## CHAPTER 2

# Binocular Vision and Space Perception

Without an understanding of the physiology of binocular vision it becomes difficult, if not impossible, to appreciate its anomalies. The reader is well advised to study this chapter thoroughly since important basic concepts and terminology used throughout the remainder of this book are introduced and defined. It is of historical interest that most of these concepts and terms have only been with us since the nineteenth century when they were introduced by three men who may be considered among the fathers of modern visual physiology: Johannes Müller, Hermann von Helmholtz, and Ewald Hering. The basic laws of binocular vision and spatial localization that were laid down by these giants of the past form the very foundation on which our current understanding of strabismus and its symptoms and sensory consequences is based.

## Fusion, Diplopia, and the Law of Sensory Correspondence

Let us position an object at a convenient distance in front of an observer at eye level and in the midplane of the head. If the eyes are properly aligned and if the object is fixated binocularly, an image will be received on matching areas of the two retinas. If the eyes are functioning normally and equally, the two images will be the same in size, illuminance, and color. In spite of the presence of the two separate physical (retinal) images, only one visual object is perceived by the observer. This phenomenon is so natural to us that the naive observer is not surprised by it; he is surprised only if he sees double. Yet the opposite—single binocular vision from two distinct retinal images—is the truly remarkable phenomenon that requires an explanation.

### Relative Subjective Visual Directions

Whenever a retinal area is stimulated by light entering the eye, the stimulus is perceived not only as being of a certain brightness and color and of a certain form but also as always being localized in a certain direction in visual space. One cannot have a visual impression without seeing it somewhere. If the stimulated retinal area is located to the left of the fovea, it is seen in the right half of the field; if it is located to the right of the fovea, it is seen in the left half of the field.

The direction in which a visual object is localized is determined by the *directional*, or *spatial*, values of the stimulated retinal elements. These directional values (the local signs of Lotze) are an intrinsic property inherent to the retinal elements, as are all the properties that lead to sensations of brightness, color, and form of a percept.

That the directional values are intrinsic properties of the retinal elements and are not caused by the location of the light stimulus in external space or by some other properties of the light stimulus can be shown by using inadequate stimuli. If the retina is stimulated mechanically (pressure) or electrically, the resulting sensation is localized in the same specific direction in which it would be localized if the retinal elements had been stimulated by light. For instance, if we apply finger pressure near the temporal canthus through the lids of one eye, we will become aware of a positive scotoma in the nasal periphery of that eye.

It must be made clear at this point that whenever *retinal elements, retinal points*, or *retinal areas* are spoken of in this book, they are to be understood in the sense in which Sherrington[85] used them. He defined these terms to mean "the retinocerebral apparatus engaged in elaborating a sensation in response to excitation of a unit area of retinal surface." None of the "properties" spoken of "belong" to the retinal elements per se. Anatomical, physiological, biophysical, and biochemical arrangements and mechanisms within the retina give rise to excitations that ultimately result in what we know as "vision." We "see" with our brain, not with our retina, but the first step in elaboration of information received by the eye takes place in the retina. Without the retina, there is no vision. Since it is vastly easier for us to visualize the retina than the totality of the retinocerebral apparatus, retinal terminology is adhered to throughout this book.

Each retinal element, then, localizes the stimulus as a visual percept in a specific direction, a visual direction, but this direction is not absolute. It is relative to the visual direction of the fovea. The fovea, the area of highest visual acuity, is also the carrier of the *principal visual direction* and the center to which the *secondary visual directions* of all other retinal elements relate. This relationship is stable, and this stability is what makes an orderly visual field possible. Since the localization of the secondary visual direction is not absolutely fixed in visual space but is fixed only as related to the visual direction of the fovea, its direction shifts together with the principal visual direction with changes in the position of the eye. Strictly speaking, visual directions are *subjective sensations* and cannot be drawn in a geometric construct. The objective correlates to visual directions for the use in such drawings are the *principal* and *secondary lines of directions*. A *line of direction* is defined as a line that connects an object point with its image on the retina. Helmholtz[44, vol. 1, p. 97] defined it (the direction ray) also as a line from the posterior nodal point to the retina. All lines of direction therefore should meet in the anterior nodal point. For simplicity, the lines of direction are represented as straight lines in schematic drawings (Fig. 2–1).

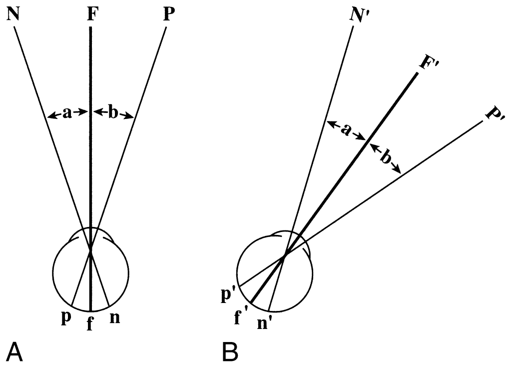

**FIGURE 2–1.** Relative lines of direction. *A*, Eye in straight-ahead position. F, principal line of direction; N and P, secondary lines of direction. *B*, Eye turned to right. The sheath of lines of directions shifts with the position of the eyes, but F′ remains the principal line of direction and N′ and P′ remain the secondary lines of direction.

## Retinomotor Values

There is a further important result of this stable and orderly arrangement of the relative visual directions. The appearance of an object in the periphery of the visual field attracts attention, and the eye is turned toward the object so that it may be imaged on the fovea. The resulting eye movement, also called a *saccade*, is extraordinarily precise. It is initiated by a signal from the retinal periphery that transmits to the brain the visual direction, relative to the foveal visual direction, where the peripherally seen object has appeared. Corresponding impulses are then sent to the extraocular muscles to perform the necessary ocular rotation, mediated and controlled in a manner discussed in Chapter 4. This function of the retinal elements may be characterized by saying that they have a *retinomotor value*. This retinomotor value of the retinal elements increases from the center toward the periphery. The retinomotor value of the fovea itself is zero. Once an image is on the fovea, there is no incentive for ocular rotation. The fovea, then, in addition to its other functions, is also the *retinomotor center* or *retinomotor zero point*. The retinal organization described here has an important clinical application: it makes it possible to measure ocular deviations by means of the prism and cover test (see prism and cover test in Chapter 12).

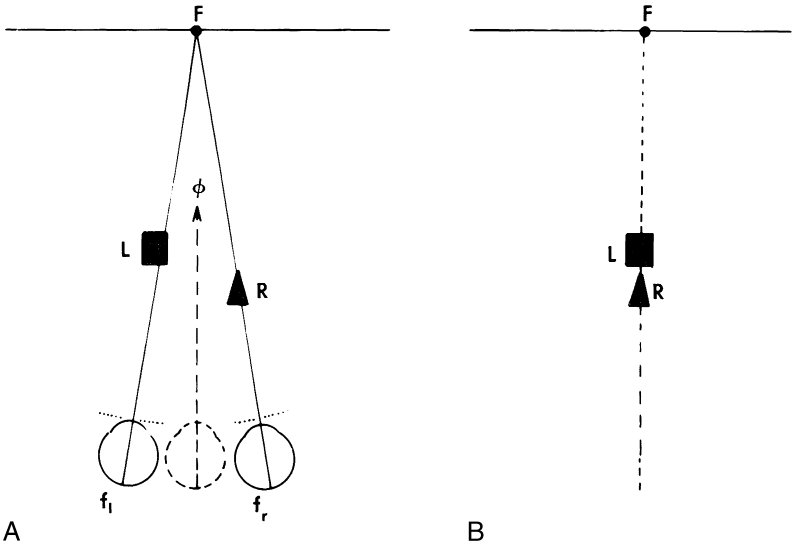

**FIGURE 2–2.** *A*, The fixation point, F, and the objects L and R all lie on the geometric lines of direction $Ff_l$ and $Ff_r$ of the two foveae. F, L, and R therefore are seen behind each other in subjective space in the common relative subjective visual direction of the two foveae, f, as shown in *B*. The imaginary "third" eye, the cyclopean eye, is indicated by dashed lines in *A*.

## *Common Relative Subjective Visual Directions*

Thus far, only the single eye has been discussed. How do the relative subjective visual directions of the two eyes relate to each other?

Let a person with head erect fixate an object, F (Fig. 2–2), called the fixation point. $Ff_l$ and $Ff_r$ are the lines of direction of the two foveae and as such are of special importance. They are also called principal lines of direction or visual axes. Other synonyms are line of gaze, line of vision, and line of regard. If the two principal lines of direction intersect at the fixation point, it is said that there is binocular fixation. If only one principal line of direction goes through the fixation point, fixation is monocular.

As we have seen, F, fixated binocularly (see Fig. 2–2), is seen not in the direction of the principal line of direction of either eye but in a direction that more or less coincides with the median plane of the head. This holds true not only for the fixation point but also for any object point in the principal line of direction. L and R in Figure 2–2, which lie on the principal lines of direction of the left and right eyes, therefore will appear to be behind each other and in front of F, although all three are widely separated in physical space. All object points that simultaneously stimulate the two foveae appear in one and the same subjective visual direction. This direction belongs to both the right and left foveae and therefore is called the common subjective visual direction of the foveae.

The two foveae have more than just a common visual direction; if an observer fixates F binocularly (Fig. 2–3), the object points, N and N′, if properly positioned, will be seen behind each other, since the peripheral retinal points $n_l$ and n have a common visual direction represented by b. What applied to $n_l$ and n applies to all other retinal elements. Every retinal point or area has a partner

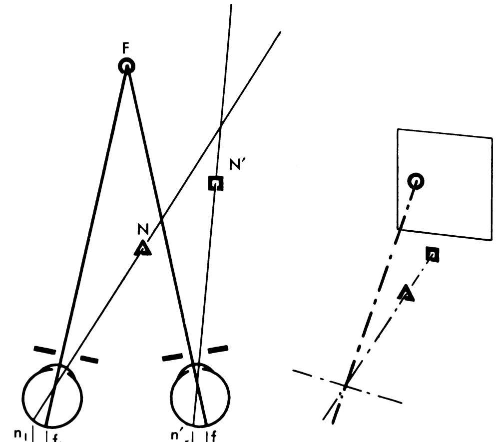

**FIGURE 2–3.** *A*, Stimulating corresponding retinal elements, objects N and N′, are localized in visual space in the common relative subjective visual direction of $n_l$ and $n'_r$ and despite their horizontal separation are seen behind each other in *B*, subjective visual space. F, fixation point.

in the fellow retina with which it shares a common relative subjective visual direction.

## Retinal Correspondence

Retinal elements of the two eyes that share a common subjective visual direction are called corresponding retinal points. All other retinal elements are noncorresponding or disparate with respect to a given retinal element in the fellow eye. This definition also may be stated in the following way: *corresponding retinal elements are those elements of the two retinas that give rise in binocular vision to the localization of sensations in one and the same subjective visual direction.* It does not matter whether a stimulus reaches the retinal element in one eye alone or its corresponding partner in the other eye alone or whether it reaches both simultaneously (see Figs. 2–2 and 2–3).

The common visual direction of the foveae is again of special importance. All visual directions, as has been seen, have a relative value in subjective space. The common subjective visual directions, too, have a fixed position relative only to the principal common visual direction. They determine the orientation of visual objects *relative to each other* with the principal visual direction as the direction of reference.

All common subjective visual directions can be represented in a drawing as intersecting at one point with the principal visual direction. Thus, they form a sheaf that is the subjective equivalent of the two physical eyes and may be thought of as the third central imaginary eye[46, p. 348] or the binoculus, or *cyclopean eye*[44, vol. 3, p. 258] (see Fig. 2–2). If the principal subjective visual direction lies in the median plane of the head, the physical correlate of the point of intersection of the visual directions, their origin, would be approximately in the area of the root of the nose (whence ‘‘cyclopean’’ eye).

Corresponding retinal elements arranged in horizontal and vertical rows provide the subjective vertical and horizontal meridians. Meridians that include the visual direction of the fovea are the principal corresponding horizontal and vertical meridians.

The existence of corresponding retinal elements with their common relative subjective visual directions is the essence of binocular vision. It may be called the *law of sensory correspondence* in analogy with the law of motor correspondence, which is discussed in Chapter 4.

The oneness of the directional sensory responses originating in each eye is impressively demonstrated by means of afterimages. If one creates an afterimage on the retina of one eye, it will appear in the binocular field of view in the common visual direction of the stimulated retinal area and in its nonstimulated partner in the other eye. It is difficult, indeed almost impossible, for the observer to judge which eye carries the afterimages. It will continue to be seen and localized in the same direction, whether the eyes are open or closed or whether the stimulated eye is closed and the other eye held open. In this latter situation some authors[19, 55] have spoken of an *afterimage transfer.* This term is a misnomer as nothing is being transferred.[43]

If a horizontal afterimage is formed in one eye by a strong horizontal light stimulus, leaving the fovea unstimulated, and if a similar vertical afterimage is created in the other eye, the resulting visual percept is an afterimage in the form of a cross with a gap in its center.[10, 49, p. 158] The gap is seen because of the lack of stimulation in the foveae. The center of the horizontal and vertical afterimages is consequently a single spot localized in the principal common visual direction. The horizontal and vertical legs of the afterimages are oriented accordingly (Fig. 2–4). It is of great importance to understand clearly that *the appearance of the afterimage cross is independent of the position of the eyes.* Once a lasting stimulus, such as an afterimage, has been imparted, its localization in subjective space depends solely on the visual direction of the retinal elements involved. One may topically anesthetize one eye and move it passively with a forceps or push it in any direction with one’s finger—the cross remains a cross. No change in the relative localization of the vertical and horizontal afterimage will occur. The use of afterimages has an important place in the diagnosis of anomalous retinal correspondence (see Chapter 13). The principles underlying afterimage testing must be fully understood to guard against gross errors in interpretation.

## Sensory Fusion

Sensory correspondence explains binocular single vision or sensory fusion. The term is defined as *the unification of visual excitations from corresponding retinal images into a single visual percept, a single visual image.* An object localized in one and the same visual direction by stimulation

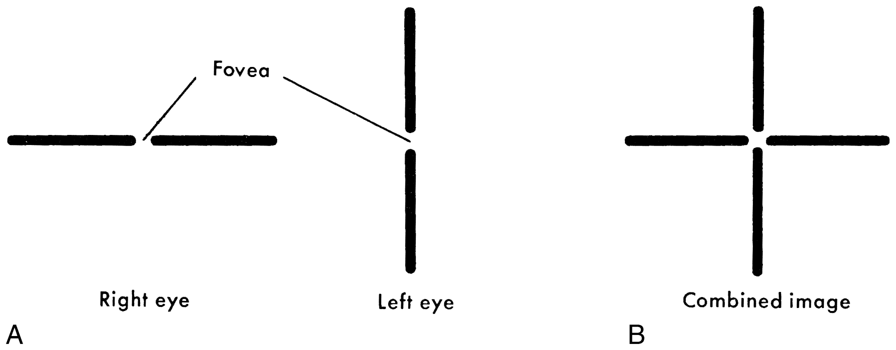

**FIGURE 2–4.** *A*, Afterimages produced in the right and left eye, respectively. The fovea is represented by the break in the afterimage. *B*, The combined binocular afterimage forms a cross. The two gaps appear single.

of the two retinas can only appear as one. An individual cannot see double with corresponding retinal elements. *Single vision is the hallmark of retinal correspondence.* Put otherwise, the stimulus to sensory fusion is the excitation of corresponding retinal elements.

Since both the central and peripheral parts of the retina contribute fusible material, it is misleading to equate sensory fusion with ‘‘central’’ fusion (as opposed to ‘‘peripheral’’ or motor fusion). Fusion, whether sensory or motor, is always a central process (i.e., it takes place in the visual centers of the brain).

For sensory fusion to occur, the images not only must be located on corresponding retinal areas but also must be sufficiently similar in size, brightness, and sharpness. Unequal images are a severe sensory obstacle to fusion. Obstacles to fusion may become important factors in the etiology of strabismus (see Chapter 9). Differences in color and contours may lead to retinal rivalry.

The simultaneous stimulation of noncorresponding or disparate retinal elements by an object point causes this point to be localized in two different subjective visual directions. An object point seen simultaneously in two directions appears double or in diplopia. *Double vision is the hallmark of retinal disparity.* Anyone with two normal eyes can readily be convinced of this fact by fixating binocularly an object point and then displacing one eye slightly by pressure from a finger. The object point, which appeared single before pressure was applied to the globe, is now seen in diplopia because it is no longer imaged on corresponding retinal areas. Qualifications that must be made about equating disparate retinal elements and diplopia are discussed on page 20. Paradoxical diplopia with ordinarily corresponding elements in cases of strabismus is discussed in Chapter 13.

### Motor Fusion

The term motor fusion refers to the ability to align the eyes in such a manner that sensory fusion can be maintained. The stimulus for these fusional eye movements is retinal disparity outside Panum's area and the two eyes are moving in opposite directions (vergences; see Chapter 4). Unlike sensory fusion, which occurs between corresponding retinal elements in the fovea and the retinal periphery, *motor fusion is the exclusive function of the extrafoveal retinal periphery.* No stimulus for motor fusion exists when the images of a fixated visual object fall on the fovea of each eye.

## Retinal Rivalry

When dissimilar contours are presented to corresponding retinal areas, fusion becomes impossible. Instead, retinal rivalry may be observed. This phenomenon, also termed binocular rivalry, must be clearly distinguished from local adaptation, or Troxler's phenomenon.[67]

If a person looks into a stereoscope at two dissimilar targets with overlapping nonfusible contours, first one contour, then the other will be seen, or mosaics of one and the other, but not both contours simultaneously. In Figure 2–5, taken from Panum,[78] each eye sees a set of oblique lines, one going from above left to below right, seen by the left eye, and another set going from above right to below left, seen by the right eye. When observed in a stereoscope, these lines are not seen as crossing lines but as a changing pattern of

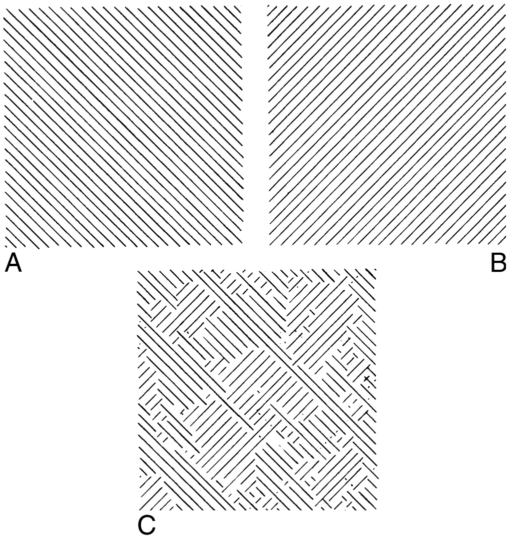

**FIGURE 2–5.** Rivalry pattern. *A*, Pattern seen by the left eye. *B*, Pattern seen by the right eye. *C*, Binocular impression. (From Panum PL. Physiologische Untersuchungen über das Sehen mit zwei Augen. Kiels. Germany, Schwerssche Buchhandlung, 1858, pp. 52 *ff.*)

patches of oblique lines going in one or the other direction.

Binocular rivalry may also be produced by uniform surfaces of different color (color rivalry) and unequal luminances of the two targets. Many combinations of contours, colors, and luminances have been studied exhaustively since the days of Panum,[78] Fechner,[41] Helmholtz,[44] and Hering.[45] Review of the literature may be found in the reports of Hofmann,[49] Ogle,[76, p. 409] and Levelt.[67]

It is of interest that it takes a certain buildup of time (150 ms) before dissimilar visual input to the eyes causes binocular rivalry. Dichoptic stimuli were perceived as ‘‘fused’’ when presented for shorter periods.[63]

The phenomenon of retinal rivalry is basic to binocular vision and may be explained as follows. Simultaneous excitation of corresponding retinal areas by dissimilar stimuli does not permit fusion; but since such excitations are localized in the same visual direction and since two objects localized in the same place give rise to conflict and confusion, one or the other is temporarily suppressed. Which of the two is suppressed more depends on the greater or lesser dominance of one eye rather than on the attention value of the visual object seen by each eye.[17] In other words, it is the eye and not the stimulus that competes for dominance under a wide range of conditions. Stimulus rivalry occurs only within a limited range of spatial and temporal parameters.[59]

The extent to which true fusion or monocular alternation in the binocular field governs normal visual activity—in other words, the significance of the rivalry phenomena for the theory of binocular vision—is considered on page 31.

It is at once clear that rivalry phenomena, or rather their absence, must in some fashion be related to what is known as suppression in strabismic patients. Suppression is discussed in detail in Chapter 13. Here we state only that constant foveal suppression of one eye with cessation of rivalry leads to complete sensory dominance of the other eye, which is a major obstacle to binocular vision. Return of retinal rivalry is a requisite for reestablishment of binocular vision.

The retinal rivalry phenomenon has been explained in neurophysiologic terms by the presence of separate channels for the right and left eyes that compete for access to the visual cortex. A third binocular channel is activated only by fusible input.[27, 102] Because of this competition and the inhibition elicited, only fragments of the image seen by each eye are transmitted to the striate cortex in the case of nonfusible binocular input. Competitive interaction occurs not only in the primary visual cortex[14] but continues at several afferent levels of the visual pathway, well after the inputs to the two eyes have converged.[64]

## Objective (Physical) and Subjective (Visual) Space

Certain terminological differentiations made earlier in this chapter will not have escaped the notice of the attentive reader. For example, *location* of an object point in physical (objective) space was separated from its *localization* in visual (subjective) space. The (objective) lines of direction determine which retinal area will be stimulated; their (subjective) counterpart, the visual directions, determine the direction in which the object will be seen in visual space.

Clear distinctions between physical space and its subjective counterpart are essential both in thinking about spatial orientation and in the expression of that thinking. Failure to do so has been the source of much confusion and error in the description of normal and abnormal binocular vision. The naive observer gives little thought to vision. His thoughts are for the things he sees. He takes it for granted that he sees things as they are and where they are. This instinctive approach is deeply ingrained in all of us, and we act in accordance with it in practical life. In fact, however, we do not see physical objects. What takes place is that energy in the form of light waves is absorbed by photosensitive receptors in the retina and is transformed into other forms of energy. Eventually this process leads in some manner to events occurring in our consciousness; we call this seeing. Thus, vision results from the active transformation of the excitations produced initially in our retinas by energy emanating from a narrow band within the electromagnetic spectrum. In consciousness this builds up our world of light, color, and spatial orientation.

This view of vision is not shared by everyone. Some maintain that events in certain parts of the brain are synonymous with vision and that what we experience in consciousness is an epiphenomenon. Others state that vision is nothing more than an overt response of the organism to stimulation, a form of behavior, but all concede that we do not see physical objects. What occurs in our brain are physicochemical and electrical events. What we experience in our consciousness are sense data. In joining one sense datum to other sense data derived from the same or from different receptor organs, we proceed from sensation to perception. Relating these sense data to past experience is enormously complex, and each new sense datum becomes either meaningful or not meaningful.

The sense datum is qualitatively different from and is not commensurate with the physical process to which it is correlated. This is immediately clear when speaking of colors. Neither radiant energy of 640 mm nor the processes evoked by this radiant energy in the retina, the optic nerve, or the brain cells is ‘‘red.’’ Red is a sensation. It is not immediately clear that similar considerations apply to the perception of space. That they indeed do apply will be evident throughout this book.

The scientific or philosophical validity of the various concepts of the nature of sensation and perception and of ‘‘reality’’ will not be argued here. The question under consideration is not which view is ‘‘true’’ or ‘‘correct’’—that is, verifiable—but which one gives the best description of the phenomena and is most likely to help in furthering the understanding and the advancement of clinical work. In this respect, the most useful view is that incorporated into the methodology termed *exact subjectivism* by Tschermak-Seysenegg.[94] This view recognizes objective and subjective factors in vision, that *physical space,* of which we and our visual system are a part, and *subjective space* are built up from sense data.

The subjective space is private to each one of us. A color-normal person can understand but never experience how a color-blind person sees the world, nor can a color-blind person ever experience colors as a color-normal person does. Similarly, a person with a normal sensorimotor system of the eyes may be able to understand but can never experience certain phenomena that people with abnormal sensorimotor systems may experience in their subjective space (see Chapter 13).

The sensations of color and spatial localization are not anarchic, however. Certain physical processes are always correlated with certain sensations and perceptions. Known changes introduced into the environment produce regular changes in sensations and perceptions. These lawful relations allow us to make quantitative determinations. We have no yardstick for the sensation ‘‘red,’’ and we have no yardstick for subjective space; but we can characterize them quantitatively by changes in the environment with which they are correlated.

Each stimulus has certain characteristics: luminance, wavelength, extent, and location in physical space. All these parameters, singly and combined, have an effect on the visual system; but how a colored object appears does not depend solely on the wavelength it emits or reflects but also on the state of the eye, particularly on the color to which it has been previously adapted. The brightness of a percept depends not only on the luminance of the stimulus but also on the state of the eye and its responsiveness. For instance, a stimulus that is below threshold for an eye adapted to bright light may appear very bright if the eye is adapted to darkness.

The ability of the eye to adapt to varying levels of illumination is involved also in one of the *constancy phenomena.* A white sheet of paper appears to be white not only at noon but also at twilight, although it reflects much more light into the eye at noon. The smaller amount of light is as effective in the dark-adapted eye as is the greater amount of light in the light-adapted eye. Up to a certain distance the size of a man remains constant as he walks away from us, although the retinal image grows smaller (size constancy). Eventually, however, he will appear smaller, and as he recedes farther he shrinks to a point and finally disappears altogether.

Most important, no stimulus is ever isolated. It

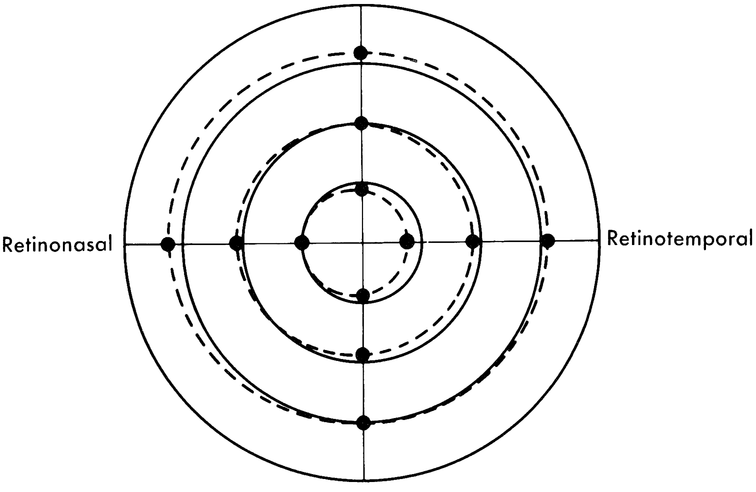

**FIGURE 2–6.** Retinal discrepancies. Subjective appearance of circles (broken lines) contrasts with objective circle (solid lines). (From Tschermak-Seysenegg A Von: Der exacte Subjectivismus in der neueren Sinnesphysiologie, ed 2, Vienna, Emil, Haim, 1932.)

has a surround, and this surround also has stimulus qualities. The effects of the surround, especially at the borders, lead to the phenomena of induction and physiologic contrast, which play a great role in visual discrimination and color vision.

Where a visual object is localized in subjective space relative to other objects does not depend on the position of that object in physical space. It depends on the visual direction of the retinal area that it stimulates. An object may be located in physical space at any place. So long as it stimulates the foveae it is seen in their common subjective visual direction.

## *Discrepancies of Objective and Subjective Metrics*

The difference between the metric of physical space and the metric of the eye is emphasized by

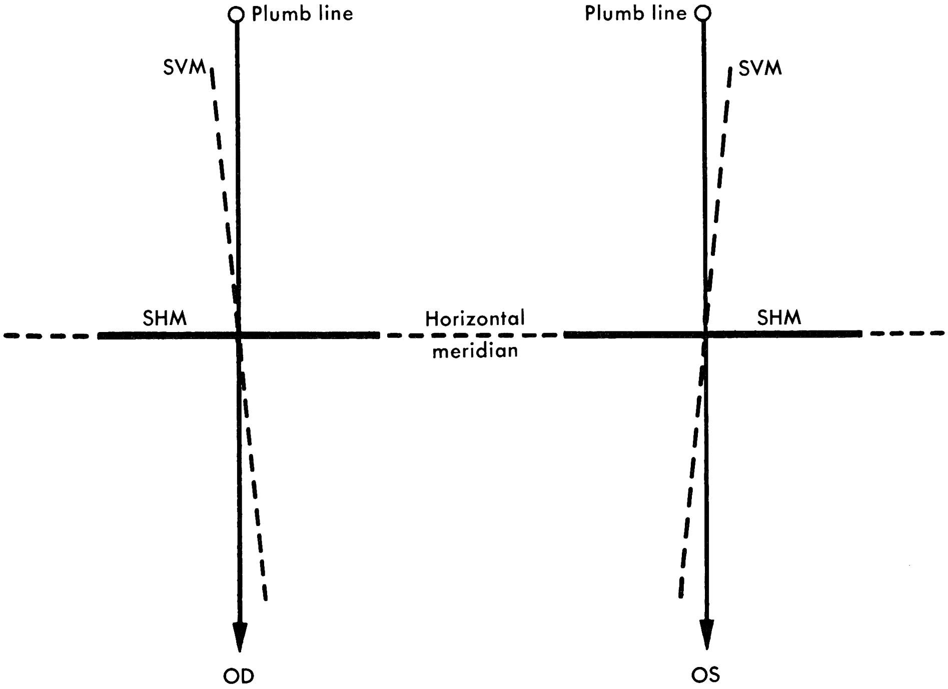

**FIGURE 2–7.** Discrepancies between subjective vertical meridian, SVM, and plumb line in the two eyes. No discrepancy exists between the subjective horizontal, SHM, and the objective horizontal meridians. (From Tschermak-Seysenegg A Von: Der exacte Subjectivismus in der neueren Sinnesphysiologie, ed. 2, Vienna, Emil Haim, 1932.)

the existence of so-called visual discrepancies. If one attempts to bisect a monocularly fixated line in an arrangement that excludes other visual clues from the field, a constant error is detected. The line is not divided into two objectively equal line segments. If placed horizontally, the line segment imaged on the nasal side of the retina, that is, the one appearing in the temporal half of the field, is larger than the temporally imaged retinonasal line segment. This is the famous partition experiment of Kundt, a German physicist of the mid nineteenth century.[95, p. 137] The opposite phenomenon, described by Münsterberg,[73] occurs only rarely. Similarly, the lower line segment (imaged retinosuperiorly) is shorter than the upper (retinoinferior) segment. In subjective space, therefore, the equivalent of a true circle fixated centrally is a somewhat irregular round figure, the smallest radius of which points outward. Accordingly, a subjectively true circle does not correspond to a true circle in physical space (Fig. 2–6). In general, the discrepancies in the two eyes are symmetrical. They compensate each other, and the partition of a line into two equal segments is more nearly correct in binocular fixation.

There are also directional discrepancies that result in a deviation of the subjective vertical from the objective vertical. A monocularly fixated plumb line shows a definite disclination with the top tilted templeward. This disclination is, as a rule, approximately symmetrical in the two eyes (Fig. 2–7). In general, the angle of disclination is not greater than 4° to 5°, but it has been reported in isolated cases to be as high as 14°.

The discrepancies described are evidence that the retinal elements that physically have the same eccentricity in the two eyes are not equivalent functionally. This is the basis of the Hering-Hillebrand horopter deviation (see p. 18).

## Distribution of Corresponding Retinal Elements

### *The Foveae as Corresponding Elements*

That the foveae have a common subjective visual direction is demonstrated by Hering's fundamental experiment,[46, p. 343] which in its classic simplicity is reminiscent of a bygone day when basic discoveries in physiologic optics could be made with a candle, some cardboard, and a few strings and pulleys.

Place yourself in front of a closed window with an open view. Close the right eye and look for an outstanding, somewhat isolated object, say, a tree. Make an ink mark on the window pane at about the midline of your head that will cover a spot on the tree. Now close your left eye, open the right eye without moving your head, and fixate the ink spot. Observe what object it covers in the landscape, say, a chimney on a house. Open both eyes and fixate the ink spot binocularly. You will note that the chimney, the tree, and the ink spot appear in a line behind each other, approximately in the midline of your head. All those objects are seen in the common visual direction of the two foveae, even though they may actually be widely separated in physical space (Fig. 2–8). If you now place the point of a fine object (e.g., the tip of a pencil) between one eye and the ink spot, it will also appear in line with the objects seen outside

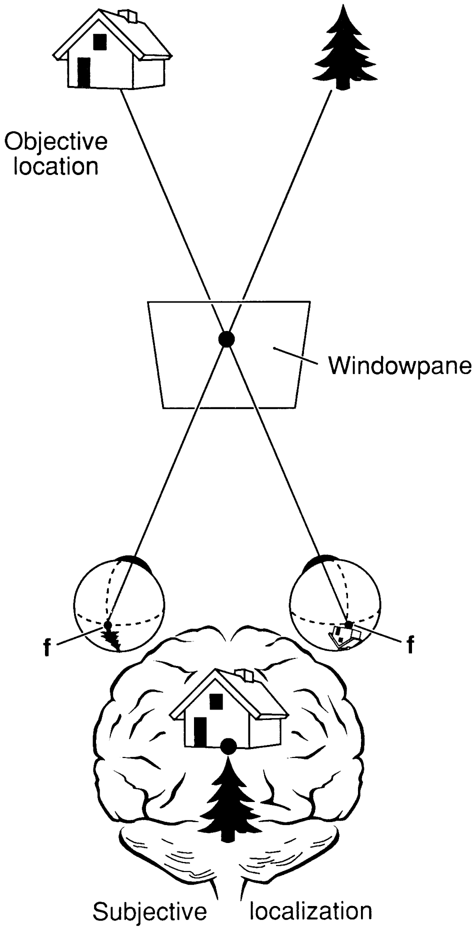

**FIGURE 2–8.** Hering's fundamental experiment. (Modified from Ogle KN: Researches in Binocular Vision. Philadelphia, WB Saunders, 1950.)

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EXPOSITIS *hactenus iis quæ naturæ viſus inſunt, ad ea progreſſum facimus, quæ ex ipſa natura, ceu ex fonte riuuli, emanant; philoſophi affectiones vocant. In quibus quæ toti naturæ, ac ſoli, ſemperque conueniunt, maximè dicuntur propriæ; quæ verò ſoli, at non omni, aut non ſemper, propriæ illæ quidem, ſed non maximè; quæ demum aliis quoque interdum obueniunt, communes vocitantur. Quæ primo genere continentur, eæ ex ipſis naturæ principiis proximè ſcaturiunt, ideoque nullam aliam cauſam habent, quàm naturam ipſam ita à prima origine conſtitutam. Ex his deinde propriæ affectiones deriuantur, quarum proinde ſuperiores, quæ maximè pro-*

*priæ*

**FIGURE 2–9.** *A*, Title page of the volume by Francis Aguilonius, S.J., *Six Books on Optics Useful to Philosophers and Mathematicians*, published in Antwerp, 1613. *B*, First page of book II of Aguilonius' volume, which deals with the horopter × 30.

the window. This simple experiment shows convincingly the discrepancies that may exist between subjective and objective physical space.

## The Horopter

Determining the distribution of the corresponding retinal elements throughout the retina is less readily achieved. For a long time the idea prevailed that the distribution of the corresponding retinal elements was strictly geometric. If this were indeed true, then corresponding points would be retinal elements having the same horizontal and vertical distance from the fovea in the right and left halves of the retinas. The following mental experiment clarifies the concept. Place the two retinas one on the other so that the two foveae and the geometric horizontal and vertical meridians coincide. Imagine a needle placed through the two retinas anywhere within the area subserving the field of binocular vision. The needle should strike corresponding points in the two retinas. On the assumption that this is in fact the case, the horopter was determined theoretically.

*Horopter* is a very old term, introduced in 1613 by Aguilonius[1] in his book on optics (Fig. 2–9) even though the basic concept of the horopter had been known since the times of Ptolemy.[36] In modern usage it is defined as the locus of all object points that are imaged on corresponding retinal elements at a given fixation distance.

The determination of the total horopter surface was approached mathematically by Helmholtz[44, vol. 3, pp. 460 ff], on the basis of assumptions about the geometric distribution of the corresponding retinal elements and about the position of the subjective vertical meridians. For our purpose, we need be concerned only with the horizontal distribution of corresponding retinal elements and to consider the longitudinal horopter curve. This is the line formed by the intersection of the visual plane (with head erect and eyes fixating a point straight

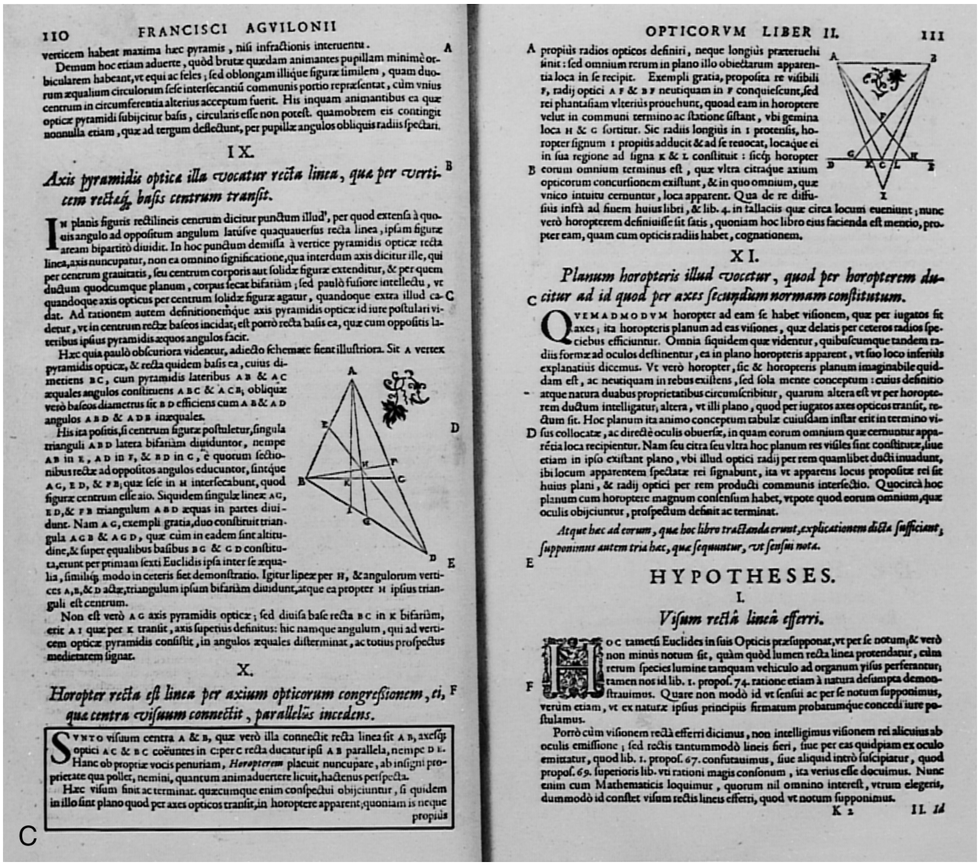

**FIGURE 2–9** *Continued. C,* Pages 110 and 111 of the volume of Aguilonius in which he introduces the term *horopter* and defines it as the line that delimits and bounds binocular vision. The pertinent paragraph is indicated by a box. (From the copy of the book of Aguilonius at Dartmouth College's Baker Library. Courtesy Dartmouth College Photographic Service, Hanover, NH.)

ahead in symmetrical convergence) with the horopter surface.

The term *longitudinal horopter* is an inadequate translation of the German term *Längshoropter*. Boeder, in his 1952 translation of Tschermak-Seysenegg's *Einführung zur physiologischen Optik* (Introduction to Physiological Optics), suggested the term *horopter of horizontal correspondence*.[95, p. 134] This much better but somewhat cumbersome term has not found general acceptance. The term longitudinal horopter refers to the locus in space of object points imaged on "subjective longitudes" of the retina.

**VIETH-MÜLLER CIRCLE.** If corresponding points have a geometrically regular horizontal distance from the two retinas, the longitudinal horopter curve would be a circle passing through the center of rotation of the two eyes and the fixation point (Fig. 2–10). This would be true because by the theorem of inscribed circles any lines drawn from two points on a circle to any other pair of points on its circumference include equal angles, as shown in the insert (see Fig. 2–10). This was first pointed out by Vieth[99] and later taken up by Müller,[72] and this circle, which is the theoretical or mathematical horopter curve, is also known as the Vieth-Müller circle (see Fig. 2–10).

**EMPIRICAL HOROPTER CURVE.** By actual experimental determinations of the horopter curve, Hering[45, 46] and his pupil Hillebrand[47] could show that the Vieth-Müller circle does not describe the longitudinal horopter. The empirical horopter curve is flatter than the Vieth-Müller circle (see Fig. 2–10). This means that the distribution of the elements that correspond to each other is not the same in the nasal and temporal parts of the two retinas (e.g., the right half of each retina). The characteristics of the horopter for each individual vary within certain limits; each person has his personal horopter.

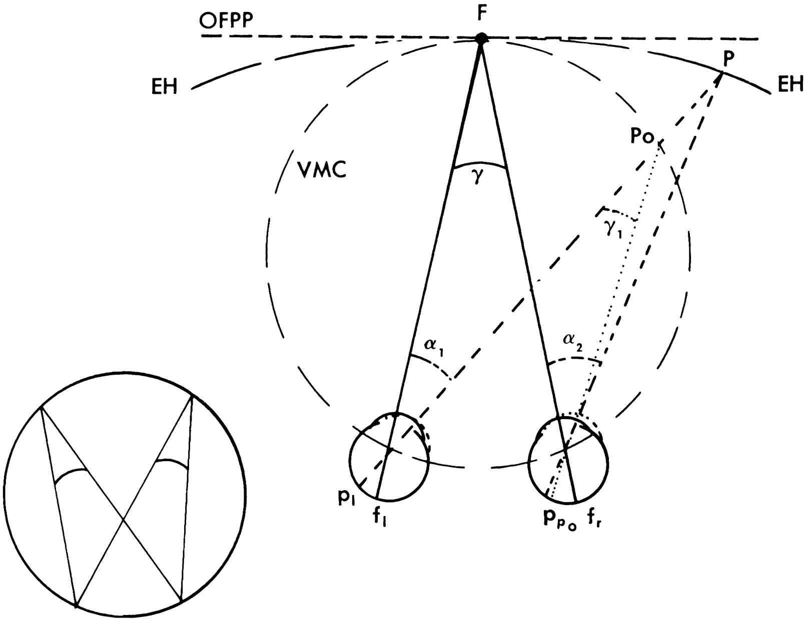

**FIGURE 2–10.** Vieth-Müller circle. VMC, empirical horopter; EH, objective frontoparallel plane; OFPP, fixation point; F, inset, law of inscribed circles. Object P on EH is seen singly, but object PO on VMC elicits double vision because of discrepancies between the empirical and theoretical horopter (see text).

The discrepancy between the theoretical horopter (the Vieth-Müller circle) and the empirically established horopter curve (the so-called Hering-Hillebrand horopter deviation) might be attributed to disturbing optical properties of the ocular media. However, Tschermak-Seysenegg[95] has shown conclusively that this is not the case.

A great deal of work has been expended on experimental studies of the horopter. Interested readers are referred to the books by Tschermak-Seysenegg[95] and Ogle.[75] Only the broad outlines of the information resulting from this work and the experimental techniques are discussed on page 28, but first other phenomena of binocular vision must be presented.

## Physiologic Diplopia

All object points lying on the horopter curve stimulate corresponding retinal elements. By definition, all points on the horopter curve are seen singly. Also by definition, all points not lying on the horopter curve are imaged disparately and, with certain qualifications, are seen double. The diplopia elicited by object points off the horopter is called physiologic diplopia.

Physiologic diplopia can be readily demonstrated to anyone with normal binocular vision. Hold a pencil at reading distance in front of your head in its midplane and select a conspicuous, somewhat isolated object on the wall in line with the pencil. Fixate the more distant object, and the pencil will be seen double. Shut alternately one eye and then the other. The contralateral double image of the pencil will disappear; that is, the image on the left will disappear if the right eye is shut, and the one on the right will disappear if the left eye is shut. In other words, when fixating a distant object, a nearer object is seen in crossed (heteronymous) diplopia. Crossed diplopia is explained by the fact that the nearer object is seen in temporal (crossed) disparity with reference to its fovea (or to a corresponding element in peripheral vision if the nearer object is located in the periphery of the visual field). This is shown in Figure 2–11, *A*.

If one now fixates the pencil binocularly it will be seen singly, but the more distant object doubles up. By again alternately closing each eye, one finds that the ipsilateral double image vanishes. There is uncrossed (homonymous) diplopia because the more distant object is imaged in nasal (uncrossed) disparity (Fig. 2–11, *B*).

### *Clinical Significance*

Physiologic diplopia, a fundamental property of binocular vision, has a twofold clinical significance.

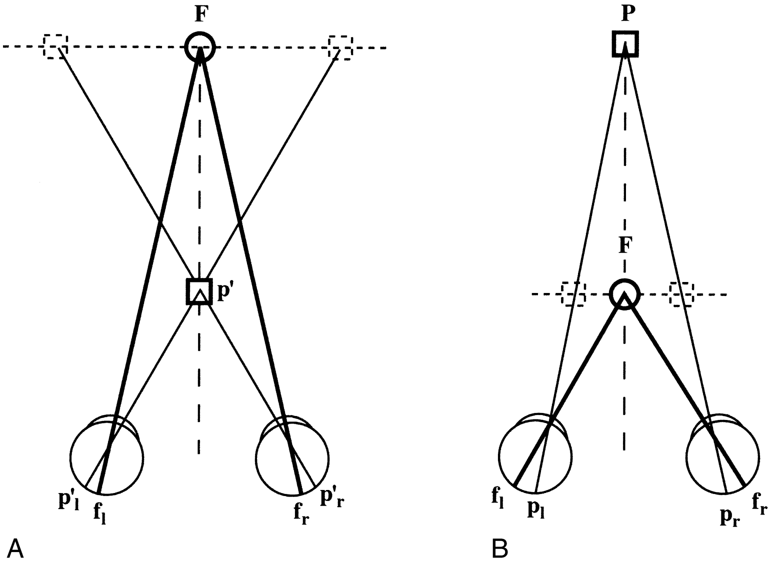

**FIGURE 2–11.** Physiologic diplopia. *A*, Crossed (heteronymous) diplopia of the object p′, closer than the fixation point F, imaged in temporal disparity. *B*, Uncrossed (homonymous) diplopia of the object P, more distant than the fixation point F and imaged in nasal disparity.

Occasionally a person accidentally will become aware of physiologic diplopia. Since double vision must appear as an abnormal situation, the individual likely will seek the help of an ophthalmologist. If the ophthalmologist cannot establish the presence of an acute paresis of an extraocular muscle or any of the other causes of diplopia mentioned in this book, one must conclude that all the patient has experienced is physiologic double vision. The ophthalmologist must attempt to explain to the patient that physiologic diplopia is a characteristic of normal binocular vision and evidence that the patient enjoys normal cooperation of the two eyes. This is not always easy. Apprehensive, neurotic patients may not accept the explanation and will reinforce the annoyance by constantly looking for a second image “that should not be there.” Many patients have spent considerable amounts of money looking for an ophthalmologist who will finally rid them of their diplopia.

This is the undesirable clinical aspect of physiologic diplopia. The desirable use that can be made of physiologic diplopia is both diagnostic and therapeutic. In diagnosing binocular cooperation, the presence of physiologic diplopia indicates that the patient is capable of using both eyes in casual seeing and presumably does so. In orthoptic treatment of comitant strabismus, physiologic diplopia is an important tool (see Chapter 24).

## Suppression

Physiologic diplopia is not just a trick produced in vision laboratories. It is a phenomenon inherent to normal binocular vision. The question arises, why are we not always aware of diplopia?

From the first moment in which binocular vision is established, we become accustomed or conditioned to the arrangements provided for binocular seeing and hence to physiologic diplopia. We learn how to disregard it, and unless some abnormal process interferes we are never aware of diplopia.

If a patient acquires an acute lateral rectus paresis in one eye, the eye turns in. An object point fixated by the other eye is now imaged on a nasally disparate area in the deviated eye. Consequently, the patient experiences uncrossed diplopia. If he or she has acquired a medial rectus paralysis, the eye turns out and the fixation point is imaged in temporal disparity. The patient has crossed diplopia. These forms of diplopia in patients with acute paralytic strabismus are to be expected from what is known about physiologic diplopia and are a *normal* response of the sensory system to an abnormal motor situation.

As a rule, patients with comitant strabismus of early onset do not see double in spite of the relative deviation of the visual lines. Visual impressions that should be transmitted to the brain by one eye may be suppressed. The ability to disregard physiologic diplopia must be distinguished from suppression, an active, inhibitory mechanism. The former is a psychological, the latter a neurophysiologic process. The ability to selectively exclude certain unwanted visual impulses from entering consciousness (the ability to disregard or suppress them) is important in normal

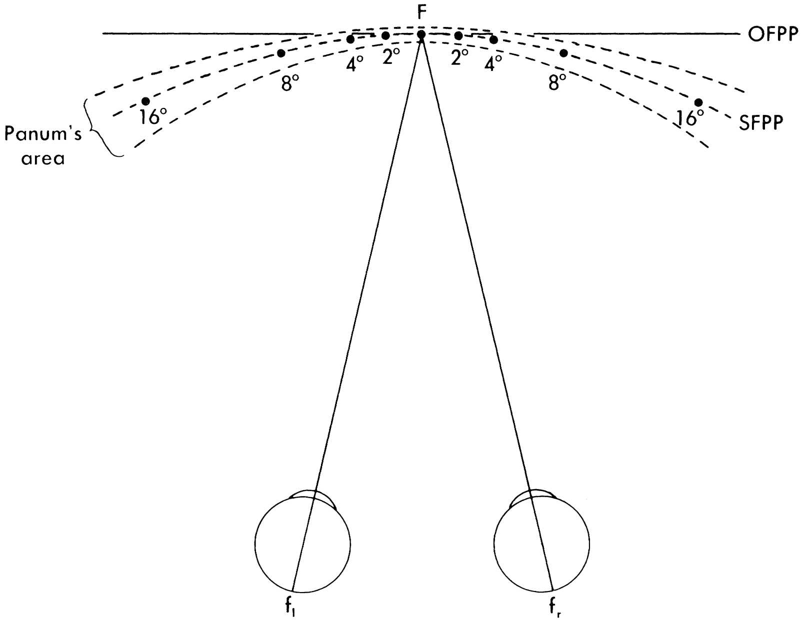

**FIGURE 2–12.** Panum's area as determined on the horopter instrument. F, fixation point; OFPP, objective frontoparallel plane; SFPP, subjective frontoparallel plane (horopter).

and abnormal vision and is given a good deal of attention in the clinical parts of this book.

## Panum's Area of Single Binocular Vision

The statement has been made that object points lying on the horopter are seen singly, whereas points off the horopter are seen double. The first part of this statement always holds true; the second part needs qualification.

If under appropriate experimental conditions, one fixates a fixed vertical wire with a number of movable vertical wires arranged to each side of the fixation wire (p. 28), all wires are seen singly if they are placed on the horopter. If one of the wires seen in peripheral vision is moved, one will notice that this wire can be displaced a certain short distance, forward or backward, away from the horopter position without being seen double. Since the wires must be imaged on disparate retinal meridians as soon as they are displaced from the horopter, it follows that within a narrow band around the horopter stimulation of disparate retinal elements transmits the impression of single vision. Panum,[78] the Danish physiologist, first reported this phenomenon, and the region in front and back of the horopter in which single vision is present is known as Panum's area of single binocular vision or Panum's fusional area (Fig. 2–12). Not only is single vision possible in Panum's area but visual objects are seen stereoscopically, that is, in depth.

According to classic views the horizontal extent of these areas is small at the center (6 to 10 minutes near the fovea) and increases toward the periphery (around 30 to 40 minutes at 12° from the fovea). The vertical extent has been variously assessed by different observers.[75, p. 66] However, more recent research suggests that Panum's area is considerably larger. Moving random-dot stereograms, which are most effective in retaining fusion while the disparity is increased, have shown that disparities of as much as 2° to 3° can be fused.[40, 54, 79]

The increase of Panum's area toward the periphery may be related to anatomical and physiologic differences known to exist between the monosynaptic foveal cone system and the rod and cone system of the periphery. It parallels the increase in size of the retinal receptive fields. Note also the ability of summation of the retinal periphery, an ability that is virtually absent in the fovea in the photopic state (see Chapter 13). The horizontal extent of Panum's area can be reduced to some degree by training.

The question is sometimes asked whether Panum's area is in (physical) space outside the eye or in the retina. This question is obviously meaningless. This “area” represents the subjective response to a specific stimulus situation eliciting single visual impressions. The areas in physical space (location of object points and their images on the retinas) simply define operationally the regions within which binocular single vision may be obtained with stimulation of disparate retinal areas.

## Fixation Disparity

A physiologic variant of normal binocular vision exists when a minute image displacement, rarely exceeding several minutes of arc of angle, occurs within Panum’s area while fusion is maintained. Although this phenomenon was demonstrated in earlier experiments,[4, 50] Ogle and coworkers[77] were the ones who clarified the nature of this condition and coined the term *fixation disparity.*

Fixation disparity can be elicited experimentally by presenting in a haploscopic device visual targets that appear as mostly similar and some dissimilar markings to the eyes. Such an experimental arrangement, from a paper by Martens and Ogle,[70] is shown in Figure 2–13. The periphery of the screen, seen by each eye, containing identical visual information is fused. At the center of the screen two vertical test lines are arranged so that the lower one is seen only by the right eye and the upper one only by the left eye. The position of one of these lines can be varied so that during the test the lines can be adjusted until they appear aligned to the observer. The actual separation of the lines, expressed in minutes of arc of subtended angle, is the fixation disparity. Whether fixation disparity is an interesting but clinically irrelevant laboratory finding or whether it represents the first step between orthophoria and microtropia is a matter of debate.[32]

The use of the fixation disparity method to measure the accommodative convergence–accommodation (AC/A) ratio is described in Chapter 5, and its possible relationship to the etiology and pathophysiology of heterophoria is discussed in Chapter 9.

## Stereopsis

When the experiment using fixation wires is performed to determine Panum’s area and the wires seen peripherally are moved backward and forward, they do not double up so long as they remain within Panum’s area of single binocular vision. As soon as they are moved out of the horopter position, however, they appear in front or in back of the fixation wire and are then seen stereoscopically. *Stereopsis* is defined as the relative ordering of visual objects in depth, that is, in the third dimension. This extraordinarily intriguing quality of the visual system requires a rather detailed analysis.

Relative localization in the third dimension in depth parallels that of visual objects in the horizontal and vertical dimensions. The ability to perceive relative depth allows one to localize the peripherally seen wires just alluded to in front or in back of the fixation wire, and it is this ability that permits one to perceive a cube as a solid.

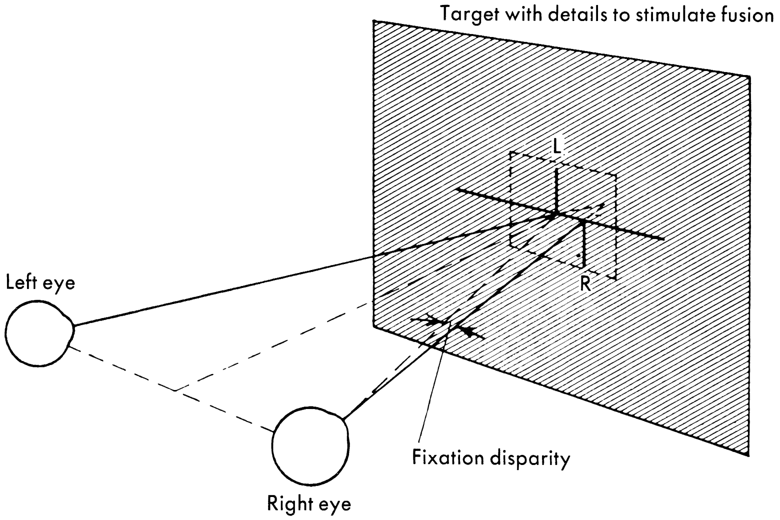

**FIGURE 2–13.** Testing arrangement to determine fixation disparity. (From Martens TG, Ogle KN: Observations on accommodative convergence, especially its nonlinear relationships. Am J Ophthalmol. 47:455, 1959.)

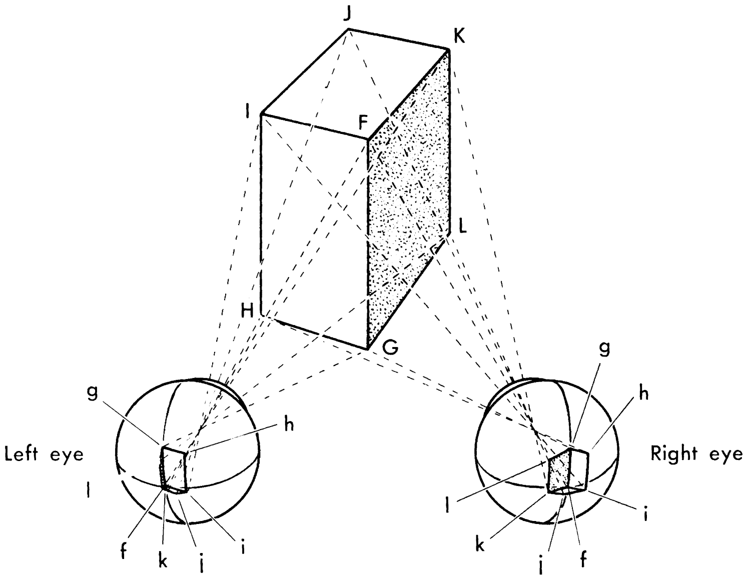

**FIGURE 2–14.** A solid object placed in the midline of the head creates slightly different or disparate retinal images, the fusion of which results in a three-dimensional sensation. The lowercase letters of the retinal image correspond to the uppercase letters of the object.

## *Physiologic Basis of Stereopsis*

Wheatstone,[101] by his invention of the stereoscope in 1838, was the first to recognize that stereopsis occurs when horizontally disparate retinal elements are stimulated simultaneously. The fusion of such disparate images results in a single visual impression perceived in depth, provided the fused image lies within Panum's area of single binocular vision, which provides the physiologic basis of binocular depth perception. Vertical displacement produces no stereoscopic effect.

A solid object placed in the median plane of the head produces unequal images in the two eyes. Owing to the horizontal separation of the two eyes (the interpupillary distance), for geometric reasons each eye receives a slightly different image (Fig. 2–14), referred to as a parallactic angle by physicists. The sensory fusion of the two unequal retinal images results in a three-dimensional percept.

The object producing slightly unequal images in the two eyes need not be a solid one. A stereoscopic effect can also be produced by two-dimensional pictures, some elements of which are imaged on corresponding retinal elements to give the frame of reference for the relative in-depth localization of other elements of figures constructed to provide horizontally disparate imagery. Such figures must be viewed separately but binocularly in a stereoscope or some haploscopic device (see Chapter 4). This is another example of a difference between physical and subjective space. Neither figure seen by each eye has depth; each provides only the appropriate stimulus situation that, when elaborated by the visual system, produces a three-dimensional percept in visual space.

A simple example will make this clear. If one presents to each eye in a stereoscope or haploscope a set of three concentric circles, they will be fused into a single set of three flat concentric circles. Each circle is imaged on corresponding retinal elements. To ensure that each eye has indeed viewed the circles, a black dot, a so-called check mark, is placed to the left of the circles seen by the left eye and to the right of the circles seen by the right eye. In the fused image a dot will be seen on each side of the three circles (Fig. 2–15*A*).

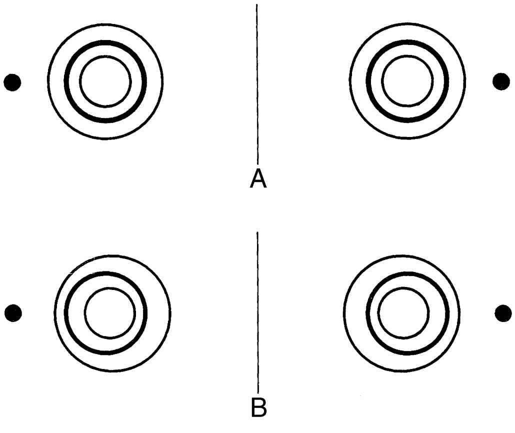

**FIGURE 2–15.** *A*, Two sets of concentric circles to be viewed in a stereoscope. *B*, Two sets of eccentric circles to be similarly viewed.

The circles may be drawn so that they are not concentric, but eccentric, by shifting the center of the two inner circles on the horizontal diameter of the outer circle (Fig. 2–15*B*). If viewed in a stereoscope, the outer circles imaged on corresponding retinal elements will be fused and serve the viewer as a frame of reference for the other two circles, which are also fused. However, they will appear in front or in back of the outer circle, depending on the direction in which their centers have been shifted. If they are displaced toward each other (i.e., toward the inner side of the circumference of the outer circles), they create a temporal disparity and therefore are seen in front of the outer circle. If they are displaced away from each other (toward the outer side of the large circles), they are imaged in nasal disparity and therefore are seen in back of the outer circle. The greater the displacement of the inner circles, the farther away from the outer circle they are localized. *The greater the depth effect, the greater the horizontal disparity.*

The inner circles are seen not only in depth relative to the outer circle in the fused image but they also appear concentric with it, although the image in each eye appears as eccentric circles. This most startling phenomenon of a shift in visual direction of the fused image is the very essence of stereopsis, and without it there is no stereopsis. It has implications for the clinical use of stereoscopic targets (see Chapter 15).

Stereopsis is a response to disparate stimulation of the retinal elements. It is this highest form of binocular cooperation that adds a new quality to vision, but it is not a ‘‘higher’’ form of fusion as is implied in the term *third degree of fusion*, used in the older literature to denote stereopsis.

The question arose whether the brain must compare the images formed on each retina before it can use the disparity of the visual input to convey the sense of depth. The answer to this question was provided by Julesz's invention[57] of *random-dot stereograms.* Random-dot stereograms, when monocularly inspected, convey no visual information other than random noise (Fig. 2–16); however, when binocularly fused by convergence or prisms, a square pattern appears in vivid depth above or below the level of the page. It follows that stereopsis does not depend on monocular clues to spatial orientation or shape recognition, since each monocularly viewed figure contains no information about the contour of the stereoscopic image. Binocularly imaged information is independent of the monocular information. Moreover, since the square is seen only because it is perceived in depth, monocular pattern recognition is not necessary for stereopsis. Julesz[58] concluded from a series of elegantly designed experiments that *form perception must occur after stereopsis* in the functional hierarchy of visual processing and not before, as was once assumed.

The principle on which random-dot stereograms is based is shown in Figure 2–17. The dot distributions seen by the right and left eyes are identical (0 and 1 squares) except for the central squares of each figure, which are shifted in a horizontal direction relative to each other (A and B squares). The retinal disparity of the central squares when both images are fused elicits stereopsis.

## Local vs. Global Stereopsis

The rather startling finding that random-dot stereopsis is not preceded by form recognition directed

**FIGURE 2–16.** Random-dot stereogram. The central square will appear behind the plane of the page when the eyes overconverge and in front of the paper when they underconverge. (From Julesz B: The Foundations of Cyclopean Perception. Chicago, University of Chicago Press, 1971.)

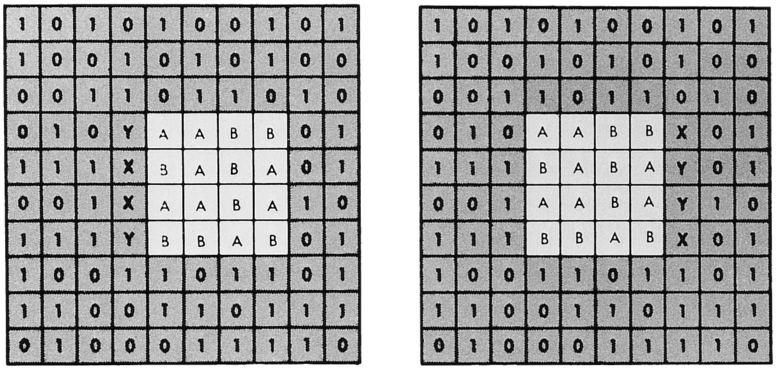

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**FIGURE 2–17.** Principle of generating a random-dot stereogram. (From Julesz B: The Foundations of Cyclopean Perception, Chicago, University of Chicago Press, 1971.)

attention to the dot-by-dot or square-by-square matching process that must occur between the right and left stereogram to elicit stereopsis. Julesz[58] applied the term *local stereopsis* to this correlation and pointed out that the elements of a random-dot stereogram (i.e., black and white dots) may give rise to many false matches within Panum's area since ambiguity exists about which elements in the two monocular fields are corresponding. There is less uncertainty about which parts of the drawing are seen by corresponding retinal elements in a classic stereogram (see Fig. 2–15). For random-dot stereopsis to occur the global neighborhood of each matching pair of dots or lines that provide the stimulus for stereopsis and, ultimately, for form recognition must be taken into account. This mechanism was termed *global stereopsis* by Julesz.[58]

The clinician must ask how the recognition of stereopsis in a random-dot stereogram relates to stereopsis under casual conditions of seeing. It is disconcerting to learn, for instance, that 40% of 162 *normal* children aged 4 1/2 to 5 1/2 years were found to have random-dot stereopsis of less than 40 seconds of arc.[59] This finding casts doubt upon the value of random-dot testing in differentiating visually normal from abnormal subjects[7] and draws attention to the fact that testing for random-dot stereopsis is not the same as testing for stereopsis under casual conditions of seeing. For instance, under ordinary visual conditions the recognition of form does not depend on intact stereopsis and the visual system is not challenged by the task of having to unscramble a seemingly meaningless pattern of black and white dots without the availability of nonstereoscopic clues to depth perception.

This should not distract from advantages of using tests that exclude contamination of testing results by monocular clues and permit the objective testing of infants[5] or experimental animals[31] for stereopsis Other clinical features of stereopsis testing are discussed in Chapter 15.

## Stereopsis and Fusion

Although it is true that sensory fusion is essential for the highest degree of stereopsis, lower degrees of stereopsis may occur in the absence of sensory fusion and even in the presence of heterotropia. Examples are microtropia and small angle esotropia. Moreover, it has been shown experimentally that binocular depth discrimination may occur with diplopia.[20] For instance, if a peripherally seen wire is located to the left and at some distance in front of a binocularly fixated wire, as in a horopter apparatus (see p. 28), the peripheral wire appears in (physiologic) diplopia. One can now attempt to place a second peripheral wire, located in the right half of the field, in line with the left peripheral wire. The closer the left peripheral wire is to the centrally fixated wire, the more accurate is the setting of the wire on the right. The accuracy decreases with increasing distance from the central wire, and eventually the settings are made by pure chance, indicating that the wire on the right is no longer placed by the criterion of stereopsis; stereopsis has broken down. These observations are important for the theory of stereopsis. Whereas this experiment shows that sensory fusion of disparate retinal images is not absolutely essential for binocular depth discrimination, it must be emphasized that to obtain higher degrees of stereopsis the similar parts of a stereogram must be fused to obtain a frame of reference (see Fig. 2–17).

On the other hand, sensory fusion (i.e., the ability to unify images falling on corresponding retinal areas) in itself does not guarantee the presence of stereopsis. There are patients who readily fuse similar targets and who may have normal fusional amplitudes but who have no stereopsis. Such patients suppress selectively the disparately imaged elements of a stereogram seen by one eye. This behavior is of clinical importance and is discussed in Chapter 15.

### *Stereoscopic Acuity*

The responsiveness to disparate stimulations has its limits. There is a minimal disparity beyond which no stereoscopic effect is produced. This limiting disparity characterizes a person's stereoscopic acuity.

Stereoscopic acuity depends on many factors and is influenced greatly by the method used in determining it. In refined laboratory examinations and with highly trained subjects, stereoscopic acuities as low as 2 to 7 seconds of arc have been found. There are no standardized clinical stereoscopic acuity tests comparable to visual acuity tests, and no results of mass examinations. Generally speaking, a threshold of 15 to 30 seconds obtained in clinical tests may be regarded as excellent.

It is clear that visual acuity has some relation to stereoscopic acuity. Stereoscopic acuity cannot be greater than the Vernier acuity of the stimulated retinal area. Stereoscopic acuity decreases, as does visual acuity, from the center to the periphery of the retina.[21] However, despite this relationship, stereopsis is a function not linearly correlated with visual acuity. It has been shown, for instance, that reduction of visual acuity with neutral filters over one eye does not raise the stereoscopic threshold, even if the acuity was lowered to as low as 0.3. A further decrease in vision to 0.2 greatly increased the threshold and with a decrease in acuity of the covered eye to 0.1, stereopsis was absent.[71] Colenbrander[28] quotes Holthuis as stating that in examining aviators he found that poor visual acuity was generally accompanied by reduced stereoscopic acuity but that there was no correlation between the two functions. On the other hand, spectacle blur decreases stereoacuity more than ordinary visual acuity.[100] Of special clinical interest is the fact that stereoacuity in patients with amblyopia may be better than what one would expect from their visual acuity.[7, 26] This observation raises doubts about the value of stereoacuity testing being advocated by many as a foolproof visual screening method for preschool children.

Since there is a stereoscopic threshold, it follows that stereopsis cannot work beyond a certain critical distance. This distance has been computed somewhere between 125 and 200 m by various authors, depending on the threshold used for computation.

## Monocular (Nonstereoscopic) Clues to Spatial Orientation

Stereopsis—the relative localization of visual objects in depth—can occur only in binocular vision and is based on a physiologic process derived from the organization of the sensory visual system. It is not acquired through experience and is unequivocal and inescapable.

Stereopsis is restricted to relatively short visual distances and is not the only means we have for spatial orientation. A second set of clues, the monocular or experiential clues, are important in our estimation of the relative distance of visual objects and are active in monocular as well as binocular vision. The importance of monocular clues in judging the relative distance between remote objects is perhaps best exemplified by an optical illusion known to every sailor and brought about by the paucity of such clues on the open sea: two ships approaching each other from opposite directions may appear to be dead set on a collision course when, in fact, they are separated by many hundreds of yards of water as they pass each other.

Monocular clues are the result of experience and are equivocal. Such clues are numerous, and descriptions of the most important ones follow.

**MOTION PARALLAX.** When one looks at two objects, one of which is closer than the other, and moves either the eyes or the head in a plane parallel to the plane of one of these objects, movement of the objects becomes apparent. The farther object appears to make a larger excursion than the near object. This behavior is learned by experience, and one makes much use of it in daily life, for instance, in sighting monocularly. If there are depressions or elevations in the fundus, one can observe the apparent movement of the retinal vessels by moving the head from side to side. The parallactic movement of the more distant vessels gives a compelling picture of the different levels of the retina.

**LINEAR PERSPECTIVE.** Object points having a constant size appear to subtend smaller and smaller angles as they recede from the subject. Railroad tracks, which are in fact parallel, seem to approach each other in the distance. Foreshortening of horizontal and vertical lines is one of the most powerful tools for creation of three-dimensional impressions on a two-dimensional surface (Fig. 2–18). Renaissance artists made exaggerated use of this "trick" to create depth in their paintings.

**OVERLAY OF CONTOURS.** Configurations in which contours are interposed on the contours of other configurations provide impelling distance clues. An object that interrupts the contours of another object is generally seen as being in front of the object with incomplete contours (Fig. 2–19); the second, farther object is also higher than the first one. This, too, is a clue made use of by early painters to indicate relative distances.

**DISTRIBUTION OF HIGHLIGHTS AND SHADOWS.** Highlights and shadows are among the most potent monocular clues. Since sunlight comes from above, we have learned that the position of shadows is helpful in determining elevations and depressions, that is, the relative depth, of objects. This phenomenon is impressively shown in Figure 2–20, taken from a paper by Burian[22]; a piece of cloth, (Fig. 2–20*C*) is photographed by throwing light on it in such a way that horizontal threads in the tissue appear as ridges. In Figure 2–20*D*, the identical photograph has been turned 180° and the ridges appear as troughs.

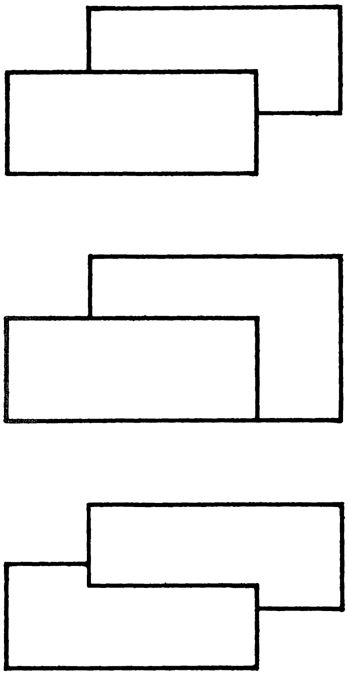

**FIGURE 2–19.** Effect of overlay of contours. The rectangle in incomplete outline generally seems farther back than the one that is complete. The incomplete rectangle is also higher, which adds to this impression.

**FIGURE 2–18.** This photograph of an airport corridor shows the strong depth effect created by the apparently decreasing width of the ceiling lights and the decreasing height of the columns.

The inversion can occur because nothing in our experience prevents it from happening. In Figure 2–20*A* and *B*, a photograph of a sculptured head is shown. Here the inversion of the print does not have the same effect. Some observers may note a general flattening in the inverted face, but a nose is a nose and can never be seen as a trough.

**SIZE OF KNOWN OBJECTS.** If the size of two objects is known, one can judge the relative distance of these objects by their apparent size. If an object known to be smaller appears to be larger than the other, we judge it to be nearer.

**AERIAL PERSPECTIVE.** Aerial perspective is the term used for the influence of the atmosphere on contrast conditions and colors of more distant objects. The bluish haze of more distant mountains is an example. Chinese painters are masters at

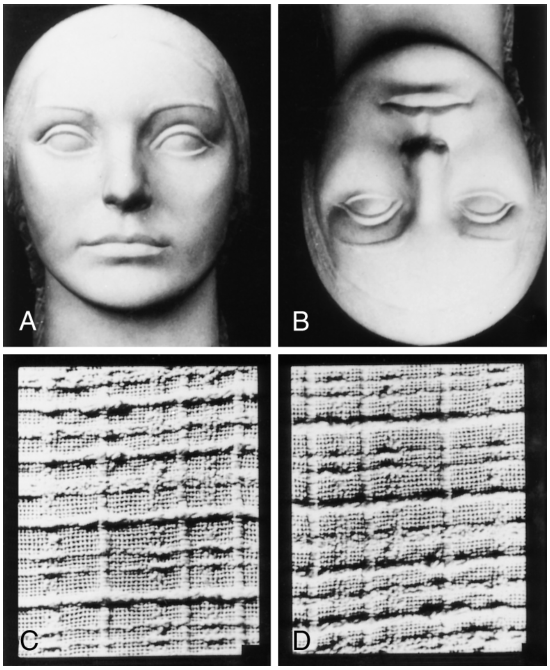

**FIGURE 2–20.** Effect of highlights and shadows. *A*, Sculpture of human head illuminated from above. *B*, Photograph *A* inverted. *C*, Piece of cloth illuminated from above. *D*, Photograph *C* inverted. (From Burian HM: The objective and subjective factors in visual perception. J Assoc Med Illustrators 9:4, 1957.)

creating extraordinary depth in landscapes by using subtle variations of shading.

**NATURE OF MONOCULAR CLUES.** The impression of three-dimensionality imparted by all these clues is a judgment, an interpretation, and implies that false judgments are possible; indeed, such is the case. It also implies that this impression depends on past experience, as does every judgment. The nature of the nonstereoscopic clues is that they are experiential and can be meaningful only when they are capable of being related to past experience.

## Interaction of Stereoscopic and Monocular Clues

All this does not mean that nonstereoscopic monocular clues are less important in everyday life than stereoscopic clues. Normally the two function together, one enhancing the effect of the other, but this is not always the case. If one introduces into stereograms monocular clues that conflict with stereoscopic clues, fascinating observations can be made.

Not everyone reacts in the same fashion to such stereograms. Some people are more responsive to disparate stimulation, that is, stereoscopic clues, whereas others respond more readily to monocular clues. These differences are caused both by physiologic peculiarities or actual abnormalities of the visual system and by past experience. A person stereoblind since infancy must rely exclusively on monocular clues and will flawlessly perform most ordinary tasks requiring depth discrimination, such as pouring milk into a glass or parallel parking. He or she will fail abysmally, however, when a higher degree of stereopsis becomes essential and monocular clues are no longer available, for instance, as occurs in the limited field of vision provided by an operating microscope.

Humans, then, have at their disposal two sets of clues for their orientation in space. By means of the monocular clues to spatial localization, interpretation of the depth relation of visual objects is achieved on the basis of experience. The clues provided by fusion of disparate retinal images afford the direct perception of this relation on the basis of intrinsic physiologic arrangements.

## Clinical Significance of Monocular Clues

All this is of considerable clinical importance in patients with strabismus. For example, if there is doubt about whether a patient actually does see stereoscopically, misleading monocular clues introduced purposely into stereograms may provide the answer. Heavy black figures (as in the circles of Fig. 2–15) appear closer than lighter figures do to a person without stereopsis, even if the stereogram is so drawn that the black figures should appear in back of the lighter ones. Furthermore, if it is not known if a patient can see stereoscopically, again use the eccentric circles and ask the patient to state whether the inner circle seems to be closer to the right or left side of the outer circle. If the patient answers that it is closer to one side or the other, one can be sure that he or she does not see stereoscopically, since the circles would otherwise have to appear concentric. In addition, the patient's answer allows one to determine which eye the patient is suppressing. For example, if the two inner circles are displaced away from each other and the patient reports that the heavier circle is to the left in the outer circle, he or she is suppressing the right eye (see Fig. 2–15).

A patient with binocular vision but who has recently lost one eye and is looking across a square will have no question that a lamppost is in front of a house. The continuous lines of the lamppost are interposed over the interrupted horizontal contours of the house. However, the patient may have considerable difficulty in pouring cream into a coffee cup and performing other tasks of visuomanual coordination. In time the patient may overcome these difficulties and become as skillful or almost as skillful as before the eye was lost. Fast-moving objects (such as a flying ball) may continue to give trouble, but as time passes monocular clues to depth perception may be used, even in near vision where formerly stereoscopic clues were relied on entirely.

## Experimental Determination of the Longitudinal Horopter and the Criteria of Retinal Correspondence

In preceding discussions in this chapter, reference has been made repeatedly to wires placed in various positions relative to a binocularly and centrally fixated wire. Such an arrangement of wires is used in the determination of the empirical horopter.

The horopter apparatus (Fig. 2–21) is operated in the following manner. The observer's head is fixed in a headrest, and a suitable aperture excludes all extraneous elements from the observer's visual field. Tracks are provided that converge at a point below the middle of the observer's basal line, that is, the line segment connecting the centers of rotation of the two eyes. In these tracks run carriers to which vertical wires are fastened. The observer fixates a vertical wire placed at a chosen near vision distance in the median plane. The position of the central wire remains unchanged. To each side of the fixation wire are situated movable wires that the observer sees at 1°, 2°, 3°, 4°, 6°, 8°, 12°, and so on in peripheral vision.

The purpose of the horopter apparatus is to determine the distribution of corresponding retinal elements. Therefore the patient must be assigned a task in which the peripherally seen wires are arranged so that they stimulate corresponding retinal elements. The patient must strictly fixate the central wire, which may be equipped for this purpose with a small bead. A number of possible criteria of correspondence can now be evaluated.

### Criterion of Single Vision

Double vision with corresponding retinal points is impossible. One could instruct an observer to set the peripheral wires in the horopter apparatus so that they would all appear singly. This is not a reliable criterion for correspondence because of Panum's area of single binocular vision.

### Apparent Frontal Plane Criterion

As we have also seen, stereopsis depends on disparate stimulation. Simultaneous stimulation of corresponding retinal elements does not produce a three-dimensional effect. *The stereoscopic value*

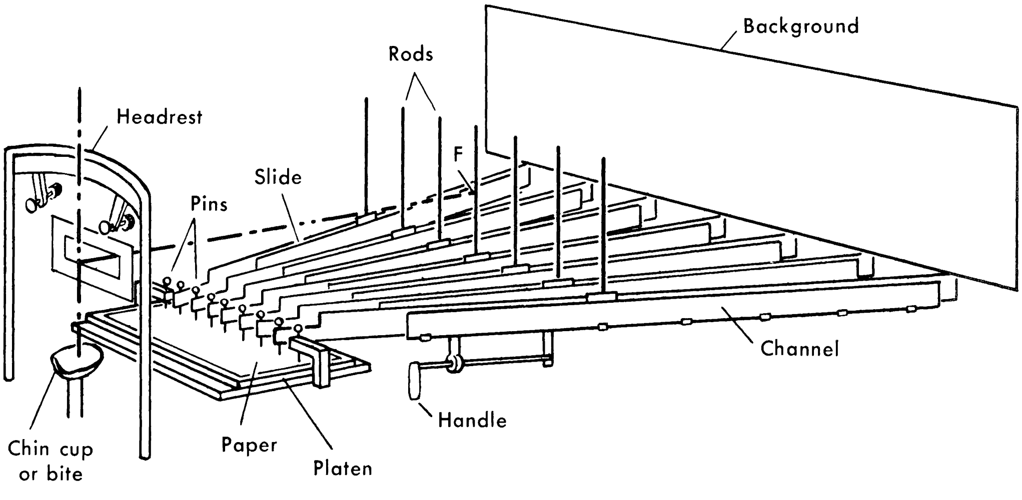

**FIGURE 2–21.** Horopter apparatus. (From Ogle KN: Researches in Binocular Vision. Philadelphia, WB Saunders, 1950.)

*of corresponding retinal elements is zero.* Therefore, if an observer is asked to place all peripheral wires in such a manner that they appear in a plane parallel with his or her forehead, the subjective frontoparallel plane, all wires presumably stimulate corresponding retinal elements and their position determines the observer's horopter.

For near vision distances, this horopter curve does not coincide with the objective frontoparallel plane. It is a curve that is slightly convex to the observer but has less of a curvature than the Vieth-Müller circle (see Fig. 2–10). At times it is amusing to see a naive observer's astonishment when it is shown that he or she has set the horopter wires in a curve. The observer is so sure they are in a plane!

### *Criterion of Common Visual Directions*

The criterion of frontoparallel appearance is convenient and easy to use. This method is sufficiently reliable so that it has been used in almost all horopter studies, but it is indirect. In principle, the most reliable criterion would be direct determination of the common visual directions, which can be done with a special arrangement of the horopter wires.

If one of the peripheral wires is partially occluded so that, for example, its upper part is seen by one eye and its lower part by the other, the line will be seen as continuous only when it comes to lie on corresponding meridians in the two retinas. This method presents considerable practical difficulty, mainly because the reduction in fusible material in the field makes it difficult to maintain the proper positioning of the eyes.

### *Criterion of Highest Stereoscopic Sensitivity*

Although the stereoscopic value of corresponding retinal elements is zero, stereoscopic sensitivity is highest in the immediate vicinity of corresponding retinal elements. This means that the smallest changes in the position in front of or behind the peripherally seen wires are detected near the horopter curve. By determining this position, an approximation of the observer's horopter curve can be obtained. This procedure is tedious and does not approximate the horopter curve as well as the much simpler determination of the subjective frontoparallel plane.

## Egocentric (Absolute) Localization

Thus far this chapter has dealt with localization of visual objects relative to each other in the three dimensions. We must now turn to the absolute and egocentric localization of visual objects, that is, to their orientation with respect to a coordinate system that has its origin in physical space (absolute localization), especially that part of physical space occupied by a person's body (egocentric localization).

The physical coordinates for egocentric localization are the median plane of the body (vertical in an upright position of the body, perpendicular to the baseline at its center), the horizontal plane of the body (containing the baseline and the two principal lines of direction), and the frontal plane of the body (containing the baseline, which is perpendicular to the median and the horizontal plane). Subjective planes correspond to these physical planes: the subjective median plane transmits the impression ''straight-ahead''; the subjective horizontal (visual) plane transmits the impression ''at eye level''; and the subjective frontal plane transmits the impression ''at a distance from me.'' In general, these subjective equivalents do not coincide with their physical counterparts.

Hering[46, p. 417] made the assumption that they did coincide since it happened to be true for him, and accordingly he placed the origin of the egocentric coordinate system at the root of the nose. It need not be there. If a person has a markedly dominant eye, the absolute position of the common visual direction of the foveae (and therefore of the subjective median plane and the ''straight-ahead'' position) may not be in the objective median plane but may be shifted toward the side of the dominant eye. Recent data suggest that the reference point for visual localization lies between the midpoint of the interocular axis and the line of sight of the dominant eye.[84]

### *Egocentric Localization and Convergence*

Of special interest is in-depth egocentric localization. How do we judge the distance of an object from us? Many factors cooperate in this function. The size of the retinal image could be one, since the retinal image of an object is smaller the farther it is from the eye. For objects of known size (e.g., a man) and relatively short distances, this clue is of limited value because of the size-constancy phenomenon. Accommodation may provide another clue. Convergence is generally assumed to be the most potent clue.

A simple experiment will demonstrate this point convincingly. Hold up one thumb in front of you at arm's length and look at a window or door at the end of the room. Then converge your eyes on your thumb and the distant objects will seem to shrink and to move closer. This is a compelling phenomenon that is not only of theoretical but also of practical clinical significance in patients with intermittent exotropia (see Chapter 17).

It was postulated in the older literature that an awareness of the impulses required to bring or keep the eyes in a particular position was at the origin of our perception of absolute distance. This theory is not satisfactory, and Tschermak-Seysenegg[95, p. 219] replaced it with the theory of an indirect sensory function of the ocular muscles. It makes the following assumption: Afferent nerve fibers respond to the active tonus of ocular muscles, but not to passive relaxation. However, there is no consciousness of the tension of single muscles or of the eye posture as such. The simple, preexisting sensation of the straight-ahead position or the equally high position is related to a certain complicated tonus distribution of the oculomotor apparatus and, therefore, to a complex of afferent excitation.

This somewhat awkwardly put explanation is, in fact, an anticipation of the way in which modern models describe control of eye movements and awareness of absolute depth. It contains the concept of ‘‘space representation’’ and of negative and, indeed, parametric feedback.

## Egocentric Localization and Proprioception

As mentioned earlier in this chapter, there are two sources of information from which the brain may determine eye position and receive spatial orientation clues: visual input from the retina, (*outflow*) and proprioceptive information from the extraocular muscles (*inflow*). While there can be little doubt that efferent outflow is the dominant mechanism in supplying the most necessary spatial information to the brain, there is mounting evidence that proprioceptive inflow may also play a role. The human extraocular muscle is certainly adequately equipped to provide proprioceptive input: there are abundant muscle spindles, Golgi tendon, and palisade endings located at the musculotendinous junction (see Chapter 6). Skavenski[86] was first to show in a carefully designed experiment that the human oculomotor system is capable of processing nonvisual inflow information. His subjects were able to correct for passively applied loads to the eyes with appropriate eye movements in the dark. Experiments in cats[42, 69, 93] strongly suggested that the ophthalmic branch of the trigeminal nerve carries proprioceptive afferents. That the same may hold true for humans was suggested by Campos and coworkers[25] who described faulty egocentric localization in patients with herpes zoster ophthalmicus. Gauthier and coworkers[42] (see also Bridgeman and Stark[18]) showed that passive deviation of one eye caused faulty localization of objects seen by the other eye in the direction of the passive movement, suggesting the utilization of inflow information for egocentric localization.

Lewis and Zee[65] reported that proprioceptive afference may influence egocentric localization in the absence of normal oculomotor innervation in a patient with trigeminal-oculomotor synkinesis. Lewis and coworkers[66] showed also that proprioceptive deafferentation of the extraocular muscles did not influence the accuracy of pointing and concluded that inflow provides sufficient information about orbital eye position for correct egocentric localization.

Mechanical vibration of the inferior rectus muscle to each eye simultaneously and under monocular and binocular conditions caused an illusionary movement of a red light presented in total darkness and induced past-pointing.[97] This visual illusion could also be elicited by vibration of the horizontal rectus muscles and cannot be attributed to retinal motion of the image of the fixated target.[96] Lennerstrand and coworkers[62] showed that vibratory activation of the muscle spindles in extraocular muscle affects eye position and these signals are processed differently in normals and in exotropic patients.

Steinbach and Smith[91] found surprisingly accurate egocentric localization in patients after strabismus surgery who had been deprived of visual input until the time of the experiment. According to these authors, this information can only be derived from inflow (see also Dengis and coworkers[33, 34]). Myotomy of a muscle had a greater effect in deafferenting proprioception than a recession, presumably because of greater destruction of the palisade endings by the former procedure.[92] However, Bock and Kommerell[16] could not duplicate Steinbach's finding and Campos and coworkers[24] were unable to correlate pointing errors after strabismus surgery with a particular surgical procedure. They did, however, show changes in egocentric localization after exerting stretch on an extraocular muscle.[23]

While some of these data are contradictory there is little doubt that inflow signals are available to the visual system. However, it is not clear how they are used by the brain and correlated with outflow information under casual conditions of seeing when visual input is abundantly available. Skavenski and coworkers[87] showed that when inflow and outflow signals conflict, the outflow signal is, as one may expect, the stronger one. It has been proposed that inflow acts as a long-term calibrator and is involved in maintaining the stability and conjugacy of gaze[89] and of smooth pursuit movement.[35] For reviews, see Steinbach[88, 90] and Lennerstrand.[60, 61]

### *Clinical Significance of Relative and Egocentric Localization*

One need not go into experimental evaluations of egocentric localization, but emphasis must be placed on making a clear distinction between relative and absolute (egocentric) localization because relative and egocentric localization may be independently affected in certain forms of strabismus. Confusion between the two forms of subjective localization leads to misinterpretations of the observed phenomena. For instance, a patient with an acute paralysis of an extraocular muscle will past-point (see Chapter 20), which is evidence of abnormal egocentric localization, but will have normal relative localization (the double images are localized according to the laws of physiologic diplopia). A patient with comitant strabismus does not, as a rule, past-point, although exceptions do occur,[3, 93, 94] but rather may experience abnormal relative localization; that is, the patient does not localize the double images according to the law of physiologic diplopia (anomalous retinal correspondence; see Chapter 13).

## Theories of Binocular Vision

### *Correspondence and Disparity*

According to the theory of binocular vision presented in this chapter, sensory binocular cooperation is based on a system of correspondence and disparity.

A given retinal element in one retina shares a common subjective visual direction with an element in the other retina. These corresponding elements form the framework or zero system of binocular vision. When stimulated simultaneously by one object point, they transmit single visual impressions that have no depth quality. When stimulated simultaneously by two object points that differ in character, binocular rivalry results. When disparate elements are stimulated by one object point, diplopia is experienced. However, if the horizontal disparity remains within the limits of Panum's area, a single visual impression is elicited that has the quality of relative depth or stereopsis. The fused component, that is, the singly appearing, disparately imaged component of the stimulus or target, is seen not only in depth but also in the subjective visual direction of the relative retinal element to which the stimulus is disparate.

The perceived depth increases with increasing disparity. With further increase in disparity, diplopia eventually occurs. Although stereopsis generally occurs with fusion, it is still possible up to a point to experience a true stereoscopic effect from double images.[20; 76, p. 281] However, increasing disparity causes the quality of stereopsis to decrease until finally there is no longer any binocular stereoscopic effect. There is, then, no sharp delineation between fusion with full stereopsis and diplopia without stereopsis, but only a gradual transition. This is consistent with many other biological processes, especially visual ones, none of which change abruptly from function to nonfunction.

One can think of each retinal element as being the center of attraction of a retinal unit, the attraction diminishing as the distance from the element increases. In considering this simile, keep in mind that (1) the retinal units are overlapping, and (2) the stimulation of neighboring units may result in inhibitory stimulation of surrounding units.

### *Neurophysiologic Theory of Binocular Vision and Stereopsis*

The correspondence theory has been built on the basis of overwhelming evidence from psychophysical data. Direct physiologic evidence for it has emerged from the work of Hubel and Wiesel.[51–53] These authors have given us insight into

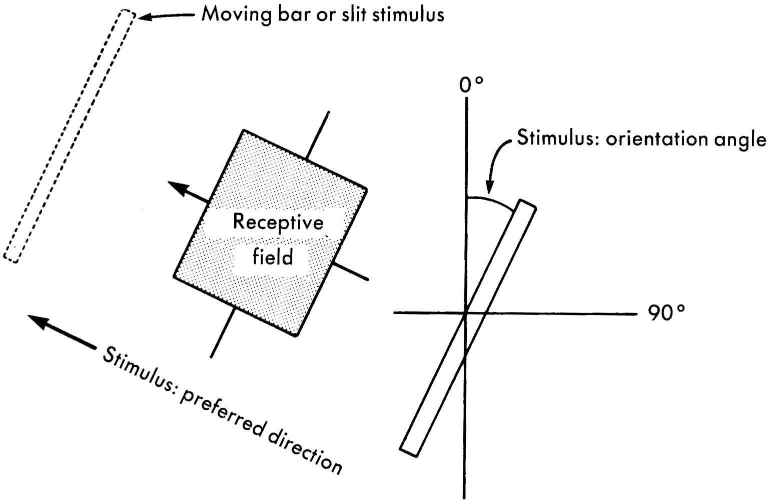

**FIGURE 2–22.** Receptive fields dependency on preferred direction and orientation of the stimulus. (Modified from Bishop P: Vertical disparity, egocentric distance and stereoscopic depth consistency: A new interpretation. Proc R Soc Lond B Biol Sci 237:1289, 1989.)

how visual stimuli from the retina to the visual cortex are modified and coded. In their microelectrode studies of single-cell responses in the striate cortex of the cat, they have found that roughly 80% of the neurons could be driven from either eye. However, only 25% of these binocularly driven cells are stimulated equally well from each eye; the remaining 75% represent graded degrees of influence from the right or left eye. Ten percent of the cells are driven exclusively from the right or left eye. Cells that can be driven by stimulation of either eye have receptive fields of nearly equal size and in approximately corresponding positions in the visual field. The *receptive field* of a visual neuron is defined as that part of the visual field that can influence the firing of that cell.[52] The activity of most striate neurons is maximal to movement of a linear slit of light in front of the eye when the slit has a particular orientation and preferred direction of movement (Fig. 2–22).

Similar experiments in monkeys yielded comparable data[8, 29] (Fig. 2–23). That this dominance in distribution of cortical neurons is easily upset when animals are reared with experimental strabismus, anisometropia, or form vision deprivation by lid suture is discussed in Chapter 14.

A reasonable assumption is that neurons in the striate cortex responding equally well to successive stimulation, and especially those in which the response can be maximized with simultaneous stimulation, are somehow involved with binocular visual processing. Indeed, Hubel and Wiesel[52] showed response summation or inhibition, depending on the alignment or misalignment of the stimulus on the receptive field, concluding that summation occurs whenever corresponding parts of the receptive field are stimulated.

The discovery of disparity-sensitive binocular cells in the striate cortex had to await the arrival of precise receptive field mapping techniques that excluded all eye movements during the experiment. The chronological sequence of a series of classic experiments that led to the discovery of the neurophysiologic mechanisms of stereopsis was reviewed by Bishop and Pettigrew.[13] Barlow, Blakemore, and Pettigrew[9] were the first to describe horizontal disparity sensitivity of binocular striate neurons in the cat and proposed that these cells may be responsible for stereopsis. Hubel and Wie-

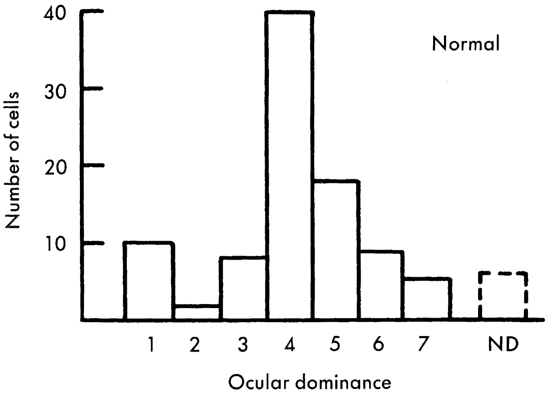

**FIGURE 2–23.** Dominance distribution of striate neurons from two normally reared monkeys. Categories 1 and 7 contain neurons driven only through the left or right eye. The remaining categories represent greater degrees of binocular influence with neurons in 4 being equally influenced by both eyes. (From Crawford MLJ, Blake R, Cool SJ, Noorden GK von: Physiological consequences of unilateral and bilateral eye closure in macaque monkeys: Some further observations. Brain Res 84:150, 1975.)

sel[53] identified cells described as being sensitive to binocular depth in area 18 of the macaque cortex. Poggio and coworkers[80–83] discovered in rhesus monkeys neurons in cortical areas 17 and 18 that responded to dynamic random-dot stereograms containing no depth clues other than disparity. They identified two functional sets of stereoscopic neurons, one tuned excitatory and the other inhibitory. These cells responded differently, depending on whether visual objects were on, in front of, or behind the horopter.[83] Bishop[11, 12] proposed that binocularly activated cortical cells may not only be selective for horizontal but for vertical stimulus disparities as well. However, in monkeys the horizontal disparities are appreciably greater than the vertical disparities and in humans vertical disparity produces no measurable stereoscopic effect.

Crawford and coworkers[29, 30] showed in behavioral and electrophysiologic experiments that infant monkeys with a severely reduced binocular striate neuron population after a period of experimental strabismus become stereoblind (Fig. 2–24). Once binocular neurons are lost they do not recover, even with extensive binocular visual experience.[30] This may explain the markedly reduced stereoacuity in spite of early surgery in children with essential infantile esotropia (see Chapter 16) and emphasizes the extraordinary vulnerability of the primate binocular system to abnormal visual experience. Thus, stereopsis has been unequivocally linked with the so-called binocular cells in the striate cortex, and there has been good agreement between psychophysical data collected from humans and neurophysiologic research in cats and primates.[30, 31]

Whether binocular striate cells subserve functions other than stereopsis is not known. The response summation depending on stimulus alignment observed in animal experiments suggests that binocular cells may also be involved in the fusion process. On the other hand, the clinician knows that sensory fusion may occur in the absence of stereopsis. The cortical centers for sensory and motor fusion are yet to be identified.

## *Older Theories of Binocular Vision*

Older theories of binocular vision still espoused in the second half of this century are mostly of historical interest now. However, familiarity with these concepts is indispensable for understanding the older literature.

**ALTERNATION THEORY OF BINOCULAR VISION.** *Sensory fusion* has been defined as the perceptual unification of the images received in corresponding locations in the two retinas. This definition is supported by the experience of single vision, which is quite compelling, but it is not necessarily the correct description of the process. Since 1760, when Du Tour[39] claimed that rivalry phenomena gave evidence that the binocular visual field is composed of a mosaic of monocularly perceived patches, this theory has had many adherents. Verhoeff,[98] in his replacement theory of binocular vision, assumed that corresponding retinal units were represented separately in the brain

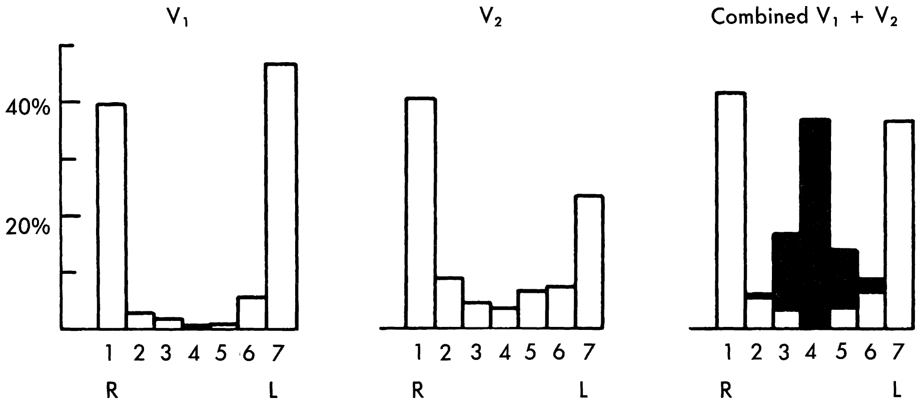

**FIGURE 2–24.** Stereoblind monkeys (N = 3) had most cortical cells controlled exclusively by one eye or the other (categories 1 and 7) with only 13% (N = 276) binocular innervation in cortex layers $V_1$ and 30% (N = 108) in $V_2$. The black bars represent the missing binocularly innervated neurons ordinarily found in control monkeys. (From Crawford MLJ, Smith EL, Harwerth RS, Noorden GK von: Stereoblind monkeys have few binocular neurons. Invest Ophthalmol Vis Sci 25:779, 1984.)

but that each one of every pair was represented in consciousness by the same single unit. This conscious unit would receive the stimulus from only one retinal unit at a time; the other was excluded. Asher[6] attempted to show that in binocular stimulation one pair of corresponding elements always suppressed the other. Hochberg[48] presented a similar view. Levelt,[67] although inclined toward the same view, did not share this all-or-none assumption. He believed that it is better to think of different levels of dominance of the eyes for each point of the visual field.

The "mosaicist" concept of the binocular visual field is supported by all its adherents with essentially the same evidence, largely based on the phenomena of rivalry. They fail, however, to explain many phenomena of binocular vision, particularly stereopsis. Also, as Linksz[68, p. 846] argued, the motor responses to the relative displacement of similar and dissimilar targets in a haploscope could not be as different as they are if alternate suppression were the basis of single binocular vision. Experiments in cats and monkeys have shown that when receptive fields from corresponding points of the retina are superimposed in the plane of an optimal stimulus, firing is markedly facilitated. When these fields are out of register, they mutually inhibit one another.[74] Moreover, "moderate summation" of responses from cortical neurons in macaques have been described following simultaneous stimulation of both eyes.[8, 53] These findings do not support the alternation theory of binocular vision.

**PROJECTION THEORY OF BINOCULAR VISION.** A theory that has now been largely abandoned is the projection theory, which contends that visual stimuli are exteriorized along the lines of direction. If a person fixates binocularly, a "bicentric" projection is supposed to occur that places the impression of each eye at the point of intersection of the lines of projection.

This theory is untenable for many reasons. It fails to explain even such fundamental observations as physiologic diplopia, not to mention the discrepancies between stimulus distribution and perception, and breaks down completely when interpretation of the sensory phenomena observed in strabismus is attempted (see Chapter 13). The basic reason for the inadequacy of the projection theory is that the distinction between physical and subjective space is disregarded and it attempts to reduce localization to a dioptic-geometric scheme.

Alexander Duane,[36–38] among American ophthalmologists, has most clearly presented the projection theory, but he modified it to meet some obvious objections. According to Duane, in both monocular and binocular vision the visual impressions are projected or referred to a definite position in physical space outside the body. There is, however, an essential difference between monocular and binocular "projection." In monocular vision each eye "projects with reference to its own axis" and in binocular vision with reference to the midline or "bivisual axis." In other words, "binocular projection" may be conceived as performed by a single cyclopean "binoculus." Duane states that the change from monocular to binocular vision is proved by the fact that in physiologic diplopia the double images are not "projected" to the plane of the fixation point but to the plane in which the object lies, which is seen double. Thus, Duane showed that physiologic diplopia cannot be explained by the projection theory and accepted the concept of the cyclopean eye. Nevertheless, he considered the projection theory to be valid.

It would not be necessary to go into the projection theory in such detail if it were not for the fact that it continues to crop up in the literature, at least in the terminology. For example, one still encounters such statements as "the functional scotoma in strabismus projected into space for the purpose of solving diplopia." *The term* projection *should be altogether avoided in connection with visual orientation.*

The projection theory, as espoused by Duane,[38] is also responsible for binocular vision being described in terms of "oculocentric localization" from each eye and for anomalous correspondence still being termed "anomalous projection" by some modern authors. Alperr[2] states that "The stimulus for stereopsis is a disparity in the oculocentric localization of a given object in the field of one eye with respect to its oculocentric localization in the field of the other eye." This gives—at least terminologically—an independence to each eye that it does not possess. Even less acceptable is "disparity of egocentric localization of the center of the visual fields of the two eyes" as the stimulus to motor fusion. Neither eye has an "egocenter." Only the subject has an egocenter to which the egocentric localization of visual objects is referred. The persistent confusion between relative and absolute (egocentric) localization has caused many misunderstandings in the ophthalmic literature.

**THEORY OF ISOMORPHISM.** Linksz[68, pp. 380 ff.] developed a theory of binocular vision based on a rigid retinocortical relationship. He believed that fusion is based on neuroanatomical features, which bring excitations from the two retinas into close proximity within the visual cortex. Those from corresponding elements are ''consummated'' in Gennari's stripe, which he considers to be the anatomical counterpart of the horopter plane in objective space and of the nuclear plane in subjective space. ''Nuclear plane'' denotes the counterpart in subjective space of the horopter surface in physical space. The term is derived from the German *Kernpunkt* (nuclear point, the subjective correlate of the fixation point) and *Kernfläche* (nuclear plane, the subjective correlate of the objective frontal plane). Objects nearer to or farther from the fixation point stimulate disparate retinal elements, and the resultant excitations converge in front of or behind Gennari's stripe in strict conformity with the distribution of objects in space. In this way the sensation of stereopsis is created. The point-to-point relationship between retina and cortex and strict conformity or isomorphism between the distribution of objects in space and cortical events form the basis of spatial orientation. Subjective visual directions as a property of the retinal elements do not exist. Retinal correspondence cannot change. There can be no ''assimilation of visual directions'' in stereopsis. Anomalous correspondence in patients with strabismus (see Chapter 13) has been misinterpreted.

Linksz extensively elaborated his fascinating intellectual theory. There is, however, no evidence for the physiologic rigidity of the retinocortical relationship or the convergence of the pathways on which it is based.

## Advantages of Binocular Vision

The current tendency is to overemphasize stereopsis as the only important reason for having binocular vision. For instance, Bishop[11] stated that ''with the exception of stereopsis, seeing with both eyes is marginally, if any, better than seeing with one—absolute threshold, differential threshold, and visual acuity being about the same.'' Indeed, binocular summation experiments show no monocular-binocular differences or at best give only equivocal results.[15] On the other hand, there are certain advantages to having binocular vision in addition to stereopsis that are not readily appreciated by the nonclinician.

Parents of strabismic children whose eyes have been aligned surgically will often volunteer the information that the child's visuomotor skills have suddenly and vastly improved. This improvement does not seem to depend on the presence of stereopsis. It is noted as long as gross binocular vision on the basis of normal or abnormal retinal correspondence is reestablished. Jones and Lee[56] substantiated this clinical observation by evaluating human binocular and monocular performance through a variety of exteroceptive and visuomotor tasks. The results indicated that binocular concordant information provides better exteroception of form and color and better appreciation of the dynamic relationship of the body to the environment, thereby facilitating control of manipulation, reaching, and balance. Also, the advantages of an intact binocular field of vision, which is larger than a monocular field, and of central visual field overlap become obvious as soon as the function of one eye becomes impaired by a disease process.

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