Stereoscopic depth perception at far viewing distances

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There has been some controversy as to whether stereoscopic depth constancy can operate at distances greater than a few meters. In the experiments reported here, observers judged the apparent depth in stereoscopic afterimages with crossed retinal disparity as fixation distance was changed. Apparent depth increased with increased fixation distance in accord with the geometry of retinal disparity. The results are discussed with reference to the perception of apparent distance.

Stereoscopic depth constancy refers to the veridical perception of depth mediated by retinal disparity as viewing distance is varied. Since a given depth interval produces less disparity at greater distances, stereoscopic depth constancy requires that retinal disparity be rescaled as absolute distance changes. With symmetrical convergence, and for objects within a few degrees of the line of sight, the depth (d) signaled by a given disparity can be calculated by the equation:

$$d = (.5I(\text{TAN}(\text{ATN}(D/.5I) + .5R))) - D, \quad (1)$$

where I is the interpupillary distance, R is the retinal disparity, and D is the fixation distance. When the depth interval is nearer than fixation (i.e., crossed disparity), R and d will be negative. When the depth is small relative to fixation distance, Equation 1 can be approximated by the equation (Graham, 1965):

$$d = (D^2 * R)/I. \quad (2)$$

Equation 1 shows that as fixation distance grows, the depth signaled increases approximately as the square of the distance. This is true, of course, only for small viewing distances. As the viewing distance grows, the function gradually changes to a nearly linear one, so that depth and distance grow at about the same rate.

It is well established that at distances less than 2 m, retinal disparity is rescaled accurately for viewing distance, yielding stereoscopic depth constancy (see Ono & Comerford, 1977, for a review). It has also been demonstrated that the distance information required to rescale disparity can be gleaned from con-

vergence (Foley, 1967). Furthermore, O'Leary and Wallach (1980) provide evidence that perspective and familiar size can serve as cues for depth constancy.

Given these findings, it is interesting that studies of stereopsis at distances greater than 2 m have found a failure of depth constancy (Ono & Comerford, 1977). It is not at all clear why this should be. Naive, everyday viewing reveals no obvious departures from constancy. Stereophotographs are capable of representing large depths at great apparent distances. Cues known to affect depth constancy such as linear perspective and familiar size could in principle provide the necessary information. Finally, as Longuet-Higgins (1982) and Mayhew (1982) have shown, vertical disparities, in conjunction with horizontal ones, are, in theory, capable of providing absolute distance information.

Two difficulties attendant to any study of depth constancy become especially severe at large viewing distances. One is the problem of holding disparity constant as viewing distance is varied. The other is the elimination of other cues to the depth interval while manipulating cues to the distance to that interval. The studies reported here used stereoscopic afterimages to surmount these problems.

Wheatstone (1838) first demonstrated that depth could be seen in binocular afterimages containing retinal disparity information. Ogle and Reiher (1962) found that the apparent depth in a stereoscopic afterimage was similar to that seen between the flashing lights used to produce the afterimage. They did not vary viewing distance.

Stereoscopic afterimages have several characteristics that make them especially useful in this kind of inquiry. First, the disparity is fixed; it is painted, as it were, on the retina. Dimensions within the afterimage itself (size, disparity, and location) cannot vary with viewing distance, accommodation, convergence, or angle of regard. Fixation distance to other objects can be varied easily, while fixation within the afterimage is locked.

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In the experiments reported here, afterimages with crossed disparity were viewed at distances ranging from less than a meter to several kilometers. Observers made depth estimates by localizing the apparent position of the disparate afterimage. The results are compared with predictions based on Equation 1 (above).

EXPERIMENT 1

Method

Apparatus. Afterimages were produced by transilluminating the target (I-fig) shown in Figure 1. The circles were punched into black opaque vinyl tape and attached to a frame. The fixation square and the ends of the horizontal bar were arranged on a separate frame. The frames were mounted together with spacers to provide the desired depth. The resulting target was mounted at eye level on an optical bench. A diffusing screen and an electronic flashgun were mounted behind the target. A dim light adjacent to the flashgun provided illumination sufficient for fixating the target. Chin and forehead rests provided constant viewing distance. A subject-controlled pushbutton triggered the flashgun.

Two fixation stimuli for observation of the afterimage were employed. For short (< 450 cm) test distances, a 6-mm white fixation point was mounted at eye level on a vertical rod located on a table. A second rod to the right of the fixation point served as a depth probe and could be moved toward or away from the observer until it appeared in the plane of the afterimage of the circles. A chin-rest helped maintain constant viewing distance. A shield occluded the observer's view of the table surface. The room was illuminated by a 5-Hz strobe, which helped maintain afterimage visibility.

For longer test distances (> 450 cm), a white (4×4 cm) fixation square was mounted at eye level near one end of a 30-m hallway. Behind the fixation target was a white sheet illuminated by a 5-Hz strobe. A rod with black and white stripes was held by the experimenter and served as the depth probe. Both the room and hallway were rich in such depth cues as cement block walls, ceiling

tiles, textured floor, doors, and the like. These cues were illuminated by the flickering strobe.

Observers. Three males and two females served as observers. Four were experienced observers knowledgeable about stereopsis and afterimages. The fifth was naive. All scored in the normal range for stereopsis on the Orthorater and the Julesz random-element stereogram series (Julesz, 1971). All had visual acuity at, or corrected to, 20/20. Not all observers participated in all trials.

Procedure. The observers were tested individually. Each trial was preceded by at least 2 min of dark-adaptation. The observer then fixated the 1-mm fixation square and triggered the flashgun. Once the afterimage was attained, the observer either turned to the test fixation target on an adjacent table or stepped into the hall and viewed the fixation target from a predetermined distance. In either case, the depth probe was then moved back and forth under the guidance of the observer until it appeared to be in the plane of the afterimage.

Care was taken to insure that a good afterimage was obtained. Observers were cautioned to fixate the induction target carefully. They were instructed to abort a trial if the horizontal bar did not appear in the plane of the test fixation target, or if the afterimage started to fade. All observers were given practice trials before data were collected. Intertrial intervals varied but were always sufficient for the afterimage to fade beyond detectability.

Two disparities were employed. For one, the circles were 0.88 cm in front of the fixation point, which was 35 cm from the observer. This yielded ~ 16.3 min crossed disparity. For the other, the circles were 0.5 cm in front of the fixation point at 50 cm distance. This yielded ~ 4.5 min crossed disparity. The disparities are approximate because interpupillary distance varied across observers.

Four observers made eight depth judgments at each of 12 fixation distances, ranging from 1 to 27 m for each I-figure. Test distances were randomized across trials for each observer. Trials in which the observer occluded one eye before triggering the flashgun provided monocular control.

Results

The results are summarized in Figure 2. The circles (16.3 min) and squares (4.5 min) each represent the mean of eight trials for each of the four observers. The curves give the predicted depth values. The standard errors across observers ranged from 3.7% to 11% of the mean apparent depth and averaged 6.5%. The results from the naive observer did not differ in any systematic way from those from experienced observers. In the monocular control condition, all observers reported that the circles appeared in the plane of the fixation target (i.e., no depth was seen in the afterimage).

All observers reported that the appearance of the afterimage agreed with the depth probe matches. That is, they agreed that at 27 m fixation distance, the circles seemed to be floating in space about 5 to 8 m away from themselves. They reported noticing a dramatic shrinking of the depth as they walked down the hallway while looking at the fixation object.

Discussion

The results show clearly that when observers are asked to set a probe to the apparent distance of a stereoscopic afterimage, they do so in accordance with the geometry of retinal disparity at fixation dis-

Figure 1. Inducing stimulus. Circles and horizontal dashed bar are translucent. Circles stand out in depth from the horizontal bar. Background is opaque.

Figure 2. Depth settings in log units as a function of viewing distance for 16.3-min (circles) and 4.5-min (squares) retinal disparity. Curves give predicted depth values. Each point represents the mean of eight trials for each of four observers.

tances up to 27 m. The data suggest that retinal disparity is rescaled as a function of fixation distance far beyond the range at which oculomotor cues could provide the required distance information.

Three questions arise immediately with regard to these data. The first concerns the method used to measure perceived depth in the afterimage, and asks whether the observers were setting the depth probe to the apparent distance of the afterimage, or were instead simply making a disparity match between the probe and the afterimage. If the latter were the case, it could be argued that the technique employed did not provide information about the depth seen by the observer, but only about how well the observers could set the disparity in the probe equal to that in the afterimage. The skeptic could even argue that little or no depth was seen in the afterimage, or that the perceived depth was unrelated to viewing distance. The observers reported that the apparent depth in the afterimage was clear and compelling. It is also the case that they were asked to set the probe so that it *looked* as though it were at the same distance as the afterimage. Nevertheless, it is important to establish that the relationship observed between fixation distance and apparent depth can be measured with methods that are not dependent on disparity matching.

The second question concerns the range over which the rescaling of disparity occurs. It is clear from Fig-

ure 2 that the results parallel the predicted values shown by the solid lines. It is also evident that the obtained values end just where the prediction begins to deviate from a straight line with a slope of two (depth related to distance squared). In order to show that the perceived depth in a stereoscopic afterimage is veridical and, in fact, follows the geometry of retinal disparity, it is necessary to make observations at distances far greater than those reported in the first experiment. A finding of veridical depth constancy at larger fixation distances could be important for several reasons. First, it would serve as a demonstration of the range of useful depth perception. Second, it would specify the rule or rules by which retinal disparity is recalibrated. Third, it would require that distance cues that can operate beyond a few meters be involved in the recalibration of disparity.

The third question has to do with the consistent tendency for observers to report apparent depth greater than that predicted by the geometry of retinal disparity. This overestimation occurs at all fixation distances. It is hidden at far distances in the log coordinates of Figure 2 since it did not increase exponentially. There are a couple of possible explanations for this. One is related to a difficulty observers experienced in making the depth probe settings. The difficulty is analogous to the situation that occurs when one tries to look at an afterimage that is not centered in the visual field. Each eye movement, of course, leads to apparent movement of the afterimage, and with repeated attempts, it moves farther and farther. In the present experiment, the observers were concentrating on an image closer than fixation and found it difficult to avoid trying to fixate the plane of the afterimage and probe. This attempt moved the afterimage even nearer. The result was a zooming effect in which the afterimage moved nearer and nearer. While observers were reminded to keep their eyes on the fixation target, the demands of the task may have made involuntary fixation attempts unavoidable.

Another possibility lies in the commonly observed tendency for observers to underestimate large distances from themselves (Gogel, 1960). Recall that apparent depth was inferred from judgments of the distance from the observer to the afterimage. If this distance were underestimated, then when these estimates were subtracted from fixation distance to give apparent depth, the computed depth would be inflated. It is also possible that observers underestimated the distance to fixation and rescaled disparity according to this estimate. This, too, would place the apparent location of the afterimage closer to the observer and result in an apparent overconstancy.

Experiment 2 was conducted to address these issues by measuring the apparent depth in afterimages with techniques not requiring disparity matching and at distances much greater than those used in the first experiment.

EXPERIMENT 2

Method

Apparatus. The I-figures used to produce afterimages were identical to those used in the first experiment and were viewed at the same distances, yielding disparities of 16.3 and 4.5 min. They were mounted on a light frame that could be hand-held, together with a diffusing screen, a flashgun, and a push-button switch. A viewing port with forehead rest maintained proper fixation distance.

Trials in which the test fixation distance was 20 m or less were conducted in a hallway similar to that used in the first experiment. The fixation target, 5-Hz strobe, and depth probe were also similar. For outdoor trials the strobe had to be omitted and observers maintained afterimage visibility by blinking rapidly or briefly occluding their eyes with their hands. The fixation targets were a triangular emergency traffic reflector (40 cm on a side) viewed across an open field at 250 m distance and red lights on radio towers viewed from 6 and 7.8 km. All outdoor observations were made at night. Objects in the natural environment (trees, shrubs, grass, buildings, and the like) were dimly visible and provided some distance cues.

Observers. Four observers with vision at, or corrected to, 20/20 were employed. All scored within normal limits on stereoacuity as measured by the Orthorater and the Julesz random-element stereogram series (Julesz, 1971). Two observers were naive; the others were knowledgeable about stereopsis and the purpose of the experiment.

Procedure. For all trials, the induction of the afterimage was the same and, except for the substitution of a portable apparatus, was similar to the procedure used in the first experiment. After dark-adapting for at least 2 min, the observer fixated the center fixation square in the I-figure and pressed a button firing the flashgun. Then the observer lowered the device and looked at the test fixation target. Three measures of apparent distance were employed. The "probe measure" was identical to that used in the first experiment. A second measure (direct measure) required that the observer make an absolute estimate of the distance, in feet, from himself to the afterimage of the circles. The third measure (percent measure) was employed only for the smaller fixation distances (5, 10, and 20 m), because observers reported difficulty in making estimates of 1% or less. Here the observer was asked to consider the fixation distance as 100 and to report the fraction of that distance between himself and the afterimage.

For the indoor trials at 5, 10, and 20 m, distance was randomized across trials. The two radio towers could be seen from the same vantage point; the other outdoor fixation distance required a different location. These were run in blocks of trials. Only one disparity value was employed in each block of trials; measurement technique was randomized across trials. Each of the four observers made eight judgments for each combination of fixation distance, measurement technique, and retinal disparity.

Results

The results are expressed in terms of the depth interval between the fixation point and the apparent location of the afterimage circles. For the probe technique, this distance was calculated by subtracting the distance of the probe to the observer from the total fixation distance. In the foot-estimate technique, the observer reported the distance from himself to the afterimage, so, again, this distance was subtracted from total fixation distance. For the percent measures, the observer reported the percent of the fixation distance occupied by the apparent interval between himself and the circles in depth. Therefore, depth was determined by multiplying the fixation distance by the reported percent and subtracting this value from the fixation distance.

Table 1 provides a comparison of the three methods for measuring the apparent depth in stereoscopic afterimages at the three fixation distances for which all three measures were employed. Data for both 16.3 and 4.5 min disparity are provided. The standard errors given are those between subjects. The probe measure shows the smallest variability and the direct measure the largest. This same trend was seen in within-subjects variability. The probe and direct measures yielded larger depth estimates, but across fixation distances the agreement among the three estimates is apparent.

Figure 3 presents the results for the probe measures for both disparities at six viewing distances. The results for the direct measures are comparable, and for both there is agreement with the depth predicted by the geometry of retinal disparity. As in the first experiment, there is a distinct tendency to overestimate the depth. Because of the log-log coordinates of Figure 3, this is most noticeable at the shorter viewing distances, but it occurred for all distances.

Discussion

The agreement of the probe and direct measures is important, for it indicates that the observers were not merely setting the probe so that the retinal dis-

Table 1
Means and Standard Errors for the Apparent Depth in Stereoscopic Afterimages as Measured by Three Techniques:
Probes, Foot Estimate, and Percent

Fixation Distance	Measure	Disparity					
		4.5 min			16.3 min		
		Probe	Foot Estimate	Percent	Probe	Foot Estimate	Percent
500	Mean	148	128	110	234	158	226
	SE	7.7	24.9	9.2	3.2	19.4	7.0
1000	Mean	417	374	434	611	469	555
	SE	2.3	15.3	6.3	1.8	11.1	7.9
2000	Mean	1098	915	1189	1395	1221	1339
	SE	5.5	12.1	6.6	4.1	6.6	6.7

Note—All measures in centimeters.

Figure 3. Apparent depth measured by the probe technique as a function of viewing distance for 16.3-min (circles) and 4.5-min (squares) crossed disparity. Curves show predicted values. Each point represents the average of eight trials for each of four observers.

parity of its images was the same as the disparity in the afterimage without seeing any depth. The direct and probe measures show clearly that the afterimages of the circles appeared in front of fixation.

Equally if not more important is the agreement between the results from the percent method and those from the other two methods. In both the probe and foot-estimate methods, apparent depth was computed by subtracting the apparent egocentric distance of the target in depth from the physical distance to the fixation target. As Gogel (1968) has pointed out, confusion between physical and perceptual measurements can lead to improper inferences, especially in work on size and distance perception. In the present experiments, discrepancies between the physical fixation distance and apparent fixation distance could bias the results. In the percent method, the observer judged the ratio between the apparent fixation distance and the apparent egocentric distance of the target in depth. If there were a bias introduced in the other two methods, there should be systematic differences between the percent measures and the other two. Inspection of Table 1 reveals no such differences.

The results from the large fixation distances show clearly that as distance increases, apparent stereoscopic depth grows essentially without limit. This growth is in accord with the geometry of retinal disparity. For the disparities used in this study, apparent depth assumed linear growth at fixation distances be-

yond about 100 m, so that the target in depth took up a constant egocentric distance. The implications of this finding are discussed below.

GENERAL DISCUSSION

It is tempting to conclude, on the basis of the results of this study, that a rescaling of the depth signaled by retinal disparity continues without limit as fixation distance increases. It might be well to consider an alternative interpretation.

As noted above, egocentric distance in stereoscopic afterimages also grows with increased viewing distance. For crossed disparity, the geometry of retinal disparity predicts that it should at first grow almost linearly with fixation distance, then level off and take up a constant value. This follows from the fact that at far viewing distances depth grows linearly with distance, so that the difference between them (i.e., egocentric distance) becomes constant. The implication of this is that for a given disparity there is a maximum egocentric distance that an afterimage, or any target carrying that disparity, can assume. If, as Foley (1980) suggests, the visual system can use disparity to compute egocentric distance directly, then once an afterimage in crossed disparity has reached the maximum egocentric distance, no further recalibration of disparity would be needed.

Foley (1980), Wallach and Zuckerman (1963), and others have pointed out that the rescaling of retinal disparity is most likely done on the basis of apparent distance, not objective fixation distance. Gilinsky (1951) has shown that there appears to be a maximum apparent distance of about 30 m. In a number of experiments, she found that apparent distance could be estimated by the equation:

$$D' = (M * D)/(M + D), \quad (3)$$

where D' = apparent distance, D = physical distance, and M = maximum apparent distance. The implication of this equation is that when physical distance is small relative to the maximum apparent distance, then apparent distance will be very close to physical distance. As physical distance grows, apparent distance approaches the maximum apparent distance asymptotically.

Gilinsky's findings suggest that no matter how far away a fixated object may be, the rescaling of retinal disparity will not exceed that required for roughly 30 m. With respect to stereoscopic afterimages, this would imply that as fixation distance approaches and goes beyond 30 m, the apparent fixation distance will grow much more slowly. Consequently, the egocentric distance to the afterimage will be underestimated. This, in turn, will result in an overestimation of depth

when it is calculated by subtracting the apparent egocentric distance of the afterimage from the physical fixation distance.

In the present study, the apparent egocentric distance of the afterimages conforms more closely to predictions corrected according to Gilinsky's findings than to uncorrected predictions based on the physical fixation distance. For instance, an afterimage containing -16.32 min of retinal disparity and viewed at 2,000 cm should show a depth interval of 1,188 cm or an egocentric distance of 812 cm. But, according to the results of Gilinsky, a fixation distance of 2,000 cm should appear no farther than 1,207 cm. The geometry of retinal disparity predicts that at 1,207 cm the same afterimage should appear at an egocentric distance of 641 cm. At 2,000 cm, the observers in Experiment 2 reported an apparent egocentric distance to the afterimage of 605 cm. This suggests strongly that the overestimations of depth are the result of the rescaling of disparity on the basis of apparent, rather than physical, fixation distance. If true, this may provide at least a partial explanation of the failure of constancy in other studies. Most of them have used points of light or other targets of no familiar size against a plain background, providing few, if any, cues to distance (Ono & Comerford, 1977). These reduced cue conditions may lead to severe misidentification of apparent distance and consequently to inaccurate disparity rescaling.

In summary, the following conclusions seem to be supported by the results of this study. Stereoscopic afterimages are useful in the study of depth perception and depth constancy. Retinal disparity is rescaled as a function of apparent viewing distance throughout the possible range of such distances. The range of apparent viewing distances is restricted by the imposition of a maximum apparent distance. The re-

scaling of disparity is simplified by scaling for egocentric distance rather than depth, so that beyond a few meters no further rescaling is necessary.

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