Effects of voluntary eye movement and convergence on the binocular appreciation of depth*

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Scaling techniques were employed to establish the relation between perceived distance ratio and physical distance ratio. Measurements were made both with and without free eye movement and under two states of convergence. The results were confirmed using a matching technique. With free eye movement, the perceived ratio is a monotonic increasing function of the physical ratio. Without eye movement, the perceived ratio generally increases, then decreases, as the physical ratio increases. For a given physical ratio, perceived distance ratio is less in the absence of voluntary eye movements. Convergence produces depth micropsia when eye movements are permitted, but not in their absence.

This paper is concerned with two questions: (1) What is the form of the relation between perceived depth and physical depth (or geometric disparity) with and without voluntary eye movement? (2) What effect does convergence have on the two relations?

In the case where the eyes are fixed, Ogle (1952) described the depth-disparity relation in terms of three regions along the disparity continuum. At small values of disparity, depth increases monotonically with disparity (patent stereopsis). At larger values, "no real sense of stereopsis exists, still the two images unmistakably appear farther (or nearer) than the fixation point [qualitative stereopsis]. Then rather abruptly even this impression ceases and each of the two half-images appears indefinitely localized [p. 255]." With stimuli centered about the fovea, Ogle found the region of qualitative stereopsis to be confined to disparities of less than 20 min of arc. Perhaps because of the narrowness of his stimulus lines, Ogle was far too low in his estimate of the maximum disparity which produces depth. As Mitchell (1969), Richards and Foley (1971), and Westheimer and Tanzman (1956) have shown, disparities at least as large as 10 deg produce discriminable depth differences. Ogle was also mistaken in his claim that the relation between depth and disparity is

discontinuous. Under similar conditions, Richards (1971a, b) found that, as disparity increases, depth first increases, then decreases following a smooth function. Over all but about the first .5 deg of this range, the stimuli are seen as double. Nevertheless, perceived depth is reliably and systematically related to the magnitude of the disparity.

On the other hand, when the observer is allowed to look back and forth between the two stimuli, perceived depth increases monotonically with disparity (Foley, 1968). Therefore, at large disparities, eye movement or the lack of it must make a big difference in the perceived depth associated with a given disparity. It is the purpose of this paper to compare perceived depth produced under these two conditions.

Even if attention is restricted to small disparities where both functions are clearly increasing, it is not clear just what role eye movements play. Although much attention has been given to the question of whether voluntary eye movements improve stereoacuity (Wright, 1951; Rady & Ishak, 1955; Ogle, 1956) and the weight of evidence seems to indicate that they do not, this in no way rules out the possibility that eye movements may contribute significantly to the appreciation of depth for small as well as large disparities (Palmer, 1962).

In addition to the eye movements themselves, Foley (1967b) has shown that the average convergence of the eyes while making a judgment may also modify the relation between depth and disparity. Thus, when the eyes are moving to and from near objects (points of light in the dark), the depth associated with a given disparity is less than if the

configuration is far away from the observer. Of interest is whether these micropsia effects occur without eye movements. If they do not, this would suggest that depth micropsia is a consequence of a diminished effect of eye movement when the eyes are converged rather than an effect of the resting state of convergence itself.

METHOD

The relation between depth and disparity was measured under two different sets of conditions: (1) the O set a black disk (probe) seen against a white background so that it was perceived to be a specified proportion of the distance from himself to a white screen; (2) while fixating a dot on the screen, the O judged the position of a rectangular flash of light seen against the same white background in proportion to the perceived distance of the screen. The independent variable of interest was eye movement vs no eye movement. The conditions differed in the size, luminance, and mode of presentation of the stimuli as a consequence of technical problems of instrumentation. Control conditions indicate, however, that the differences between the conditions are attributable primarily to the eye movement variable. A second independent variable was the fixation distance. This took on two values and was varied by introducing prisms and lenses in front of the eyes. Head movement was eliminated by a chin- and headrest.

In the eye movement condition, the O was instructed to set a probe to a position between himself and the screen such that the ratio of the perceived distance to the probe equaled a specified ratio of the perceived distance to the screen. He was told to look back and forth between the probe and the screen. The range of ratios was from 0.1 to 0.9. These measurements were obtained with the screen at 250 cm, seen under two viewing conditions corresponding to a fixation distance of 250 cm (no prisms or lenses) and 24 cm (+13D prisms and -3d lenses). The probe consisted of a black disk 1.5 cm in diam. It was supported by a thin metal rod attached to a motorized carriage which moved it in depth. The probe moved along a path perpendicular to the screen and intersecting the screen 4 cm below and 10 cm to the left of the fixation point—just below and to the left of the test flashes. The probe moved at a speed of 5 cm/sec. The O was allowed to move the probe as much as he wished before accepting a setting. The reason for employing the production method rather than the estimation method was to keep the conditions comparable with those used

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Fig. 1. Data of O.W.R. Within each panel, the upper graphs (A) show the relation between judged perceived distance ratio and physical ratio of the probe in the eye-movement condition. The middle graphs (B) show the relation between judged perceived distance ratio and physical distance ratio of the flash in the no-eye-movement condition. The lower graphs (C) show the relation between the physical distance ratio of the probe and the physical distance ratio of the flash when probe and flash are perceptually matched in distance. In Conditions B and C,

in a matching task to be described below, where again the O controlled the position of the probe.

When no eye movements were allowed, the O was fixating a small ($\frac{1}{4}$ -cm-diam) black dot on the screen, located at a distance of 250 cm. The effective fixation distance of the screen, however, was altered as above, using appropriate prisms and lenses so that the equivalent fixation distance was either 250 cm or 24 cm. In order to determine the relation between depth and disparity in the absence of eye movements, test flashes were rear-projected onto the screen, which consisted of a piece of sand-blasted translucent Plexiglas. The luminance of the screen was 4 mL; the flashes had a luminance of 40 mL (seen through the polarizers) and a duration of 80 msec. Each flash consisted of two vertical bars, 1.2 deg in height and .12 deg in width, situated symmetrically to the left and right of the fixation point. Appropriately oriented Polaroids in the beam and in front of the O's eyes allowed each eye to see only one of the bars, so that the stimulus simulated that produced by a single bar in front of the screen. Separations between the bars corresponded to a range of crossed

disparities of 7-210 min of arc. In order to help prevent an induction of a phoria by the repeated presentations of crossed disparities, vertical nonius lines were projected continuously above and below the fixation point.

The O initiated each flash by indicating to the E that he was ready. The O could look at each flash as many times as he wished—typically 5-10. He then estimated the ratio of the perceived distance of the flash to the perceived distance of the fixation point. During the experiment, these estimates of flash distance and probe settings (eye movement condition) were interspersed and taken in two random sequences.

In order to confirm the validity of the depth-disparity relations obtained above with and without eye movements, a third procedure was also used that has been called "depth matching" (Richards, 1971b). This method required the O to fixate the screen when the flashes were presented and then to set the probe to the same frontal plane in the field where the flashes were seen. Eye movements were used while adjusting the position of the probe. These probe settings are thus comparable to those made according to the first method

physical distance ratio of the flash is based on the simulated distance corresponding to the disparity used. The left-hand graphs are for a fixation distance of 250 cm, the right-hand graphs are for an equivalent fixation distance of 24 cm. All axes are normalized so that the distance to the screen is taken as unity. A disparity scale appears on the bottom left.

Fig. 2. Same as Fig. 1, for O.J.F.

described above, except that, in this case, they correspond to the perceived depth of the flashes instead of to specified ratios. Introspective reports indicated that the O generally placed the probe at the remembered position of the flash and did not make a simultaneous judgment of the positions of both the probe and the flash. These measurements were made 6 months earlier than the ratio judgments for W.R. but at the beginning or end of the ratio judgment sessions for the remaining Os.

RESULTS

The results for five Os are presented in Figs. 1-5. Each point represents the median of three trials on 3 separate days. Both the stimulus and the response are given in terms of distance ratio, i.e., the ratio of the distance from the stimulus (flash or probe) to the screen to the distance from the O to the screen. In Conditions B and C, the stimulus distance is the simulated distance corresponding to the disparity used. For the judgments (A and B in the figures), perceived distance ratio is plotted on the ordinate and physical distance ratio on the abscissa. The lines at 45 deg thus indicate the positions where perceived distance

Fig. 3. Same as Fig. 1, for O.C.M.

Fig. 4. Same as Fig. 1, for O.J.P.

ratio equals actual distance ratio. For the matching data, the ordinate represents the physical position of the probe when matched to the perceived position of the flash. It is an indirect measure of perceived ratio whose relation to the other measures is discussed below. Correction has been made for the minification produced by the lenses. A disparity scale is also shown at the bottom left. This scale is based on an interpupillary distance of 6.4 cm, which is the interpupillary distance of W.R., J.F., and J.P. The scale is only approximate for B.L. ($i = 6.3$) and C.M. ($i = 6.0$). Smooth curves were fitted to the data by eye.

Depth-Disparity Relation With Eye Movement

The function relating the perceived distance ratio to the physical ratio is monotonic increasing. The perceived ratio almost always exceeds the corresponding physical ratio. (Exceptions are the first two points in the 24-cm condition for J.F. and B.L.) As can be seen by comparing the left and right graphs in the upper portions of the figures, except for J.P., the ratio judgments are farther from the 45-deg diagonal for the 250-cm fixation distance than they are for the 24-cm condition. Thus, when convergence is increased, more disparity is required to produce a given perceived distance ratio. In these respects, the results confirm the findings of Foley (1967b, 1968), who used points of light in an otherwise dark field as stimuli. However, the magnitude of the effect of increased convergence is less here,

being on the average only about 10% for small depth ratios compared with 50% to 130% found by Foley.

Depth-Disparity Relation Without Eye Movement

In contrast to the previous monotonic rise in the depth-disparity relation, the relation here is generally nonmonotonic. For most Os, the relation rises to a maximum at about .3 (40 min of disparity) and then declines. It should be noted that this maximum occurs at a larger disparity than that at which the stimuli are first seen as double. Some depth is indicated even at the largest disparity of 3.5 deg. There are two major exceptions to the generalization that without eye movement the relation is nonmonotonic: the data of Os B.L. and J.P. O.B.L. is stereoanomalous, as defined by his failure to discriminate among crossed, monocular, and uncrossed disparities in a forced-choice test (Richards, 1970). In particular, he fails to discriminate between crossed and monocular stimuli. Such differences have been noted before (Richards, 1971b), and the present data provide further examples of the variations in stereoscopic mechanisms. So far, tests on J.P. have not revealed any stereoanomaly. If the functions obtained with and without eye movement are compared, it is seen that even at small values of disparity, perceived depth is less when eye movements are excluded. In contrast to the eye movement condition, perceived distance ratio does not always decrease when the eyes are

converged. For W.R., it clearly increases.

Matching Relations

The lowermost two graphs in all the figures show the relation between the physical ratio of the probe and the physical ratio of the flash when the O sets the probe (viewed with eye movements) to the same perceived distance as the flash (seen without eye movements). The basic form of the functions obtained in this way is quite similar to the judged distance ratios obtained without eye movement. This shows, qualitatively at least, that there is a relation between performance in the matching and scaling tasks. That this should be so is not immediately obvious, for it might be expected that the disparities indicated by the probe matches should equal the true disparity of the flashes (just as if one were performing a stereoacuity test). In this case, the depth-disparity relation for matches between the probe and the flashes would be described by the diagonal straight line at 45 deg. Instead, however, the depth matches depart considerably from the 45-deg diagonal and are similar to the ratio judgments obtained without eye movement.

DISCUSSION

The similarity in the form of the distance matches (lowest set of graphs) and the perceived distance ratios for flashes (middle set of graphs) suggests that the matches are also indicators of perceived depth. If so, then the matching data should be predictable

Fig. 5. Same as Fig. 1, for O B.L.

from the scaling data. The exact relation between the two sets of data can be made explicit. The argument is similar to, but not identical with, that used by Stevens (1966) in his cross-modality matching experiments. Our purpose in doing the matches was the same as that of Stevens, namely, to test the validity of magnitude estimation scales in an experiment which involved no numerical responses. Consider first the depth matches, where the perceived depth of a flash seen without eye movement is indicated by a probe setting that is made with eye movements. The perceived depths of two different stimuli are being compared. One is the depth of the flash seen without eye movement; the second is the depth of the probe seen with eye movement. Now, if the O overestimates the distance of the probe (as indicated by the data in the upper set of graphs in Figs. 1-5), then the actual probe

setting will be less than the perceived distance of the flash as indicated by a ratio judgment. Thus, for the flashes, the matching data should differ from the ratio judgments by the error in judging depth when eye movements are allowed.

To examine this prediction, it is easiest to compare the ratio judgments made with fixation with the corresponding depth matches in order to obtain an estimate of the effect of eye movements upon the depth of the probe. These indirect estimates of the errors in judging depth in the presence of eye movements should agree with those errors obtained directly from the upper graphs in the figures.

Let $F(R_p)$ be the function relating perceived distance ratio to physical distance ratio, R_p , for the probe seen with eye movements. As can be seen by inspecting all of the uppermost pairs of graphs in Figs. 1-5, this function is nonlinear. However, only

the first portion of the function is necessary for the prediction, since in the other conditions perceived distance ratios do not exceed .5. $F(R_p)$ is linear over this range and approximately proportional to physical distance ratio. Thus, we may take $F(R_p) = KR_p$ where K is a constant. The value of K may be determined by fitting a straight line by the method of least squares to the first 4 points on the perceived distance function for the probe (upper set of graphs). This procedure gives the values labeled K' in Table 1 for each O for the two conditions of convergence (screen at 250 cm or equivalent to 24 cm).

A second independent estimate of K can be obtained by comparing the two lower sets of graphs. Let $G(R_f)$ represent the function relating perceived distance ratio to physical distance ratio for the flash (middle graphs). In the matching experiment, the perceived ratio of the probe is equated to the perceived ratio of the flash, $F(R_p) = G(R_f)$. And, since $F(R_p) = KR_p$, we have,

$$K = \frac{G(R_f)}{R_p}$$

where R_p is the physical ratio of the probe when matched to the flash (bottom graphs). For any pair of graphs, there are 10 such estimates, one corresponding to each physical distance ratio. The median values of these are listed in Table 1 under the heading K'' . (It is appropriate to use all 10 points here, since the psychological ratio does not exceed .5 over the entire range of physical ratios.)

As can be seen by inspecting Table 1, the agreement between the observed and predicted K values is good, except for C.M. The large discrepancy found for C.M. is not yet understood. For the other Os, even the anomalous O B.L., the results are consistent with the hypothesis that the results of all three tasks depend on the same underlying variable, namely, perceived depth.

Table 1
Comparison Between the Slope of the Initial Portion of the Eye Movement Function, K' , and the Estimate of that Slope Derived from the Other Two Functions, K''

O	250 cm		24 cm	
	K'	K''	K'	K''
WR	1.34	1.52	1.05	1.10
JF	1.25	1.03	1.10	0.83
JP	1.18	1.29	1.37	1.54
BL	1.01	0.83	1.16	0.99
CM	1.53	4.39	1.36	3.10

On the basis of the foregoing, it is possible to argue that the attribution of the difference between Condition A and Condition B to eye movement has not been substantiated, because the conditions differed also in the size, shape, luminance, and duration of the stimuli. In order to demonstrate that eye movement is the critical factor, several of the flashed stimuli were left on continuously and viewed with free eye movement while being matched by the probe. Under these conditions, the matches corresponded very closely to disparity matches. Further, changes in the duration of the flash from 10 msec to 1 sec and changes in size over a range of 10X were found to have little or no effect on matched depth as long as fixation was maintained. The possibility remains that the changing retinal image size of the probe influenced its perceived depth slightly. This means that, at small disparities, it is not certain that the slightly greater perceived depth found with eye movement can be attributed to that factor. However, it is clear that at disparities greater than 1 deg, the presence or absence of eye movement has a large effect.

Two features of the data are somewhat paradoxical and should be emphasized. The first is the nonmonotonic relation between depth and disparity. It is clear that man can detect large disparities and can order them with respect to magnitude, if in no other way than on the basis of the separation of the double images. In the cat, neural units which encode disparities as large as 6 deg have been identified (Barlow, Blakemore, & Pettigrew, 1967; Blakemore, 1970). Given that disparity information is transmitted and that physical depth increases monotonically with

disparity, why does perceived depth not increase monotonically with disparity? A possible answer is that disparity detection constitutes only one stage of the process underlying depth perception and that perceived depth is not determined simply by which disparity detectors are maximally activated but, rather, on the relative activity of a large number of differently tuned detectors (Richards, 1971a, b).

A second paradoxical finding is that depth may increase following convergence when eye movements are excluded. This is clearly evident for W.R., for J.P. at disparities greater than 90 min, and to a lesser extent for B.L. and C.M. When this effect occurs, it is not only opposite in direction to the depth micropsia effect produced by convergence when there is free eye movement (Foley, 1967b), but it is also opposite in direction to the change in the relation between physical depth and disparity as distance changes and therefore acts against depth constancy. This micropsia is evident particularly at the large disparities and is slight or occasionally reversed for small disparities. Depth micropsia, therefore, is a phenomenon associated with eye movement and not simply the resting state of convergence. Size micropsia, on the other hand, occurs in the absence of eye movements (Richards, 1971a). This suggests that different mechanisms underlie the two phenomena.

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