariani, 1972; Long & Over, 1973).

The fact that detectors of retinal disparity have been found in visual cortex supports the basic Keplerian model, for these detectors would be responding to the points of intersection of the gridwork. Such a proposal was first clearly stated by Boring (1942), and subsequently modified by Charnwood (1951), Dodwell and Engel (1963, 1970), Julesz (1962, 1971), and Sperling (1970). Sperling's model may be r-.duced to two classes of neurons underlying stereopsis. The first class, designated as inflow neurons carry monocular signals along axons that cross at an angle similar to the Keplerian grid. A second type of neuron, a level detector, then indicates a correspondence in binocular activity at one level in the field created by the neural grid. These neurons are ingeniously designed with triangular dendritic arborizations to inhibit other level detectors. Accessory neurons in this class further tune up the disparity detection process. The output of the binocular level-detecting neurons is then combined with neurons

analyzing shape and texture. Sperling, like others before him (Ogle, 1964; Mitchell, 1970) proposes two stereoscopic mechanisms, one global, handling large disparities without the need for feature-by-feature correlations and a second mechanism concerned with fine stereopsis (less than .25° disparity) that is more a part of the pattern recognition process.

The major difficulty with such Keplerian models is the elimination of "ghost" correlations. If two neighboring lines A and B are placed at different distances in visual space, a total of four intersections or disparity detectors are activated, as shown in Fig. 7. How does the brain choose the correct intersections? Although in the real world such confusions are unlikely because of slight textural, size, or shape differences between objects, the ghosts are also not seen in the laboratory where highly redundant patterns are used. The Julesz binary random-dot pattern is an example. To solve this problem, Julesz (1971) proposes cluster-by-cluster disparity matching rather than point-by-point matching. Sutro and Lerman (1973) on the other hand, merely truncate the nearest and farthest vertices of the quadrilateral, *AxBy*. These two methods represent examples of two classes of solutions to the problem of obtaining a single neural image from images that are disparate on each retina. In one case the problem is solved by (global) fusion, whereas, in the other, a process of suppression is invoked. Kaufman (1974) has provided an excellent review of the facts and theories related to fusion, suppression, and the problem of single binocular vision. This problem falls somewhere between that of object recognition and object localization (Dodwell, 1970), for the localization of objects in threedimensional space will occur even when they are seen as diplopic (Mitchell, 1969; Jones & Kerr, 1972), and, in fact, the greatest depth generally occurs for disparities that do not yield single binocular images (Foley & Richards, 1972).

B. DISPARITY POOLS: GLOBAL CORRELATIONS

A completely different kind of model for stereopsis has been proposed that lies outside of the Keplerian framework (Richards, 1969, 1973). Rather than requiring disparity detection based upon correlations of local regions in space, the model states that only two global correlations are performed, one for a spectrum of convergent disparities and a second for divergent disparities. Earlier work that suggested such global, feature-free correlations appeared in studies by Kaufman (1964), and Kaufman and Pitblado (1965), and was also implied by a demonstration of the lability of disparity correlations by Fender and Julesz (1967). More recently, considerably more evidence has appeared showing that the disparity mechanism is capable of rather wide-field correlations, which need not be shape dependent (Westheimer & Tanzman, 1956; Mitchell, 1969; Jones & Kerr, 1972; Foley & Richards, 1972). Much earlier Linksz (1952) was also thinking in terms of a global separation of disparity correlation mechanisms. In order to make sense of the horopter, Linksz believed that the
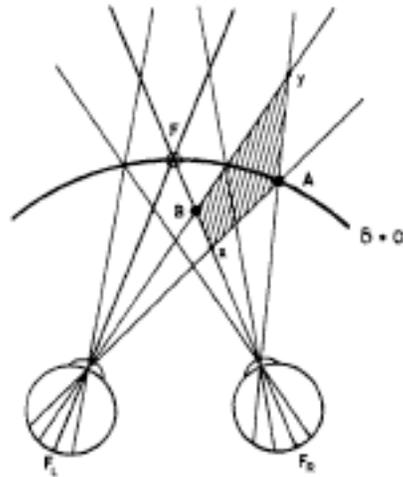
FIG. 7. Basic Keplerian model for stereopsis. The external geometry of binocular parallax is assumed to be reflected in the nervous system. Thus each intersection will activate a different binocular neuron or "disparity detector." The difficulty with the model is the presence of false intersections x and y arising from similar objects A and B located at different distances. Why are the "ghosts" not seen?

spectrum of disparities should be divided functionally into convergent and divergent regions. The horopter locus of zero disparity could then represent a functional equilibrium between two types of disparity analyzers (convergent and divergent). Although still thinking in Keplerian terms, Linksz (1952) elaborated earlier proposals of Bárány (1925) and Kleist (1926) that each type of disparity could be encoded separately in cortex, one above and the other below the stripe of Gennari (where the incoming geniculate fibers arrive).

The first demonstration of a separate encoding process for convergent and divergent disparities was by Richards (1970a), who found that some observers could process one type of disparity but not the other. Such individuals were designated as "stereoanomalous," and represented about 30% of the population.

Since this first demonstration that convergent and divergent disparities must be treated as separate functional entities, a large number of differences have been noted in the manner by which the visual system extracts these two kinds of disparity information (Richards & Regan, 1973). The visual system must therefore have at least two kinds of disparity filters: one for convergent and a second for divergent disparities.

The model proposed to account for these two types of disparity filters is quite simple. It is based upon the fact that stereopsis in the region of the fixation point requires an overlap in the nasal and temporal retinae or their projections. The consequence of this overlap is to cause a slight displacement in the correlations between retinal positions in each eye as they are projected onto the separate geniculate laminae. This is shown schematically in Fig. 8. As the temporal retina of the left eye is paired with the nasal retina of the right eye at the lateral geniculate body, the registration of the pairing will be off by the extent of the nasal-temporal overlap (estimated to be approximately .75° in man). For the first two pairs,

the error will be a convergent disparity.[5] This model proposes that whenever the displacement in the registration of pairs of geniculate laminae does not occur, then a disparity filter will be missing.

Clearly, such a model is quite different from the Keplerian schemes, for only two types of correlations are performed, namely those between the adjacent laminae. There is not a series of difference-field operations, but only one for each class of disparity. The closer the stimulus disparity approaches that of the nasal-temporal shift, then the higher the correlation in activity. The two types of correlations of disparate stimuli thus serve to "pool" the disparity information. The simplicity of the model lies in the notion that the same anatomical constraint required for foveal stereopsis (i.e., the nasal-temporal overlap) sets up the stereoscopic mechanism itself.

An estimate of the extent of two correlation processes corresponding to the convergent and divergent pooling of disparities is shown in the upper part of, Fig. 9. The graph relates the depth sensation to disparity for two observers, one who lacks the divergent mechanism (ID) and a second who lacks the convergent correlation mechanism (RD). Only depth relative to the distance to the fixation point is plotted, ignoring the sign (front or back). For both observers, the flat region where depth remains constant is the region where disparities are not discriminated under a forced-choice method (Richards, 1971). Over the region of convergent disparities
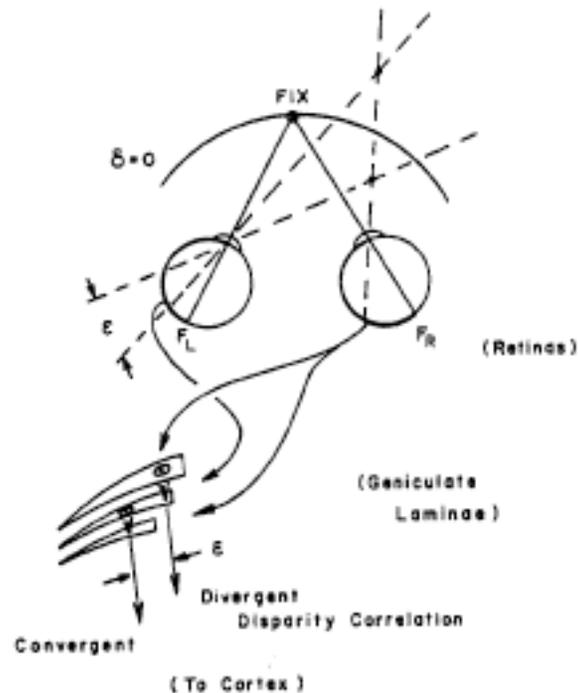

Fig. 8. Schematic showing effect of a nasal-temporal overlap upon binocular correlations. The retina of each eye projects to separate geniculate laminae, each of which are functionally displaced approximately by .75°, owing to the overlap of the nasal and temporal retinas. Because the displacement occurs twice, first between the upper two geniculate layers and again between the lower two, the total displacement will be 2 X .75° = ε. Disparity correlations between each eye based on the upper geniculate

discriminated by ID, the depth sensation first rises and then falls as the stimulus disparity exceeds .75°. A similar, but symmetrical function is obtained from RD who discriminated only divergent disparities. The rise and fall in these depth sensation curves presumably represents the extent of the disparity correlation process, *which is* maximal at the value for the nasal-temporal shift.

For the complete stereoscopic mechanism, comprising both convergent and divergent mechanisms, the depth sensations may be approximated by subtracting the two types of correlation functions given in the upper part of Fig. 9. Such a difference comparison will yield a curve similar to that obtained for RS, shown in the middle portion of the figure. Of course, RS had been previously shown to possess both divergent and convergent disparity mechanisms.

The complete depth-disparity correlation function of RS now appears very similar to the weighting function used to direct fixation to the primary direction in the fly (see Fig. 4). Following the earlier analogy, we would now propose that this depth-disparity correlation function will be used to mediate vergence eye movements. Direct support for this construction has already been obtained by Jones (1972), who measured vergence movements in several types of stereo observers and found individuals whose pattern of vergence responses was formally similar to the depth functions shown in Fig. 9. It seems reasonable to assume, therefore, that both depth and vergence are mediated by a comparison of two global correlation processes that are set up by the same mechanism (Richards, 1970b, 1973; Jones, 1972).

111. FIXATION REFLEXES AND DISPARITY TUNING

When the two eyes converge onto a fixation point, two steps are involved: (1) the initial grasping or tracking of the target and (2) holding the target on the fovea. Three separate eye-movement systems are involved in this task: the saccadic, the pursuit, and the vergence systems (see Robinson, 1968 for a summary). Not surprisingly, each system utilizes separate sensory cues that are, respectively, positional displacement, velocity, and binocular disparity. Once stationary targets are acquired, both eyes do not necessarily orient the foveas directly at the target.
directly at the target. Some observers fixate slightly behind the target (divergent phoria), whereas others fixate in front (convergent phoria). Such "fixation disparities" have been extensively studied by Ogle (1964) and his co-workers (Ogle, Martens, & Dyer, 1967). For any individual, these imbalances in fixation generally fall into one of four categories, which appear related to the stereoscopic abilities
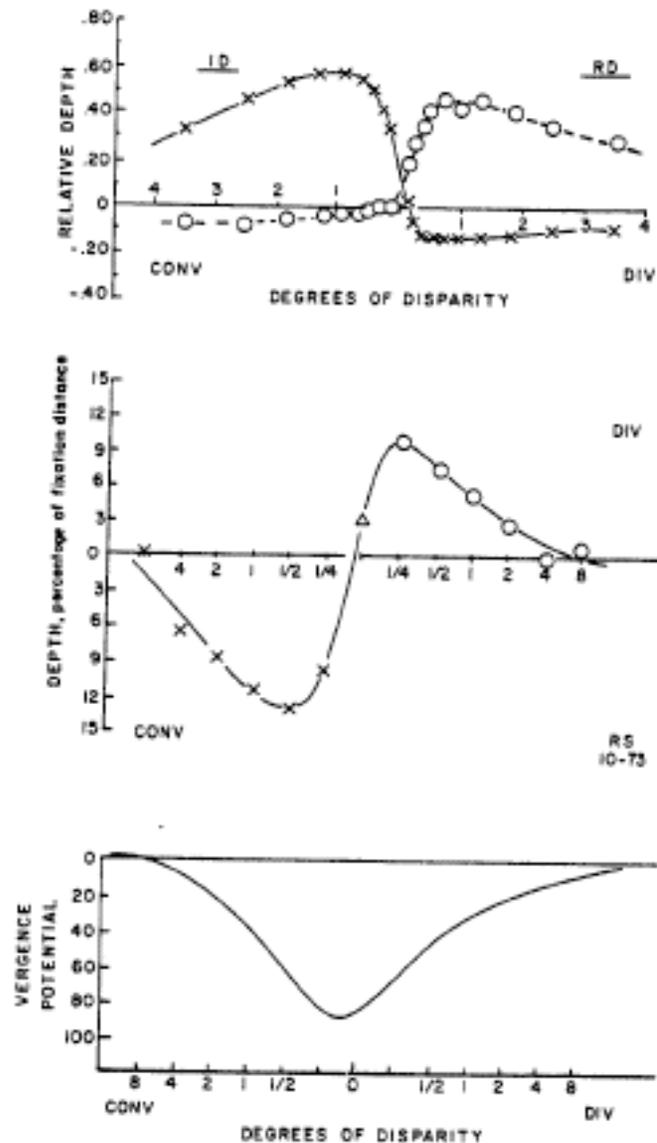
FIG. 9. Upper graph illustrates for two stereoanomalous observers the Magnitude of the (unsigned) depth sensation associated with a given stimulus disparity. For both observers, the greatest depth is elicited by stimulus disparities near .75°, but for ID the stimulus must be convergent while RD requires a divergent stimulus. For the opposite disparities the depth sensation approximates that seen for monocular stimuli.

Middle graph shows the depth sensation for a third subject (RS) whose stereomechanism is a composite of the two separate components illustrated in the upper graph. The potential well associated with RS's depth-disparity sensation curve is given in the lower graph. The potential of this well is labeled "vergence potential" to stress the close relation between depth sensations and the vergence control mechanism.

of the observer (Richards, in preparation). Examples taken from the two most common categories are shown in Fig. 10. Individuals lacking the divergent stereoscopic mechanism generally have a slightly divergent phoria and fixation

disparity that remains constant over a wide range of forced convergence induced by prisms, as shown in the right-hand portion of the figure.

Normally, fixation disparity does not create a problem for space perception because depth judgments about object relations are made independent of the fixation point (i.e., the eye position is not sensed). However when excessive fixation disparity occurs on a larger scale, then squint or strabismus is observed, which may affect space perception. For example, when fixation imbalance reaches 50, a value that approaches or exceeds the possible binocular correlations, then stereopsis on a fine scale becomes impossible. Perception of visual space must then be built up from the remaining cues, the spatial relations of objects in the Euclidean environment.

A further difficulty imposed upon the stereoscopic mechanism arises when objects are magnified in one eye but not the other. This situation occurs naturally during asymmetric convergence at near distances, where the distance from the eye to the object is different for each eye.[6] Different image sizes may also occur when the eyeball length is greater in one eye, or when spectacle corrections are unequal, or when the refractive powers of the cornea are unequal. These conditions exist, to some degree, in all observers, and are called aneisekonia. The effect of these kinds of differences in the image sizes to the two eyes is to rotate the frontal plane about the vertical axis. For a known difference in magnification, such rotations may be predicted precisely from purely geometrical considerations (Ogle, 1964; Gillam, 1967; Smith & Wientzen, 1973; Kaye, 1973). Even for small magnification differences the effect is sizable. For example, at 50 cm a 10% magnification difference can lead to a rotation of 45˚ (Ogle, 1964; Blakemore, 1970c; Fiorentini &Maffei, 1971).

To prevent such rotations due to aneisekonia or asymmetric conver**gence,** the visual system utilizes the vertical image disparity between the two eyes. The effect of a vertical disparity is to induce a tilt opposite to the geometric tilt, but about the same axis (Fig. 11). Thus, the vertical disparity in one eye is treated as a horizontal disparity in the other. This induced effect of vertical disparity has been studied extensively by Ogle (1964), who has shown that over its range it compensates precisely for the improper geometric tilt.[7] Thus, in order to prevent rotations of the
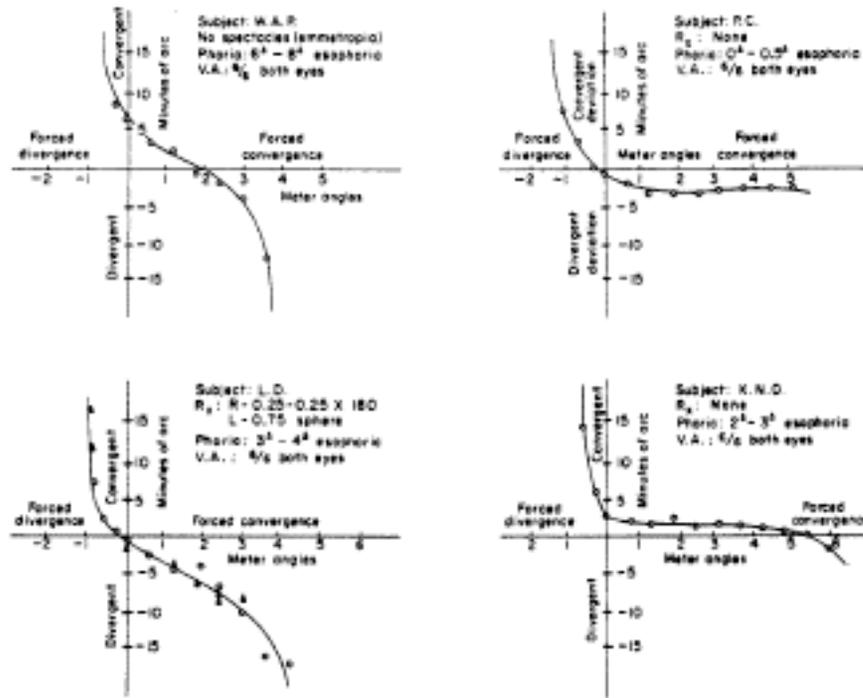
FIG. 10. Fixation disparity curves generated by forced vergence, indicated by meter angles. The ordinate shows the degree of misalignment of two nonius lines presented separately to each eye. [From Ogle (1964). Consult this reference for details.]
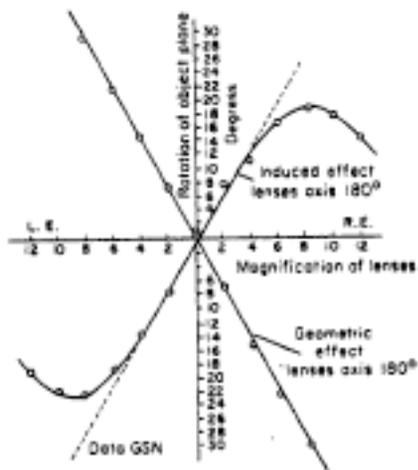

FIG. 11. The induced effect. The vertical magnification of an image in one eye acts like a horizontal disparity in the other, causing a rotation of the frontal plane (ordinate). Over the range from ±4% the induced effect will exactly cancel the geometric effect caused by asymmetric fixation. [From Ogle (1964).]

egocentric frame, vertical disparity is extracted and becomes an important participant in the analysis of visual space.

IV. THE HOROPTER

By definition, the horopter is the locus of points in space having equal visual direction in each eye. Ideally, the horopter locus would correspond to the circle defined by the nodal points of each eye and the fixation point (the Vieth-Müller circle). In practice, the horopter generally lies outside this locus.

The significance of the horopter in visual space perception has probably been exaggerated. Not only is its physiological significance obscure, but even its psychophysical definition has become ambiguous (Ogle, 1964, lists six different horopters!). Probably the horopter that is most closely related to visual physiology is the equidistant locus,[8] which yields the smallest standard errors and which probably corresponds to the locus of greatest visual acuity (Blakemore, 1970b). Such a horopter can be understood to represent a balance between the activities of convergent and divergent disparity analyzing mechanisms.[9] However, even this horopter, like all others, applies only to loci in the horizontal plane of the Vieth-Müller (V-M) circle. The geometric horopter does not exist outside this plane except for the special case when the two eyes are parallel.

Figure 12 illustrates the nature of the horopter locii in the horizontal plane. As fixation distance increases, the locus becomes more convex, deviating more and more from the geometric horopter (V-M circle). For the most part, this change in curvature is largely an artifact of the plotting method. If disparity rather than distance is plotted on the ordinate, the deviation of the horopter locus from the V-M circle remains constant over fixation distance for many observers (Shipley & Rawlings, 1970), at least for the nonius horopter based upon visual direction. When changes in curvature do occur, they may be due solely to shifts in the nodal points of the eyes rather than to any neural mechanism (Bourdy, 1972; Blank & Enoch, 1973). The equidistant horopter, on the other hand, is known to undergo modifications from neural factors, particularly during asymmetric convergence (Ogle, 1964; Lazarus, 1970). The nature of these modifications is in the direction of keeping the equidistant frontal plane normal to the axis of fixation.
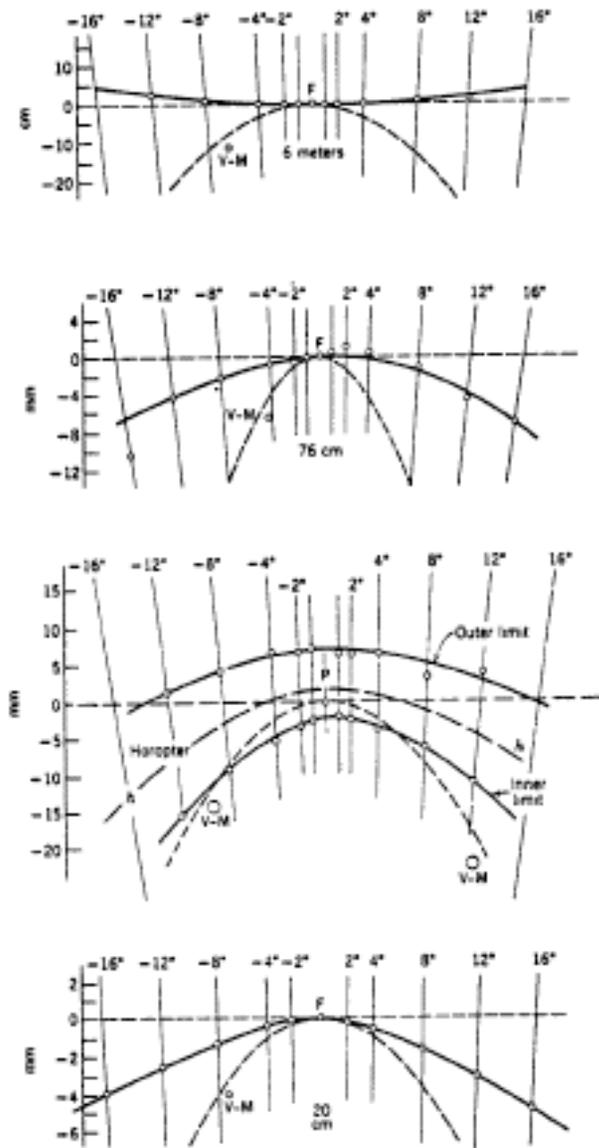
Fig. 12. Data for the apparent frontoparallel plane for different observation distances. In each case, F is the point of fixation. The data for 40 cm are based on the criterion of single vision. The vertical dimensions have been magnified. [From Ogle (1964).]

V. DYNAMIC STEREOPSIS

A complete analysis of objects in visual space must also include the dynamic situation where objects move relative to one another. Clearly, the stereoscopic mechanisms detecting the flow of patterns toward and away from the observer are particularly important for many everyday problems, including understanding an answer to the simple question of *How do we catch a ball*? Yet information about the dynamics of the disparity detecting mechanisms has only just begun to become available (Lee, 1970; Richards, 1971; Tyler, 1971; Harker, 1973). The

study most directly related to this problem is that by Regan and Beverley (1973; see also Beverley & Regan, 1973). These authors have shown that the detection of motion in three-dimensional space may be subdivided into three regions: a central region lying between the fixation axes where forward-moving objects would eventually strike the head, and the two regions to the left or right of the fixation axes. Within the central region, two subpopulations of in-out motion detectors were also suggested, each with different directional tuning curves. Together, these two populations would help to yield a high sensitivity to object direction in the central region of vision. These mechanisms could easily be set up by the nasal-temporal overlap, with the introduction of a time delay analogous to that proposed by Barlow *et al.* (1964) for motion detectors. Clearly, a considerable amount of further study about the dynamics of the stereoscopic process is needed. Perhaps of particular interest might be the relation between this dynamic binocular process and the dynamic monocular cue of motion parallax (Wallach, Moore, & Davidson, 1963; Epstein, 1969). Does one serve as a substrate for the other?

VI. MOTION PARALLAX

Although parallax induced by head movement is an effective cue to depth even with one eye (Ferris, 1972), the fact that this cue is monocular does not require that it precede stereopsis when extracted by the visual system. In fact, the motion parallax cue probably follows stereopsis in the sequence of information processing by the visual system. One test of the hypothesis that motion parallax cues are processed after stereopsis is to present to each eye dynamic noise patterns that individually contain no flow gradients, but when seen binocularly do generate a gradient. The fact that a moving gradient may be seen demonstrates that at least a portion of the movement parallax cue is extracted after stereopsis (Julesz, 1971). Enright (1970) also has demonstrated the strong dependency of the parallax cue upon stereopsis by a completely different method. If a neutral density filter is placed before one eye, the visual signal is delayed slightly (Lit, 1949), but the rate of change of flow patterns will remain unaltered. When the observer is stationary but the object moves in the frontal plane, this interocular delay elicits a disparity sensation and the object will appear to move off the frontal plane (Pulfrich effect; Lit, 1949; Levick *et al.*, 1972). On the other hand, if it is not the object but the observer who moves with one eye attenuated (as when riding a motor vehicle), then the objects moving by will still move in one plane but their relative depths will be altered. This change in the depth sensation in turn alters the perception of the rate of motion, suggesting that the motion information depends upon and hence follows the processing of the stereoscopic cue.

The actual manner in which the visual system extracts the parallax information induced by head movement is not clear (Gogel & Tietz, 1972; Eriksson, 1973). The geometric basis for this cue is straightforward, however. Referring to Fig. 13, if the observer moves laterally through a distance L while fixating a point P, then for small movements the angular change of points F and N lying at distance $\pm\Delta D$ from P will be

$$\theta = L \cdot \frac{\Delta D}{D^2}.$$

If ΔD is positive for objects farther than P and negative for closer objects, then a positive angle corresponds to movement in the same direction as the head movement whereas a negative angle will correspond to angular
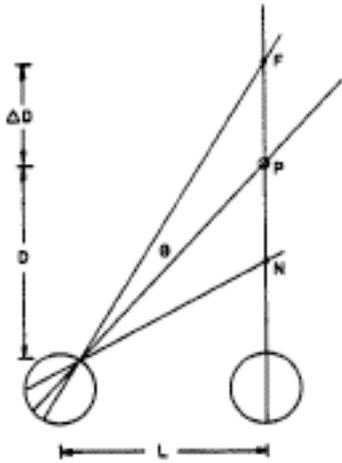
Fig. 13. Motion parallax cue to distance. Observer fixates P while moving laterally through a distance L. The relative displacements ΔD of F and N cause both points to sweep through angle θ.

changes opposite to the change in head position. This equation is formally identical to the equation relating binocular parallax to retinal disparity, except that in the latter case, L remains fixed at the interpupil distance. Considering this formal equivalence, it is of interest to determine whether movement is the cue extracted during self-produced parallax, or whether only positional change is noted.

If motion is the relevant cue, then the rate of angular change across the retina will be

$$\omega = \frac{d\theta}{dt} = \frac{L\Delta D}{D^2 \Delta t}.$$

The motion parallax cue becomes most useful at large distances. Consider, at a distance of 10 m, the relative velocity induced in an object lying at 11 m by a head translation of 5 cm in 1 sec. The relative velocity, ω will be about 2'/sec. This rate is well below the 1-2°/sec optimal rate for stimulating bar and edge detectors in the cortex (Hubel & Wiesel, 1962; Pettigrew, Nikara, & Bishop, 1968; Jung, 1973), and also below the optimal rate of 2 to 6° for motion detection in man (Sekuler & Ganz, 1963; Richards, 1971a). Yet Graham, Baker, Hecht, and Lloyd (1948) have shown that parallax changes occurring at rates as low as .5'/sec may be detected even if the average speed of movement of the display is near 6°/sec. Detection at these low rates suggests that if the parallax cue utilizes the movement information, then it must do so by comparing relative motions of objects as they flow past one another. The cue would thus be the "shear rate" between objects in motion. If motion detectors responded optimally near 4°/sec, then the detection of shear might be optimal for objects moving near these speeds. If this motion system is assumed to have an accuracy of one part in 50 (a reasonable Weber fraction for a sensitive sensory system), then the detection of shear would approach the measured values.

When shear does hot occur, the parallax cue would become ambiguous, for there are no differential velocities to signal relative motion. Other cues to depth will then prevail, or in their absence, the object may be assumed to retain its shape but rotate in an orthogonal dimension in space. Ames's trapezoid window (Ames, 1951) is an example of an illusion of the first kind, where a trapezoidal object rotating through 36° about the vertical axis may be seen to oscillate back and forth through about 150°, centering about the perpendicular to the frontal plane. The stimulus

conditions providing this type of ambiguity in rotation in depth have been specified by Graham (1965), Guastella (1966), and Jansson and Börjesson (1969).

Examples of the second kind of illusion induced by ambiguous motion cues have been studied extensively by Johansson (1964, 1974) and his coworkers (Johansson & Jansson, 1968; Börjesson & v. Hofsten, 1972; Eriksson, 1973). The typical display is a two-dimensional pattern which

undergoes linear distortion along the x or y axes or both. These distortions confined to the frontal plane nevertheless induce an illusion of rotation of an object in depth, in the direction predicted by assuming shape invariance. The fact that motion in the absence of shear will induce depth may be taken as support for the notion that the shear rate between two objects is the relevant cue for motion parallax.

VII. PERSPECTIVE AND GRADIENTS: CONTEXTUAL CUES

Two railroad tracks separated by a fixed distance subtend smaller and smaller angles as the tracks disappear into the horizon. Similarly, the angular size of a long corridor will shrink as it recedes away from the observer. These are examples of the linear perspective cue to distance (Fry, 1952). When combined with linear and texture gradients, these cues together provide a powerful stimulus to depth, as shown in Fig. 14.

Despite the obvious importance of perspective cues to interpreting visual space, little experimental work has been done. J. J. Gibson (1950) has contributed the most to this field through his studies of "ecological optics." This is an optics of projective geometry and perspective in which the point sources are the vanishing points of the railroad tracks and the rays are the linear perspective cues to distance. Such projections, as well as gradients of texture, carry information about the orientation, slope, and distances of objects on surfaces. The scale is set by the texture density or
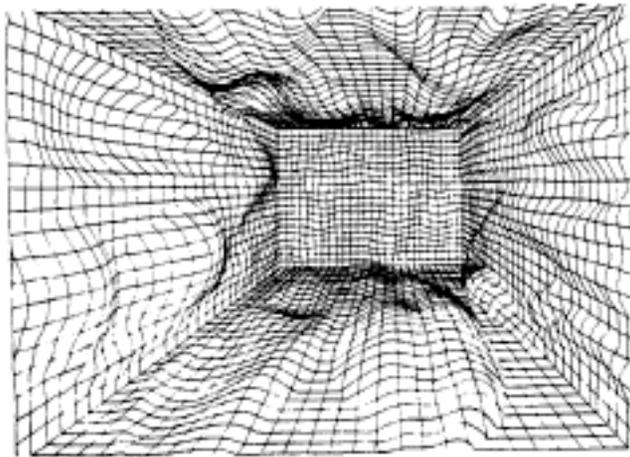

Fig. 14. Drawing of a "wire" room. This drawing depicts a wire room with fluctuation in the walls drawn to enhance the feeling of depth. (Courtesy of the Carpenter Center for the Visual Arts, Harvard University.]

the angular dimensions of the projection lines. These cues provide an important background or context for the estimation of object sizes, and remain relatively invariant under translation of the egocentric coordinate system.

Although the physiological basis for the perspective and gradient cues to visual space are little understood, they clearly represent a special static case of the dynamic flow patterns set up by the moving observer. However, the dynamic flow patterns appear to be more peripheral and more appropriate for guiding an orienting response or to defining a primary visual direction. In contrast to this more global function, the perspective cues are more local and are most important in the foveal region where objects are to be localized in three-dimensional space (Gogel, 1971, 1972). Thus, it would not be surprising to learn that the contextual cues provided by linear perspective and gradients were extracted quite separately from the dynamic flow patterns. Perhaps our understanding of the physiological basis for an ecological optics will progress more rapidly once we have understood how textures are analyzed, for certainly a texture analysis must underlie the perception of texture gradients. Until then, the physiological interrelations among texture, distance, and relative retinal sizes will remain obscure.

VIII. INTERPOSITION AND SHADOW

Interposition is the cue offered when one object overlaps the other, as in Fig 15. Because the overlapping object cuts off a view of part of the second object, the overlapping object appears nearer. Although it may not be immediately obvious, shadows and highlighting aid in the use of the interposition cue, for they help to define edges or surfaces that may be occluded (Waltz, 1972). In isolation, shading and highlights may provide ambiguous information about depth, such as when the direction of the light source is misinterpreted (see Fig. 16).

One of the first attempts to define the conditions for the interposition cue was by Helmholtz (republished in 1962). A more recent formalization of Helmholtz's definition states that the sole determinant of the cue is whether the first spatial derivative of the object's contour is continuous at the points of intersection (Ratoosh, 1949). If two contours meet at a point of intersection and if both contours have continuous derivatives, then no interposition cue will be provided. However, Chapanis and McCleary (1953) have devised a number of patterns (Fig. 15) which raise difficulties for Ratoosh's simple formulation. Clearly, the interposition cue can be utilized even if the derivatives of both contours are discontinuous.

Still more recently, a simpler model has been developed at M.I.T.'s Artificial Intelligence Laboratory (Minsky & Papert, 1969). This approach attempts to identify objects in three-dimensional space by examining the nature of the intersections appearing in the scene. The attempt is to use the local properties of the intersections to constrain decisions about the
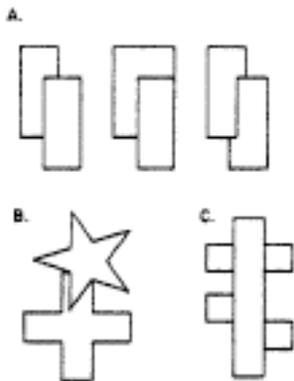
FIG. 15. Examples of interposition as a cue for the perception of relative distance. In part A, the first two outlines give obvious cues, whereas the third is ambiguous. In B, the star and cross intersect at junction points that have no continuous first derivatives and hence should be seen ambiguously in depth according to a modification of Helmholtz's model. The star is obviously in front

of the cross, however. In C, the interposition cue may be slightly stronger when the intersected parts of the partly hidden bar may be completed by extrapolation across the occluding object. [Adapted from Ratoosh (1949) and Chapanis & McCleary (1953).]

FIG. 16. Turn this upside down and you will see the optical illusion of two craters from what really is a photograph of two cones in the desolate Ka'u Desert lava fields on Island of Hawaii. The illusion was photographed on a helicopter trip over the area. [From Wide World Photos, November, 1972.]

global properties of the display (Guzmán, 1968). To accomplish this, the scene is first analyzed in terms of five types of vertices:
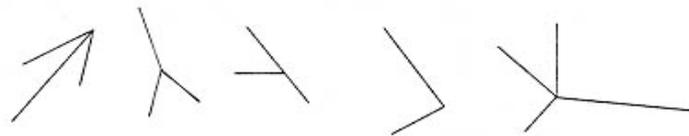
ARROW   FORK   TREE   ELL   TRANS

Each type of vertex is considered to provide some evidence about how the regions they abut may be grouped together, and then decisions are made as to whether "links" should be formed between regions. For example, the most usual physical cause of a TEE is an edge of one object that has disappeared behind an edge of another object. Hence the TEE junction should be taken as evidence against linking the regions lying on each side of the intersected line. Alternatively, the presence of a FORK, which is usually due to the intersection of three planes of one object, would be taken as evidence for linking the adjacent regions. Extensions of this scheme have been made by Winston (1970), Huffman (1970), Clowes (1971), and Waltz (1972). Quite naturally, the most informative of these studies is the most recent. Waltz's primary contribution was the discovery that objects in three-dimensional space may be identified quite accurately with only a few rules about their intersections, provided that shadow was taken into account to define the nature of an edge or junction more precisely. This reduction became possible only by an

exhaustive computer search, which revealed that the possible real-life features greatly constrained the independence of the labeled junctions.

Perhaps the most striking finding of the object-recognition process devised by Waltz (1972) is the similarity between the important elements of his artificial analysis and those actually used by the visual system. The most useful junctions were found to be the ELL and the TEE, both of which are typical features detected by the hypercomplex units of Hubel and Wiesel (1965). Clearly, at this level of object identification, the localization must now be encoded simultaneously with an analysis of object properties. The problem of visual space perception has thus merged with the problem of pattern recognition.

Acknowledgments

Notes

1. The strong form of this hypothesis is that different body-centered frames are loosely coupled internally and tightly coupled only by external feedback through separate afferent pathways.

2. An eisekonic transformation is one limited to translations or rotations. This is a special case of conformal transformations, which also include dilations and inversions. Dodwell (1970) proposes that-the visual system makes use of conformal transformations, at least in adapting to optical distortions.

3. Although such a division of the egocentric coordinate system appears necessary in principle, the distinction of depth versus direction columns may not be the appropriate correlate of behavior. Instead, we cannot yet exclude the very real possibility that these differences between cortical columns are merely a reflection of the variance in the encoding of position in three-space.

4. The general rule will be that the closer the rate of eye movement approximates the optimal velocity of the motion detector, the greater the need for suppression or compensation. Blinks are a most useful suppressive device and occur frequently during vergence fixations which elicit object movement near optimal speeds.

5. For simplicity, Fig. 8 has been drawn with the displacement at the geniculate. Because the actual displacement is retinal, the correlations will be opposite to those shown.

6. For very near distances, excessive asymmetric convergence will also cause an equal blur in each eye. Problems of irradiation stereoscopy must also then be considered (Ogle, 1962; Cibis & Haber, 1951).

7. Ocular dominance columns that run perpendicular to the vertical meridian could provide a substrate for vertical disparity detection. (See LeVay, Hubel, & Wiesel, 1975, for supporting anatomy.)

8. The fact that the fovea lies 5° off the optical axis produces a close approximation to an equidistant horopter for a fixation distance of 50 cm.

9. However, note that stereoacuity near the horopter may be upset by peripheral factors (Luria, 1969) suggesting that even "fine" stereo mechanisms may be subject to more global constraints.

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