Human Stereopsis

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This paper reviews much of the basic literature on stereopsis for the purpose of providing information about the ability of humans to utilize stereoscopic information under operational conditions. This review is organized around five functional topics that may be important for the design of many stereoscopic display systems: geometry of stereoscopic depth perception, visual persistence, perceptual interaction among stereoscopic stimuli, neurophysiology of stereopsis, and theoretical considerations. The paper concludes with the presentation of several basic ideas related to the design of stereoscopic displays.

INTRODUCTION

Stereopsis is the perception of depth based on retinal disparity, a cue that derives from the presence of horizontally separated eyes. Wheatstone (1838) was the first to report that disparity is the cue for stereopsis, or what he called "seeing in solid." He created a pair of drawings and presented one to each eye. The drawings mimicked the disparity occurring when natural scenes are viewed; parts of the drawing presented to one eye were shifted laterally relative to corresponding parts of the drawing presented to the other eye. Those parts appeared to Wheatstone as single (perceptually fused) and standing out in depth from other portions of the drawings. These observations were the first in a long line of research on the visual mechanisms of stereopsis.

Currently government and industry have a growing interest in employing stereoscopic information in visual displays because of its potential benefits. For instance, stereopsis can serve as an important coding dimension, assisting in the perceptual discrimination of figure from ground (Yeh and Silverstein, 1990). As one example, the Armstrong Laboratory at Wright-Patterson Air Force Base has been developing the Super Cockpit Program (Furness, 1986; Furness and Kocian, 1986). Whereas conventional displays offer only two-dimensional views, the Super Cockpit provides the pilot with three-dimensional spherical awareness. On binocular helmet-mounted displays, the pilot sees a representation of the terrain—including natural and person-made objects (from a stored data base)—and information from aircraft avionic systems, weapons, and sensors. Certain kinds of information (e.g., other aircraft) are presented to the pilot stereoscopically so as to provide enhanced spatial awareness. Because

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the displays are under electronic control, the system designer can implement stereoscopic cues tailored to the individual. To interact with the aircraft systems, the pilot uses line-of-sight (i.e., looking at display elements), voice, and other psychomotor responses.

There are myriad other potential applications of these technologies, such as air traffic control, telerobotics, computer-aided design, medicine, meteorology, and the entertainment and amusement industries (Wickens, Todd, and Seidler, 1989). It is clear that stereoscopic displays are here to stay, and several emerging technologies should ensure that they are developed into an ever-expanding variety of applications.

This paper reviews much of the basic literature on human stereopsis. In addition to providing the reader with an entry point into that literature, this review provides basic information about the ability of humans to utilize stereoscopic information that should be applicable to many operational conditions and presents several practical or functional topics that may be important for the design of stereoscopic display systems. This paper is concerned with issues related to stereoscopic displays; the perception of real-world depth is not discussed. Nor do we discuss different methods of stereoscopic display, specific engineering systems such as head-up displays or helmet-mounted displays, various types of imagery, or topics other than stereopsis (e.g., binocular vs. monocular sensitivity). There have been excellent reviews of stereopsis by Arditi (1986), Graham (1965), Gulick and Lawson (1976), Hochberg (1972), Julesz (1971), Julesz and Schumer (1981), Ogle (1964), Tyler and Scott (1979), Tyler (1983), Wickens et al. (1989), and Wolfe (1986); the reader should consult these sources in addition to the present review.

The topics covered by this review are geometry of stereoscopic depth perception, visual persistence, perceptual interaction among stereoscopic stimuli, neurophysiology of stereopsis, theoretical considerations, and concluding remarks.

GEOMETRY OF STEREOSCOPIC DEPTH PERCEPTION

Retinal Disparity and the Horopter

Retinal disparity is an interocular difference in the relative position of corresponding monocular images. Stereopsis is induced by horizontal disparity—that is, horizontal differences in the position of images. This paper discusses issues related to horizontal disparity. For discussion of vertical disparity, see Tyler (1983) and Tyler and Scott (1979).

Consider the concept of corresponding retinal points (Ames, Ogle, and Gliddon, 1932; Shipley and Rawlings, 1970). Figure 1, a geometric diagram, depicts a top-down view of two eyes fixating point F. The curved line through F is the *longitudinal horopter*. Each object on the horopter gives rise to images
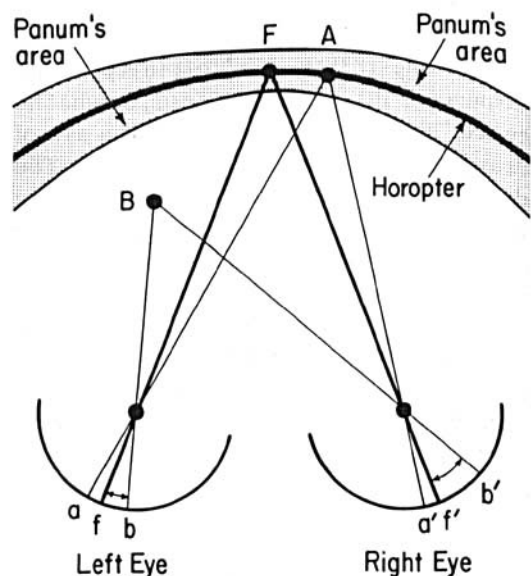

Figure 1. *Top view depicting two eyes fixating point F, the longitudinal horopter, and Panum's fusional area.*

that strike corresponding retinal points in the two eyes. For example, an image from object A strikes point a in the left eye and another image strikes a' in the right eye. These are corresponding points, equally distant from f and f'; A has zero disparity relative to F. The horopter is a concept that defines the locus of all points in space that give rise to images that stimulate corresponding retinal points for a given degree of convergence. The horopter can be thought of as a baseline of zero disparity to which nonzero disparity information is compared.

Object B, in front of the horopter, gives rise to images that strike point b in the left eye and b' in the right eye (see Figure 1). These are noncorresponding retinal points—they are not equally distant from f and f'; B has disparity because angle f'b' in the right eye is larger than angle fb in the left eye. For an object behind the horopter, the larger angle would be in the left eye for objects in the left visual field (the geometry is reversed for objects in the right visual field). Objects positioned at greater depths in front of or behind the horopter have greater disparity.

The horopter defined empirically by psychophysical measurements is not the horopter defined by geometry (Ogle, 1964; Shipley and Rawlings, 1970). The geometric horopter is called the *Vieth-Muller circle*, which passes through the nodal points of the two eyes and the point of fixation (not shown in Figure 1). The empirical horopter is based on several different criteria, such as common perceived direction (nonius method) or the equidistant plane; the nonius horopter is the more appropriate measure from a physiological viewpoint (Shipley and Rawlings, 1970). The horopter varies as a function of fixation distance and gaze direction for reasons that are not well understood (Ogle, 1964).

There also exists a vertical horopter, an imaginary vertical line passing through point of fixation, which also gives rise to images that impinge upon corresponding retinal points. The vertical horopter also changes with distance: it becomes more inclined, with its top tilted away from the observer. For a complete determination of disparity, one must know the position of both longitudinal and vertical horopters. For discussion of both horopters, see Tyler (1983) and Tyler and Scott (1979).

Crossed and Uncrossed Stereopsis

Disparity in front of the horopter is said to be *crossed* and disparity behind the horopter is *uncrossed*. This distinction stems from the spatial relationships of images within the monocular views. For crossed disparity, the disparate image is right of fixation in the left eye's view and left of fixation in the right eye's view. For uncrossed disparity, the disparate image is left of fixation in the left eye's view and right of fixation in the right eye's view.

Psychophysical and physiological research suggests that the mechanisms mediating depth perception in the crossed direction are separate from those mediating depth in the uncrossed direction (Mustillo, 1985). For example, in tests involving the discrimination of crossed and uncrossed disparity using brief (e.g., 80 ms) stimulus exposures (Richards, 1970, 1971), approximately 30% of people are insensitive to disparity information of one direction. This asymmetry in sensitivity between the two directions is called *stereoanomaly*. Its selective nature implies that the neural mechanisms mediating depth perception in the two directions are separate and that one of them is impaired in the stereoanomalous observers.

However, the classification of stereoanomaly may be an artifact of brief exposures. Patterson and Fox (1984) tested 98 observers on two depth perception tasks, one involving 160 ms exposures and the other involving continuous viewing (eye movements were

eliminated by using disparate afterimages). Of the observers, 30% were stereoanomalous with brief exposures, yet all but one perceived depth correctly with continuous viewing, indicating that the incidence of stereoanomaly (a putative neurological deficit) has been greatly overestimated.

This means that the selection of operators of stereoscopic displays does not require special testing procedures (Fox, 1985); from a viewpoint of design, most individuals show good stereopsis with extended exposures (e.g., hundreds of milliseconds). Because some individuals show poor stereopsis for the crossed or uncrossed direction when stimuli are exposed briefly, it is recommended that stereoscopic stimuli be exposed for long durations (e.g., hundreds of milliseconds or longer). Nonetheless, the difference between crossed and uncrossed directions with brief exposures shows that depth in the two disparity directions is mediated, at least in part, by different mechanisms (see Mustillo, 1985).

This definition of crossed and uncrossed disparity, which is based on the horopter and corresponding retinal points, is the only relevant one for the visual system because disparity is based on retinal coordinates. The magnitude and direction (crossed or uncrossed) of disparity stimulating the visual system can be known as long as the position of the horopter (and thus convergence angle) is known. This definition is consistent with a large body of knowledge concerning the psychophysics and neurophysiology of stereopsis.

However, other definitions of disparity and horopter are used in many applied situations. The baseline of zero disparity is taken to be the face of the display screen, and disparity is defined relative to the screen; disparity in front of the screen is crossed and disparity behind the screen is uncrossed (e.g., Parrish and Williams, 1990; Warren, Genco, and Con-

non, 1984; Yeh and Silverstein, 1990). In a general sense this approach is concerned with the relative disparity between objects in visual space. Consider two objects, X and Y, positioned in space such that X is in front of Y. One can say that X has a crossed disparity relative to Y or that Y carries an uncrossed disparity relative to X. Regardless of convergence angle, the relative disparity between X and Y remains constant. Because this definition of disparity is not based on retinal coordinates, the need to know vergence angle and horopter is avoided (see later section on Eye Movements and Retinal Disparity). Note, however, that the effective disparity of X and Y as delivered to the visual system depends upon vergence angle: if one fixates or places the horopter on Y, then Y has no disparity and X presents a crossed disparity to the visual system; if one fixates X, then X has no disparity and Y presents an uncrossed disparity.

As long as the operator is fixating (i.e., placing the horopter) on the display screen, disparity defined relative to the screen is equivalent to that based on corresponding retinal points. If, however, the operator converges to a depth plane different from the one defined by the screen, the visually relevant disparities are inaccurately specified with the former definition. This might pose problems for developing reliable design criteria for stereoscopic displays, depending on the degree to which crossed and uncrossed disparity are processed by separate visual mechanisms that function differently. For example, if under certain conditions uncrossed but not crossed disparities are processed poorly by the visual system, depth perception of an object could be invalid if the operator converges to a depth plane in front of that object, thereby placing it behind the horopter and in the uncrossed disparity region. However, depth could be valid if the operator converges

to a plane behind the object, thereby placing it in front of the object and in the crossed disparity region.

There is abundant evidence that crossed and uncrossed disparity are processed by separate mechanisms (Mustillo, 1985), and most applied situations allow operator-initiated eye movements to occur. Thus the issue of how to define disparity is a real one. For any given system, it remains an empirical question as to whether conclusions made about depth perception when disparity is defined relative to the display screen are different from conclusions made when disparity is defined relative to the horopter.

Note also that the perception of relative depth from disparity would be different from depth perception based on variation in vergence position. Although changes in vergence are induced by disparity, such changes would provide only indirect information about depth, with depth perceived by the sensing of a difference between two different vergence positions. In this case, depth would be derived from proprioceptive information, not disparity directly. Depth estimates from proprioception would be relatively imprecise compared with those from disparity (stereopsis; Ono and Comerford, 1977; see also Patterson, Moe, and Hewitt, 1992 [this issue]).

Binocular Fusion   •

Objects slightly in front of or behind the horopter give rise to small disparities. Such objects are within a region surrounding the horopter called *Panum's fusional area.* (Objects located on the horopter are also within Panum's area; see Figure 1.) Fusion is the sensory process of blending into one perceived image the two corresponding monocular images (Julesz, 1971; Tyler, 1983). Objects farther away from the horopter and outside Panum's area give rise to large disparities and images that are not fusible and which may be

seen as diplopic (double). The ability to fuse disparate images depends on disparity magnitude; the largest disparity at which fusion occurs is called the *disparity limit of fusion.* (This limit is measured with the diplopia threshold—that is, the threshold at which fusion is lost and double images are perceived.)

Many factors affect the disparity limit of fusion (see Arditi, 1986, for a recent review). The following discusses stimulus factors that display designers could manipulate or control in order to promote binocular fusion. The disparity limit for fusion covaries directly with stimulus size or scale and inversely with spatial frequency; large disparities can be fused with large stimuli. For example, Schor and Tyler (1981) showed that the limit increased from 2 arcmin to 10 arcmin or greater when the spatial frequency of the stimulus decreased from 2.0 cycles/deg (15 arcmin wide sinusoidal bars) to 0.125 cycles/deg (4 deg wide bars). The increase in disparity limit with size is called *disparity scaling* (see Table 1). The limit, however, does not vary with stimulus contrast (Schor, Heckmann, and Tyler, 1989).

The disparity limit increases with eccentricity; large disparities can be fused at large eccentricities. In the fovea the limit is 6 arcmin, whereas at 6 deg eccentricity the limit is 15–20 arcmin (Ogle, 1952). Tyler (1983) reported a similar value for the fovea (Table 1). The disparity limit also varies with temporal modulation of disparity information (Schor and Tyler, 1981). Using thin test lines, Schor and Tyler showed that the limit increases by a factor of 10 when low spatial and low temporal frequencies of modulation are employed.

These values and those in Table 1 provide only rough estimates because actual limits vary widely from one study to another. Nonetheless the values presented here provide an idea of the disparity limits of fusion. These

TABLE 1

Representative Disparity Limits for Binocular Fusion, Patent Stereopsis, and Qualitative Stereopsis for Two Stimulus Sizes and Two Retinal Eccentricities

	Small Size (<15 arcmin)			Large Size (1.0–6.6 deg)		
	Fusion	Patent	Qualitative	Fusion	Patent	Qualitative
Foveal area	10 arcmin	20 arcmin	2 deg	20 arcmin	2 deg	8 deg
6 deg eccentricity	20 arcmin	2 deg	3.5 deg	—	—	—

values apply to both crossed and uncrossed disparity; they correspond to the distance of the test stimulus from the horopter. To obtain the total range of fusion, the values should be doubled; this will provide an estimate of the maximum range of disparity over which stimuli can be fused simultaneously when fixation is at an intermediate depth plane.

Patent and Qualitative Stereopsis

Stereopsis is classified according to disparity magnitude (Bishop and Henry, 1971; Norcia and Tyler, 1985; Ogle, 1952, 1964). *Patent stereopsis* involves perceiving depth from small disparities and (mostly) fused images; the depth monotonically increases with disparity (Ogle, 1964). Near its disparity limit, patent stereopsis occurs with diplopia. *Qualitative stereopsis* involves perceiving depth from large disparities and diplopic images; the depth does not bear a one-to-one relationship with disparity (depth declines toward the horopter at a disparity value of about 1 deg or greater). Bishop and Henry (1971) offered a similar classification scheme using the terms *fine* and *coarse* stereopsis, respectively. Electrophysiological evidence (i.e., evoked potentials) in humans suggests that small disparities are processed differently from large disparities (Norcia and Tyler, 1985).

As with fusion, many factors affect the disparity limits of patent and qualitative stereopsis, and the following section discusses factors that designers could control in order to promote valid depth perception. The disparity limits for patent and qualitative stereopsis covary directly with stimulus size or scale and inversely with spatial frequency; large disparities can induce depth with large stimuli (disparity scaling). Using a wavy-line stimulus, Tyler (1973; see also Burt and Julesz, 1980) reported that the limit of qualitative stereopsis is 5 arcmin with a stimulus spatial frequency of 3.0 cycles/deg and 150 arcmin or greater with a frequency of 0.03 cycles/deg. Richards and Kaye (1974) used a 3 arcmin wide bar as a stimulus; they showed that the limit of patent stereopsis was 30 arcminutes and the limit of qualitative stereopsis was 2 deg. With a 48 arcminute wide bar, the limit of patent stereopsis was 2 deg and the limit of qualitative stereopsis was 8 deg. Schor and Wood (1983) showed that the limit of qualitative depth was 40 arcmin with a spatial frequency of 2.4 cycles/deg (12.5 arcmin wide bar). The limit increased to 4 deg with a frequency of 0.075 cycles/deg (6.6 deg wide bar; see Table 1).

Disparity limits of patent and qualitative stereopsis also increase with eccentricity. In the foveal area, the limit of patent stereopsis is 15–20 arcmin and the limit of qualitative stereopsis is 20–25 arcmin. At 6 deg eccentricity, the limit of patent stereopsis is 2 deg and that of qualitative stereopsis is 3.5 deg (Ogle,

1952). Tyler (1983) reported larger values for the foveal area. He found that the limit of patent stereopsis is 20–40 arcmin and the limit of qualitative stereopsis is 8–10 deg. Blakemore (1970b; see also Westheimer and Tanzman, 1956) reported that for thin stimuli, the limit of patent stereopsis is 1.5 deg and the limit of qualitative stereopsis is 7–12 deg in the foveal area; the limit of qualitative stereopsis is 12–14 deg at 10 deg eccentricity (see Table 1).

These values and those in Table 1 provide only rough estimates because actual limits vary widely across studies. These values apply to both crossed and uncrossed disparity; they correspond to the distance of the test stimulus from the horopter. As with fusion, to obtain the total range of patent and qualitative stereopsis the values should be doubled; this will provide an estimate of the maximum range of disparity over which stimuli can be perceived in depth simultaneously with intermediate fixation.

Eye Movements and Retinal Disparity

As we discussed earlier, vergence eye movements change the magnitude and possibly the direction of all visually relevant disparities in the visual field by changing horopter position relative to objects in that field. For stereoscopic displays, changes in vergence alter the disparity of a stimulus by changing the position of the horopter relative to the display screen (for discussion of vergence movements, see Schor and Ciuffreda, 1983). For example, fixating a disparate stimulus eliminates its previous disparity, thus placing the stimulus on the horopter; the display screen then presents disparity information to the visual system.

In basic research a common method to prevent vergence eye movements from changing disparity is to employ brief stimulus exposures (e.g., Foley and Richards, 1972; Rich-

ards, 1970). The stimulus is exposed for 180 ms or less (briefer than the latency of vergence movements); thus stimulus-initiated vergence movements cannot occur during the exposure of the stimulus. Although this method solves the eye movement problem, it introduces another problem: the stimulus is degraded because the observer views it briefly. Results obtained from experiments using brief exposures do not necessarily generalize to situations involving extended viewing.

From a design viewpoint, it is desirable to allow vergence eye movements to occur so that a greater range of disparities can be processed by shifting the horopter to various positions in the visual field. Voluntary eye movements have been shown to increase disparity limits of fusion (limits of 24–27 arcmin without eye movements versus limits of several degrees with movements; Yeh and Silverstein, 1990) and to improve stereoscopic depth perception (Foley and Richards, 1972). Yet in many ways the effects of eye movements on stereopsis are complex and unknown. For instance, the longitudinal horopter, which is normal in the frontoparallel plane with symmetric convergence, rotates horizontally with asymmetric convergence (fixation off the midsagittal plane; Ogle, 1964; Shipley and Rawlings, 1970). The effects of a rotated horopter on stereopsis have not been systematically studied.

On a related point, in situations where eye movements are permitted and an operator fixates a disparate stimulus appearing in a depth plane different from that of the display screen, the stimulus for accommodation (display screen) may be at one distance while vergence angle is appropriate for another distance (disparate stimulus), thereby producing a mismatch between accommodation and vergence. Such situations are known to produce much discomfort for the operator

(R. V. Parrish, personal communication, August 10, 1990).

Stereoacuity

Threshold discrimination of depth from very small disparities is called *stereoacuity,* a topic with a long history of investigation (Berry, 1948; Blakemore, 1970b; Howard, 1919; Ogle, 1964; Westheimer, 1979). The interest in stereoacuity stems from the observation that thresholds can be only a few seconds of arc (i.e., high sensitivity). The level of processing involved with stereoacuity is not known, but one suggestion has been that it is the early cortical levels (Barlow, 1981).

Many factors affect stereoacuity (e.g., configuration and separation of test stimuli); see Arditi (1986) and Yeh and Silverstein (1990) for discussion. The following discusses stimulus variables that designers could control in order to promote keen stereoacuity. Stereoacuity thresholds are low (e.g., 8 arcsec) under photopic levels of illumination, rising by a factor of five or more under scotopic levels (Graham, 1965). According to Ogle (1964), stereoacuity is good as long as background luminance is such that stimulus detail can be seen. Halpern and Blake (1988) suggested that good stereoacuity is obtained with stimuli in which contrast is a factor of about 5–10 above contrast threshold. They also found that interocular differences in contrast of a factor of about 4–5 increase stereoacuity thresholds (decrease sensitivity); this effect is greatest at low spatial frequencies (1.2 cycles/deg or 25 arcmin wide bars). Schor and Heckmann (1989) reported increases in stereoacuity thresholds of 150% with interocular differences in contrast of only 25%–50%.

Thresholds are low with small stimuli composed of high spatial frequencies (Ogle, 1964; Schor and Wood, 1983; Schor, Wood, and Ogawa, 1984). Schor and Wood (1983) showed that stereoacuity is good (15 arcsec threshold) with a stimulus spatial frequency of 3.0 cycles/deg (10 arcmin wide bar) or higher, but that stereoacuity is poor (10 arcmin threshold) with a lower spatial frequency of 0.075 cycles/deg (6.6 deg wide bar).

Low stereoacuity thresholds are obtained at the foveal area and increase as the test stimulus is moved to eccentric locations (Tyler, 1983) or in depth in the crossed or uncrossed direction (Badcock and Schor, 1985; Blakemore, 1970b). Blakemore (1970b) reported that with thin targets (2.25 arcmin wide), stereoacuity threshold was about 10 arcsec at the foveal area and rose to 1.5–2.0 arcmin at 10 deg eccentricity. The threshold rose to 8–15 arcmin when the test stimuli were positioned in depth at disparities of 1.5–2.0 degrees, depending on eccentricity. (The increase in threshold with stimulus disparity is more gradual in the periphery than in the foveal area.) Similar results were reported by Badcock and Schor (1985). Thus stereoacuity is keen (e.g., 10 arcsec threshold) only near the fovea and horopter. This means that good depth discrimination over different portions of the visual field requires eye movements.

Westheimer and McKee (1978) found that low thresholds are obtained with moving stimuli. Thresholds on the order of 10–20 arcsec were obtained up to a velocity of 2.5 deg/s, a relatively low value. A recent study by Patterson (1990b) investigated stereoacuity with stimuli that were counterphase flickered or briefly exposed. He found that low thresholds (e.g., 20 arcsec) are obtained only with high spatial frequencies (e.g., 6–8 cycles/deg, or 5 arcmin wide sinusoidal bars) and low temporal frequencies (e.g., 1 Hz), or with high spatial frequencies and long exposure durations (e.g., 110 ms).

These values provide only a rough estimate of stereoacuity threshold; actual values vary across situations. In general, for best stereoacuity performance (low thresholds), isolated objects with high spatial frequency content (i.e., small or thin stimuli) should be pre-

sented foveally under sustained viewing conditions.

Stereoscopic Displays

This section discusses the geometry of binocular vision as it applies to stereoscopic displays. As demonstrated by Wheatstone (1838), disparities associated with viewing in the natural environment can be mimicked by presenting a pair of two-dimensional visual displays or drawings separately to the eyes. This scheme is presented in Figure 2, in which a top-down view of two eyes is shown; one drawing is presented to one eye, the other drawing to the partner eye. The half-images of stimulus A (A and A') are presented to corresponding retinal points a and a' while the half-images of stimulus B (B and B') are presented to disparate retinal points (b and b'). Binocular fusion causes an observer to per-

ceive two stimuli (stimulus B appears in depth behind stimulus A); the left portion of Figure 3 depicts the expected perceptual result. Note that although Figure 2 shows four elements involved in the production of depth (A, B, A', and B'), in fact only three elements are needed: one element in one eye and two elements in the other eye. The induction of stereopsis with only three elements is called *Panum's limiting case*, which may be based on multiple fusion: the single element fuses with each of the two contralateral elements (Ogle, 1964). See the right portion of Figure 3 for a depiction of the expected perceptual result in this case.

The computation of disparity in stereoscopic displays has been discussed by Cormack and Fox (1985) and by Graham (1965). Disparity is computed as:

$$r(\text{degrees}) = 57.3 \cdot S/D$$

where r = disparity in degrees of visual angle, S = separation between the half-images of a stereoscopic display, and D = viewing distance from the observer to the fixation point, which is usually the plane of the display screen. The geometry of stereopsis allows for the quantitative prediction of the magnitude of depth that should be perceived by the observer (Cormack and Fox, 1985):

$$d = S \cdot D/(I + S) \quad \text{for crossed disparity,}$$

$$d = S \cdot D/(I - S) \quad \text{for uncrossed disparity,}$$

where d = the predicted depth interval of the apparent object from the display, S = separation between the half-images of the display, D = viewing distance, and I = interpupillary distance (average interpupillary distance is 6.5 cm). Thus perceived depth should be a linear function of viewing distance, half-image separation, and the observer's interpupillary distance. (In real space, disparity is proportional to the square of viewing distance
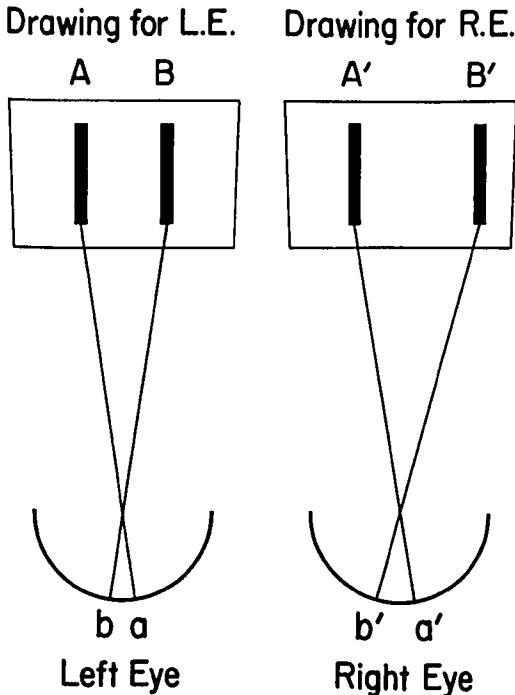
Drawing for L.E.   Drawing for R.E.

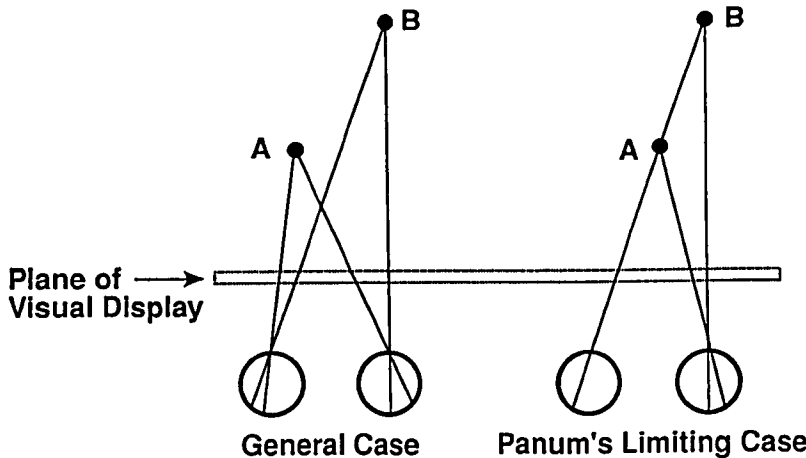Figure 2. *Top view depicting two drawings, one presented to each eye.*

Figure 3. *Top view depicting the expected perceptual results when viewing stereoscopic displays.*

for close distances, and depth is not a linear function of distance.)

The effects of these variables on predicted depth has been discussed by Cormack and Fox (1985): (1) With respect to separation, there is an asymmetry between crossed and uncrossed disparity directions. For crossed disparity, as separation increases, predicted depth is bounded by the distance between observer and display (i.e., depth can never exceed viewing distance). For uncrossed disparity, as separation increases, predicted depth is positively accelerated until separation equals interpupillary distance, at which point depth goes to infinity. Thus separations used for uncrossed disparity should be restricted to values that do not exceed the observer's interpupillary distance (although an observer's interpupillary distance would rarely be exceeded, considering that such separations would lead to excessively large disparities—e.g., greater than 1.0 deg). Given an equal separation, depth with uncrossed disparity should be greater than depth with crossed disparity (see Figure 4 'of Cormack and Fox). (2) With regard to viewing distance, predicted depth varies as a linear function of

distance when other factors are held constant. Thus longer distances should be used when large depth intervals are needed. For example, for a separation of 0.5 cm, an interpupillary distance of 6.3 cm, and distances of 100 and 200 cm, corresponding values of depth are 7.4 and 14.8 cm, respectively. (3) With regard to interpupillary distance, the larger the distance, the smaller the magnitude of predicted depth. This effect is greater for large separations and uncrossed disparities. Overall, however, this effect is small: for instance, for a separation of 0.5 cm, a viewing distance of 100 cm, and interpupillary distances of 5.8 and 6.9 cm, corresponding values of depth are 7.9 and 6.8 cm, respectively.

These relations derive from geometry, and as such they serve as predictions. It remains an empirical question as to whether depth is actually perceived as predicted; this is a question of *depth constancy*, which refers to the ability to perceive veridical depth from disparity despite changes in viewing distance that alter disparity magnitude. Somehow the visual system calibrates disparity information differently for different distances to yield veridical depth (Cormack and Fox, 1985; Ono

and Comerford, 1977; Wallach and Zucker-man, 1963). This topic is discussed later in the section on theoretical considerations.

Research has shown that depth with crossed disparity follows predictions quite closely in most cases. However, depth with uncrossed disparity may be less than pre-dicted (Patterson and Fox, 1984; Patterson et al., 1992; Patterson, Short, and Moe, 1989). For example, Patterson, Short, and Moe (1989) investigated the temporal sensitivity of crossed and uncrossed stereopsis using briefly exposed stimuli. Perceived depth thresholds for crossed disparity were much briefer (greater sensitivity) than those for un-crossed disparity, and depth in the crossed direction was closer to predictions.

In a recent study, Patterson et al. (1992) in-vestigated five variables that affect depth perception in stereoscopic displays: (1) mag-nitude of half-image separation, (2) direction of separation (i.e., crossed or uncrossed), (3) viewing distance, (4) stimulus size, and (5) ex-tended versus brief stimulus exposures. They found that perceived depth in the crossed di-rection frequently followed predictions: in-creases in separation and distance produced appropriate increases in depth. (Parrish and Williams, 1990, also reported that increases in distance produced increases in depth). Depth in the uncrossed direction was fre-quently less than predicted, especially for small stimuli presented at a long viewing distance, with a large half-image separation, or with a brief duration. For large stimuli exposed for a long duration, depth equaled predictions in both crossed and uncrossed directions.

Parrish and Williams (1990) reported a dif-ferent asymmetry, in which depth in the un-crossed direction is greater than predicted. They employed as test stimuli large vertical rods (size ranged from 0.7 × 5.9 deg to 1.96 × 17.6 deg) presented for long durations, and it

therefore is not surprising that they did not find underconstancy in the uncrossed direc-tion; it is surprising that they found overcon-stancy. We cannot offer any explanation for why they found overconstancy whereas the studies reported earlier found undercon-stancy. Consistent with Parrish and Williams, Schor and Howarth (1986) reported that depth in the uncrossed direction is perceived more distally than predicted (overconstancy) when large, low-contrast (below 0.50) stimuli are employed.

Under conditions that promote veridical depth perception (e.g., long exposures), sepa-ration and distance can be large, thus maxi-mizing perceived depth in both crossed and uncrossed directions. In this case vergence eye movements (which change horopter posi-tion and thus vary effective disparity) can be ignored and long exposure durations can be employed, because depth should be veridical in all portions of the display. As discussed earlier, such eye movements would permit a greater range of disparities to be visually pro-cessed by shifting the horopter to various po-sitions in the display. Under conditions that impair depth perception (e.g., small stimuli), vergence eye movements and corresponding variations in horopter position occurring with long stimulus exposures should not be ignored, because depth may not be veridical in all portions of the display (e.g., invalid depth behind horopter/fixation). The remedy to this problem would be to employ condi-tions that promote veridical depth percep-tion, or to enhance perception by bolstering disparity information with other depth cues (e.g., linear perspective).

Binocular Rivalry

Images from objects positioned at large distances from the horopter are diplopic, leading to the situation in which different

monocular images strike corresponding retinal areas in the two eyes, thereby provoking *binocular rivalry*. Rivalry is a process in which the visibility of the monocular images alternates every few seconds; first the left eye's image is visible (the right eye's image is perceptually suppressed), then the right eye's image is visible; rivalry occurs because the visual system cannot fuse the dissimilar images (for recent reviews, see Blake, 1988, and Wolfe, 1986). An important aspect of rivalry is that the characteristics of the suppressed stimulus are almost completely vanquished from perceptual awareness during suppression.

Both fusion and rivalry are believed to operate during natural viewing: images from objects close to the horopter should be fused, whereas images from objects at large distances should be rivalrous (Blake and Camisa, 1979). Therefore an appreciation of rivalry is important for understanding binocular vision. For example, it has been suggested that stereopsis and rivalry can coexist if each is subserved by a separate visual spatial-frequency (size) channel (Julesz and Miller, 1975), though Blake, Yang, and Wilson (1991) have argued against this possibility.

In stereoscopic displays, rivalry should be encountered whenever different, unfusable images impinge upon corresponding retinal areas—for example, when multiple objects with large disparities are viewed and the operator cannot fuse all corresponding images simultaneously. Because rivalry suppression is so complete, its existence in visual displays could be dangerous—for example, in the case of binocular helmet-mounted displays. Thus an attempt should be made to avoid presenting patently different stimuli to corresponding retinal areas in the two eyes of an operator, such as when stimuli with large crossed or uncrossed disparities (e.g., larger than 30 arcmin) are viewed.

Disparity Gradients

Rogers and Cagenello (1989; Cagenello and Rogers, 1988, 1989) have investigated the role of interocular differences in stimulus orientation and curvature (i.e., orientation and curvature disparities) on the perception of slant and curvature of stereoscopic surfaces in complex, textured scenes. Such orientation and curvature disparities produce disparity gradients across the visual field. They found that orientation and curvature disparities are important cues for the perception of slant and curvature of surfaces. Related research on disparity gradients by Stevens and Brookes (1988) and by Gillam, Flagg, and Findlay (1984) has shown that abrupt variations in disparity provide a robust cue for stereopsis.

Motion in Three-Dimensional Space

One kind of "disparity" that can provide information about motion in three-dimensional space is disparity between the direction or speed of motion of the retinal images delivered to the two eyes. For example, motion of an object toward the observer (e.g., stimuli that move toward the observer's head) involves a disparity between the direction of the motion of the two eyes' images, with the left-eye image moving temporalward or to the left while the right-eye image moves temporalward or to the right. Motion away from the observer would entail both images moving nasalward and in opposite directions. Psychophysical evidence for the existence of visual mechanisms that mediate the perception of motion in depth comes from the work of Regan and Beverley (1973a, 1973b; Beverley and Regan, 1973, 1974a, 1974b; Hong and Regan, 1989). These mechanisms appear separate from those that mediate the perception of lateral motion in the frontoparallel plane or the perception of static depth. Neurophysiological evidence of such mecha-

nisms has been obtained in the cat (Cynader and Regan, 1978) and monkey (Zeki, 1974). The ability to accurately perceive motion in depth may be important in certain applied situations: for example, in the case of a pilot estimating the speed and changing position of an approaching aircraft; see Hong and Regan (1989) for discussion of this issue.

Distortions of Stereoscopic Space

Interocular differences in the horizontal magnification or size of corresponding monocular images (aniseikonia) lead to a rotation of the longitudinal horopter about a vertical axis positioned through the fixation point (Ogle, 1964). As discussed by Ogle, this rotation should lead to a distortion of stereoscopic space. Recent research has provided evidence of such distortion, showing that interocular differences in stimulus size produce stereoscopic tilted surfaces (Blakemore, 1970a; Halpern, Patterson, and Blake, 1987; Wilson, 1976), decreases in depth sensitivity (i.e., increased stereoacuity thresholds; Schor and Heckmann, 1989), and decreased horizontal and vertical fusion limits (Schor and Heckmann, 1989). Thus interocular differences in size should be avoided.

Interocular differences in light intensity can lead to the perception of depth when a stimulus undergoes motion relative to a stationary background; this is called the *Pulfrich phenomenon* (e.g., Enright, 1985; Lit, 1949; Pulfrich, 1922; Williams and Lit, 1983). For example, when an observer views a pendulum moving in the frontoparallel plane, with a neutral-density filter placed in front of the left eye, the object will appear to move in an illusory elliptical path. The pendulum will appear farther away during left-to-right motion and closer during right-to-left motion; with the filter placed in front of the right eye, the situation is reversed. The effect is caused by a reduction in intensity received by the eye

with the filter, which produces an increase in the latency of the visual responses of that eye. The increased latency produces a temporal disparity in the arrival of the neural input from the filtered eye to the cortical processes responsible for signaling the position of the pendulum. Whenever there is movement and interocular light-intensity differences in a visual display, the potential for stereoscopic information exists. Such information could alter the magnitude and possibly direction of the disparity already present in a display; thus interocular differences in luminance should be avoided.

VISUAL PERSISTENCE

One common method for inducing stereopsis is to present each eye's view on alternate frames of the display so that the two views are temporally interlaced; they are never seen simultaneously. This is called the *field-sequential* or *time-multiplexing* method of stereoscopic presentation (e.g., each eye's view is presented at a 30 Hz rate, for a field rate of 60 Hz). The successful induction of stereopsis under these conditions implies that some kind of *visual persistence* occurs in each monocular (visual) channel and that the persistence overlaps temporally with the representation of the other eye's information.

Visual persistence is the temporally extended image or trace of stimulation that lasts about 100 ms or more following physical offset. It has been studied for hundreds of years, and several different kinds of persistence have been identified (Boyton, 1972; Breitmeyer, 1984; Coltheart, 1980; DiLollo, 1984; Long, 1980; Patterson, 1990a). Note that visual persistence is different from phosphor persistence, which is a physical process of most display systems in which the phosphors of the system take some time to decay (e.g., 2.6 ms for green P22 phosphor). Phosphor persistence produces image retention on

the display screen as the two eyes' views are alternated; this leads to interocular crosstalk, which can degrade depth perception (Yeh and Silverstein, 1990).

One kind of visual persistence relevant for stereoscopic displays has been studied by Engel (1970), who investigated persistence and stereopsis using stereoscopic stimuli created from disparity embedded in a random-dot stereogram (see discussion of random-dot stereograms in the section on theoretical considerations). Engel presented the left- and right-eye half-images of the stereogram alternately, varying stimulus duration and stimulus onset asynchrony, and measured perceived depth.

Engel found that the visual persistence contributing to stereopsis is positively related to the duration of the half-images. At very brief durations (e.g., 1 ms), persistence is about 20 ms; for half-image durations of 10 milliseconds or more, persistence is constant at 80 ms (Coltheart, 1980). This suggests that displays involving frame durations of 10 ms or greater (i.e., 100 Hz field rate or lower) should produce good stereopsis because of longer persistence and greater binocular integration. (One potential problem with low field rates, however, may be the perception of flicker, which could degrade depth perception.)

Engel's study stands alone in the investigation of visual persistence and stereopsis. For that reason, the aforementioned values are presented for illustrative purposes only; they should be viewed with caution until the factors affecting visual persistence and binocular integration (stereopsis) for field-sequential display systems are studied further.

PERCEPTUAL INTERACTION AMONG STEREOSCOPIC STIMULI

When stereoscopic stimuli are presented in close spatial and temporal proximity, they may perceptually interact. This perceptual interaction may take one of two forms: lateral interaction among the stimuli (e.g., perceptual interference) may depend on relative depth position, or the perceived depth position of the stimuli may depend on lateral separation.

With regard to the effects of relative depth position on lateral interaction, Gogel and colleagues (for reviews, see Gogel, 1977, 1978, 1984) have shown that the degree of perception interaction among stimuli depends upon their lateral separation (x and y axes) or their depth separation (z axis), the so-called *adjacency principle.* According to this principle, the magnitude of perceptual interaction should decline as stimuli are separated in any of the three axes. For example, Gogel and MacCracken (1979; see also Gogel and Tietz, 1976) examined the effect of depth separation on induced motion (up-and-down movement of a small test object appearing to be deviated from vertical because of the presence of two horizontally moving inducing objects, one located above and the other below the test object). Gogel and MacCracken found that stereoscopically placing the test object either in front of or behind the inducing objects by up to 68.8 arcmin of disparity (lateral separation was fixed at 36 arcmin) decreased the magnitude of the induction by about one half, which provides support for the adjacency principle.

Not all studies have obtained support for the adjacency principle in its strong form. Lehmkuhle and Fox (1980) investigated stereoscopic depth separation and metacontrast masking (interference between briefly exposed target and masking stimuli). They found that the effect of depth separation on masking was asymmetrical: when the target was in front of the mask (i.e., the two half-images of the target were presented in crossed disparity relative to the half-images of the mask) by about 1 deg of disparity, masking declined; when the mask was in front of the target, masking increased, rela-

tive to an equal depth condition. Fox and Patterson (1981) found the same pattern of results for lateral interference (interference between continuously exposed stimuli), and Patterson and Fox (1983) found a similar pattern of results for the Ponzo illusion (Sekuler and Blake, 1990, pp. 235–236). In these cases, the stimulus that appeared closer to the observer gained greater perceptual weighting than did other stimuli (called the *front effect*). One possible explanation for this effect is based on attention: positioning a given stimulus in front of other stimuli may make it difficult to ignore (Gogel, 1984).

With respect to the effects of lateral separation on perceived depth, Westheimer (1986; see also Westheimer and Levi, 1987), using simple stimuli (e.g., small points and lines), found that when stimuli were separated laterally by less than 2–8 arcmin, their perceived depth differences were diminished; the stimuli attracted one another (this is similar to the idea of the *equidistance tendency*, the tendency for adjacent targets to appear to be at the same depth; see Gogel, 1977). When stimuli were separated laterally by 2–8 arcmin or greater, depth differences were enhanced; the stimuli repulsed one another. Beyond a lateral separation of 36 arcmin, the stimuli no longer interacted.

Perceptual interaction in visual displays is a complex problem. Depending on whether attraction or repulsion occurs, lateral separational changes may result in either an increase or a decrease in the depth position of a given object. For example, consider two adjacent stereoscopic stimuli, one presented with a disparity greater than that of the other. Because the stimuli are adjacent, assume that they are undergoing perceptual attraction (i.e., their depth difference is diminished). If the stimuli are separated laterally, the stimulus with greater disparity will increase in depth while the stimulus with lesser disparity will decrease in depth. Note also that an

effective separation in one situation may not be effective in another situation. Under some conditions, valid depth perception may be accomplished by keeping targets relatively close. In summary, there is much more to be learned about perceptual interaction in visual displays.

NEUROPHYSIOLOGY OF STEREOPSIS

This section discusses the neurophysiology of stereoscopic depth perception. Although it may seem that neurophysiology is not relevant for the design of stereoscopic displays, we believe otherwise. For example, recall that under most conditions depth perception is valid with crossed disparity but not with uncrossed disparity, which is important for the design of such displays (as discussed earlier). In this section we argue that separate classes of neural mechanism seem to mediate disparity processing in the crossed versus uncrossed direction. It is possible that the functional difference (i.e., valid versus invalid depth) between crossed and uncrossed stereopsis is related to differences between neural mechanisms, which is an example of how neurophysiology can be relevant for the design of stereoscopic displays.

Twenty years ago, several researchers (e.g., Barlow, Blakemore, and Pettigrew, 1967; Hubel and Wiesel, 1970; Joshua and Bishop, 1970) investigated the response properties of cortical neurons in cats or monkeys. Employing anesthetized animals, the researchers plotted the position and configuration of pairs of receptive fields of binocular neurons located at lower levels of visual cortex (e.g., area 17 or V1). Some neurons had receptive fields positioned on corresponding retinal areas, whereas others had receptive fields positioned on disparate retinal areas (receptive field disparity); these latter neurons were believed to be the substrate for stereopsis. Variation in receptive field disparity was finely graded across neurons, suggesting that the

neurons would be selective for disparity. (This assumption has been challenged by von der Heydt, Adorjani, Hanny, and Baumgartner, 1978.)

More recently, Poggio and others (Maunsell and Van Essen, 1983; Poggio and Fischer, 1977; Poggio, Motter, Squatrito, and Trotter, 1985; Poggio and Poggio, 1984; Poggio and Talbot, 1981) investigated the response properties of disparity-sensitive neurons, also at lower cortical levels in cats or monkeys. Employing awake, behaving animals, the researchers recorded the neural responses elicited by a stimulus in a particular depth plane and discovered several types of disparity-activated neurons. Two types—the near and far neurons—are activated by disparity in the crossed or uncrossed direction, respectively, and are inhibited by disparity in the opposite direction. These neurons are broadly tuned for disparity, suggesting that responses are pooled prior to that level of processing. Two other kinds—the tuned-excitatory and tuned-inhibitory neurons—are excited and inhibited, respectively, by a small range of disparities around the horopter.

Whereas the earlier work suggests the existence of neurons that are highly selective for disparity, the recent results suggest the existence of neurons broadly tuned for disparity. The reasons for this discrepancy are not known. Many conditions were different among the studies, particularly the kind of experimental paradigm employed (e.g., anesthetized animals versus awake, behaving animals). Nonetheless, the disparity-activated neurons found at lower levels of the visual cortex in mammals seem to provide the substrate for the initial processing of retinal disparity (Poggio and Poggio, 1984).

Recent anatomical and physiological studies in primates suggest the existence of parallel visual pathways, the parvocellular (color-opponent) and magnocellular (broadband) pathways (Livingstone and Hubel,

1987, 1988). The parvocellular pathway begins with type B retinal ganglion cells and projects via the parvocellular layers of the lateral geniculate nucleus (LGN) to areas in temporal cortex. Neurons of this system have small axons, small receptive fields, and slow conduction velocity. They are activated by sustained stimuli; many are sensitive to wavelength. Livingstone and Hubel proposed that this pathway mediates the processing of fine stimulus detail and color perception. The magnocellular pathway begins with type A ganglion cells and projects via magnocellular layers of the LGN to areas in parietal cortex. Neurons of this system have large axons, large receptive fields, and fast conduction velocity. These neurons are not sensitive to wavelength; many (in cortex) are sensitive to moving stimuli and to disparity. Livingstone and Hubel suggested that this pathway mediates the perception of motion and stereopsis.

This model of parallel pathways and attendant perceptual functions has been challenged, however. DeYoe and Van Essen (1985) suggested that the substrate for stereopsis may be parvocellular: they found neurons with strong binocular interaction at cortical levels of the parvocellular pathway. Schiller, Logothetis, and Charles (1990) recently showed that, in primates, parvocellular lesions impaired color vision, fine-detailed form vision, and fine stereopsis, whereas magnocellular lesions impaired high-temporal frequency flicker and motion perception but not stereopsis. This suggests that the perception of fine details, color, and fine depth perception is mediated by the parvocellular pathway, whereas the perception of flicker and motion is mediated by the magnocellular pathway. Coarse-form vision and coarse stereopsis were not affected by either kind of lesion, suggesting that these latter perceptual abilities are subserved by both pathways. For recent criticism of the Livingstone and Hubel model, see Ingling and

Grigsby (1990) and Logothetis, Schiller, Charles, and Hurlbert (1990).

THEORETICAL CONSIDERATIONS

This section presents a working framework that is related to issues of depth perception in stereoscopic displays. The content of this section is drawn from ideas found in Julesz and Schumer (1981), Marr (1982), Marr and Poggio (1976, 1979), Mayhew and Frisby (1981), Ono and Comerford (1977), and Poggio and Poggio (1984). We propose a simple hierarchical framework of disparity processing involving two stages. One stage involves establishing a perceptual match between corresponding images in the two eyes (i.e., establishing binocular correspondence) and detecting disparity, whereas the second stage entails perceiving depth from disparity (involving a perceptual constancy).

Binocular Correspondence/
Disparity Detection

Studies performed during the past 20 years (Julesz, 1971, 1978, 1982; Marr and Poggio, 1976; Nelson, 1975) suggest that establishing binocular correspondence may involve activation of some kind of cooperative network of disparity-selective neurons. Those studies primarily employed computer-generated, random-dot stereograms developed by Julesz (1960). Such stereograms are composed of two arrays of thousands of randomly ordered dots; each array is presented to one eye of an observer. Disparity is created by shifting laterally a subset of dots in one eye's view and leaving unshifted corresponding dots in the other eye's view (the shift is camouflaged by background dots). An observer with stereopsis perceives the stereoscopic stimulus defined by the shifted dots as a form appearing in a depth plane different from that of the background dots; the form can be seen neither monocularly nor by someone who lacks stereopsis.

Random-dot stereograms provide a good test of the correspondence process: in principle, a dot in one eye can be paired with any dot in the partner eye, a possibility that should confound the matching process. Yet correspondence must be established, for depth is readily perceived in such displays. It has been suggested (Julesz, 1971, 1978; Nelson, 1975) that correspondence is established because neural units interact cooperatively via excitation and inhibition: units tuned to the same disparity in different parts of the visual field excite one another, whereas units tuned to different disparities in the same part of the visual field inhibit one another. Stereopsis induced with random-dot stereograms has been called *global stereopsis* because establishing correspondence under such conditions should involve global-network operations (as opposed to stereopsis induced with simple contours, called *local stereopsis*, which should involve only local operations). From a human factors viewpoint, random-dot displays have disadvantages relative to displays with a small number of unique contours: vergence eye movements are slow and inaccurate in random-dot displays (Mowforth, Mayhew, and Frisby, 1981).

The stimuli created from disparity embedded in random-dot stereograms are purely stereoscopic, functionally existing only at levels of the visual system involving binocular integration. To reflect this property, Julesz (1971) called such stimuli cyclopean. Perceptual phenomena revealed by cyclopean stimulation are inferred to represent levels of processing at or beyond the stage of binocular integration. The logic of this approach is discussed by Julesz (1971, 1978), Julesz and Schumer (1981), and Tyler (1983).

Processes other than network operations may underlie the establishment of binocular correspondence. Establishing correspondence may involve activation of spatial-frequency (size) tuned channels (Marr, 1982;

Marr and Poggio, 1979), and the range of disparities matched by each channel may be scaled spatially such that coarse channels (mediating low spatial frequencies or large stimuli) match large disparities and fine channels (mediating high spatial frequencies or small stimuli) match small disparities. The correspondence problem in random-dot stereograms would be solved by having the range of disparities processed by each channel reduced relative to the number of potential disparities present in the display (Marr and Poggio, 1979; Pollard, Mayhew, and Frisby, 1985; Trevedi and Lloyd, 1985). However, Yang and Blake (1991) suggested that the idea of an inverse relation between spatial frequency and disparity may be incorrect. Employing a noise-masking paradigm, the authors investigated the spatial frequency tuning of stereopsis. Based on obtained tuning curves, Yang and Blake concluded that only two spatial frequency channels underlie stereopsis, one with a peak tuning of 3.0 cycles/deg, the other with a peak tuning of 5.0 cycles/deg. Such results provide no support for models of stereopsis that assume the existence of a continuum of spatial frequency channels for which the range of disparities processed by a given frequency channel is inversely related to the spatial frequency tuning of that channel.

McKee and Mitchison (1988) have shown that the establishment of binocular correspondence is governed primarily by the disparity of the edges of stimuli. Employing an array of dots, they found that the edges of the array are first matched by the visual system over a duration of several seconds, followed by changes in vergence angle from the plane of initial fixation to that associated with the edges. McKee and Mitchison suggested that binocular correspondence is achieved according to a coarse-to-fine strategy because only coarse spatial channels would detect the edges of the stimulus.

Once correspondence is established, the binocular visual system must compute the magnitude of disparity. This apparently involves the metrical encoding of signals from disparate retinal areas in the two eyes. Poggio and Poggio (1984) proposed that the neural substrate underlying disparity detection is found at lower cortical levels of vision.

Perceiving Depth From Disparity

Once disparity is computed, depth must be derived from it; this is no trivial task, given that disparity is an inherently ambiguous depth cue. There is no one-to-one relation between disparity and depth: the same value of disparity will yield different magnitudes of depth depending on viewing distance. Disparity information must be calibrated differently for different distances in order for veridical depth to be computed by the visual system—a process termed *depth constancy* (Cormack and Fox, 1985; Ono and Comerford, 1977; Wallach and Zuckerman, 1963). In stereoscopic displays, constancy occurs when depth corresponds to that predicted by the geometry of stereopsis, as discussed earlier. Recall that for crossed disparity, perceived depth follows predictions derived from constancy in most cases; however, for uncrossed disparity perceived depth is frequently less than predicted (Fox, 1985; Patterson, Cayko, Flanagan, and Taylor, 1989; Patterson and Fox, 1984; Patterson et al., 1992; for different results, see Parrish and Williams, 1990).

There are several possible distance cues that may enter into the computation of perceived depth. One set of cues involves proprioceptive information from accommodation, vergence, or both; these cues would be valid only for close distances (e.g., 2 m). In support of this idea, there is evidence that depth constancy occurs for close distances (Foley, 1980; Ono and Comerford, 1977) and that manipulation of accommodation and

vergence affect perceived depth (Fisher and Ebenholtz, 1986; Foley and Richards, 1972; Ono and Comerford, 1977; Ritter, 1977). In the absence of other cues, vergence, in particular, seems to be a valid cue for distances of up to 2 m (Ono and Comerford, 1977).

In published work, Roscoe (Roscoe, 1985; Roscoe, Olzak, and Randle, 1976) suggested that the mechanism underlying size constancy (veridical size perception at different distances) is visual accommodation. In this idea, constancy results from accommodation serving to decrease retinal image size at close distances, which would compensate for an increase in image size. This is different from the idea expressed earlier in which proprioceptive information from accommodation yields distance information for the purpose of constancy. Roscoe's theory is relevant for depth constancy insofar as changes in retinal image size also produce changes in disparity magnitude. Although accommodation may influence, to a small degree, retinal image size and therefore impede the process of size constancy, accommodation cannot be the principal mechanism of constancy. The amount of change in retinal image size produced by accommodation would be much smaller than that required for an explanation of size constancy. Also, studies have shown that good size and depth constancy occur with retinal afterimages (Cormack, 1984), stimuli that are immune to accommodative effects.

The mechanism for constancy probably resides in the central, rather than the peripheral, nervous system: Blake, Fox, and Westendorf (1974) showed that the mechanism of size constancy occurs subsequent to that for binocular rivalry, the latter of which is a cortical phenomenon depending on confluence of the two eyes' pathways. In a recent personal communication (August 8, 1990), S. N. Roscoe agreed that accommodation is not the principal mechanism of constancy, though he pointed out that errors of accommodation in visual displays may change retinal image size slightly and therefore change size perception.

It is commonly believed that oculomotor responses provide distance information only for small distances (e.g., 2 m). This view tacitly assumes that these responses become inoperative at larger distances; this is incorrect. It is true that oculomotor responses can provide valid information only for small distances, but at longer distances the oculomotor mechanisms still play a role in distance perception: they bias perceived distance toward smaller distances, especially under degraded conditions (Owens, 1986a, 1986b; Owens and Leibowitz, 1980, 1983). The normal response biases of accommodation and vergence may introduce inappropriate oculomotor adjustments under many operational conditions. These anomalous adjustments could influence the perception of distance directly—and the perception of depth and size indirectly—via the perceptual constancies. The misaccommodation and misconvergence that occur when head-up displays are viewed may underlie, via perceptual constancy, reports of misperceived depth and size (Bell and Ciuffreda, 1985; Iavecchia, Iavecchia, and Roscoe, 1988; Roscoe, 1985; Roscoe et al., 1976).

Distance information provided by the oculomotor responses can be altered by adaptation—that is, by stimulating the oculomotor system with prisms or lenses. In classic work by Wallach and colleagues (Wallach, Frey, and Bode, 1972; Wallach, Moore, and Davidson, 1963), observers viewed stereoscopic displays through devices such as telescopes, and perceived distance and depth were altered over time. The modifications of perceived distance and depth apparently involve adaptive changes in the resting tonus of vergence and/or accommodation (Ebenholtz and Fisher, 1982; Owens, 1986a). The problem of adaptive modification of the relation between distance and depth may be encountered, for ex-

ample, in binocular helmet-mounted display systems in which the operator views the display over long periods of time and then attempts to perform a task under natural viewing conditions (e.g., landing).

Another set of distance cues for depth constancy may be environmental or field cues, such as perspective and texture (Fox, 1985); these cues should be valid for short or long viewing distances. There is evidence that depth constancy occurs for longer distances when such cues would be operative (Cormack, 1984) and that familiar size and linear perspective affect perceived depth (O'Leary and Wallach, 1980). Another cue may be vertical disparity information (Gilliam and Lawergren, 1983; Mayhew and Frisby, 1981; Mayhew and Longuet-Higgins, 1982). Vertical disparity is produced when stimuli are positioned off the longitudinal and vertical horopters (Tyler, 1983). There are problems with this hypothesis because vertical disparity can provide distance information only up to about 1 m (Gilliam and Lawergren, 1983), a small portion of the distance over which stereopsis operates (Graham, 1965). Fox, Cormack, and Norman (1987) showed empirically that vertical disparity plays no role in affecting depth from horizontal disparity, which suggests that vertical disparity does not provide distance information for depth constancy.

The implications of the framework just presented are the following. In general, factors that disrupt the establishment of binocular correspondence, disparity computation, or the scaling of disparity by distance information (depth constancy) may lead to nonveridical depth perception in stereoscopic displays. Such factors include highly textured or complex displays (disruption of correspondence), the use of large disparity values (disruption of disparity computation), or misregistration of viewing distance (disruption of depth constancy). For example, if a stereo-

scopic display is viewed from a relatively long viewing distance under conditions in which field cues are absent, depth perception may be inaccurate because the oculomotor responses would bias perceived distance toward closer values. In any given application, one should consider the factors affecting the various stages of disparity processing.

CONCLUDING REMARKS

This section brings together previous topics and presents several basic ideas about the design of stereoscopic displays:

The disparity limits of binocular fusion, patent stereopsis, and qualitative stereopsis vary with display characteristics. The disparity limits increase with stimulus size and eccentricity. This reflects the concept of disparity scaling: small disparities are probably processed by mechanisms activated by small stimuli and large disparities are probably processed by mechanisms activated by large stimuli.

Factors that work in favor of small disparity limits also favor good stereoacuity. Stereoacuity is good in the fovea and close to the horopter, but it worsens as eccentricity and distance from the horopter increase.

Crossed and uncrossed stereopsis are mediated by different classes of visual mechanisms. This should be taken into account when stereoscopic displays are designed because the perceived depth of objects presented in uncrossed disparity (as defined relative to the visual system) may be nonveridical under certain conditions (e.g., brief exposures). The incidence of stereoanomaly—a putative neurological deficit in one of those classes of mechanism—has been greatly overestimated because of an artifact of brief stimulus exposures. The selection of operators of stereoscopic displays need not entail special testing procedures (Fox, 1985) as long as extended exposures and large stimuli are employed.

To increase the disparity range over which fusion and stereopsis operate, voluntary vergence eye movements may be desirable because such eye movements allow the observer to relocate the position of the horopter and to process disparities that would otherwise go unprocessed.

The process of perceiving depth from disparity involves the calibration or scaling of disparity by viewing distance information in order for depth to be veridical. For stereoscopic displays, veridical depth means that perceived depth should be a linear function of half-image separation and distance, which suggests that larger separations and/or longer distances should be used when larger depth intervals are needed. Veridical depth perception occurs for both crossed and uncrossed disparity when stimuli are large and presented for long durations. When stimuli are small or presented briefly, disparity information should be bolstered with other (monocular) depth cues. Because distance cues for perceiving veridical depth at close distances appear to be accommodation and vergence responses, variables that alter those responses (e.g., as in head-up displays) should also affect depth perception.

For visual displays operating on the field-sequential method, different frame rates may produce better depth perception than may other rates because of a longer duration of visual persistence in each monocular channel, producing greater binocular integration.

Perceptual interaction in stereoscopic displays involving multiple stimuli can involve interference in stimulus visibility or alteration of depth position.

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