Anomalous Stereoscopic Depth Perception*

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Normal or complete stereoscopic depth perception is based upon at least two and probably three mechanisms. These mechanisms may be isolated by studying depth judgments made by stereoanomalous individuals who are unable to discriminate disparities over wide ranges of disparity. The nature of the reductions observed among these stereoanomalous observers suggests that at least three ranges of the disparity are sampled in order to create three different pools of binocular activity. The pools correspond roughly to crossed, near-zero, and uncrossed disparities.

Index Heading: Vision.

Since Wheatstone's discovery[1] of stereopsis in 1838, the experimental studies of this phenomenon have primarily utilized the techniques of psychophysics[2]; neurophysiological data have only recently been reported.[3] Both approaches have emphasized the effect of stimulus variations upon mechanisms for stereopsis, and, with few exceptions,[4] have largely neglected or have intentionally avoided complications that might be due to individual differences. Consequently, the widespread occurrence of stereoblindness has been overlooked, and only recently has it become clear that a very large percentage of the human population is unable to make use of the normal range of disparity cues.[5] These deficiencies in the processing of disparity information become quite obvious when appropriate test procedures are used. Two such independent procedures, and the interrelation between their results are described below.

PROCEDURE I: THREE-ALTERNATIVE FORCED-CHOICE DISCRIMINATIONS

This test is identical to one described in detail elsewhere[5]; only the essentials will be mentioned here. The subject views through polarized glasses a screen of sandblasted Plexiglas seen illuminated at 17 cd/m² at 200 cm, onto which are flashed (80 ms) polarized images having an equivalent steady-state luminance of 170 cd/m². All the images consist merely of two adjacent vertical lines, $\frac{1}{4}°$ wide by 2° high. Each line is polarized independently so that the disparities will be either crossed, uncrossed, or monocular (both lines go to one eye). When the subject is fixating correctly, as indicated by correct alignment of nonius lines above and below a fixation cross, he signals for the stimulus. Approximately 1 s later, the pair of lines is presented with the lines positioned so that the members of the pair appear symmetrically on opposite sides of the fixation cross. The brief presentations preclude the possibility of detecting the direction of the disparity of the stimulus by means of eye movements.

The separation between the lines used for each stimulus was either $\frac{1}{2}°$, 1°, 2°, or 4°. These values thus comprised the range of uncrossed and crossed disparities sampled; the null or monocular condition used lines of the same spacing, but in this case both lines went either to the right or left eye, alternating in a random manner. In contrast to binocular stimuli having zero disparity, these monocular stimuli appeared qualitatively identical to the two other conditions, except that they usually were not seen in depth. There are two practical disadvantages to using binocular stimuli of zero disparity for the null condition: First, it is not possible to obtain an exact color and brightness match to the polarized stimuli; second, binocular stimuli of zero disparity do not possess the appropriate luster or shimmer that appears with disparate, polarized images. Both these effects made the binocular stimuli of zero disparity easily distinguishable from the disparate stimuli. On the other hand, when a monocular stimulus went to one eye only, the slight luster or shimmer produced by the rivalry was indistinguishable from the luster that appeared in the two disparity conditions. No subject was ever informed or ever spontaneously mentioned that a subset of the stimuli appeared monocular.

The subject's task was to identify the disparity of the stimulus, as seen relative to the plane of fixation. His responses of front, on-the-plane, or behind were interpreted to correspond to judgments that the stimulus disparity was, respectively, crossed, null (monocular), or uncrossed. The dependent variable was the percent of the responses that were correctly paired with the corresponding stimulus condition. The method of calculating this percent correct involved totaling the identical responses to stimuli having the same spatial separation of the lines, and then determining the percentage of these responses that were, in fact, correct. For example, the total number of crossed (or front) responses was determined for all three kinds of stimuli constructed with a 2° spatial separation between the lines. The percent of correct responses would then be the fraction of this total of front responses that were correctly paired with the crossed disparities. This definition of percent correct is not the same as the classical one, but the modified version has the distinct advantage that the discrimination performance for each stimulus condition can be assessed

more accurately. Consider the case when a subject reports uncrossed (or behind) for all stimulus conditions. According to the classical measure, he will score 100% correct for the uncrossed disparities. He has clearly not made a discrimination between the uncrossed, monocular, and crossed stimuli, however. Instead, a better measure of his ability to discriminate the uncrossed stimulus is to determine the percentage of the total number of uncrossed (or behind) responses that were properly correlated with the uncrossed stimuli. In the above case, where the subject always responded behind, the present scoring method would give a percent-correct score of 33%—the chance value in a three-alternative forced-choice situation. In order to obtain scores for all three types of response, the trials were continued, whenever necessary and possible, until the subject gave a minimum of 10 front or behind responses for each of the four spatial separations of the lines. The total number of trials averaged about 150.

FORCED-CHOICE RESULTS

Figure 1 presents three sets of data that reveal the general form of the differences between the stereoblind individual and a normal observer. The percent of correct responses is plotted against the stimulus disparity; the performance at zero disparity was estimated from the $\frac{1}{2}°$ and $1°$ monocular stimuli.[6] The normal observer CR clearly performs well above chance (33%) for all disparities over the range $\pm 4°$. On the other hand, MW (lowest graph) shows good performance for the uncrossed stimuli, but his responses are only about 50% correct when he is presented with crossed disparities. The explanation for this above-chance level is clear; once the uncrossed category has been eliminated as a possibility for confusion, MW divides his remaining two responses between the remaining two stimulus categories. Thus, the 50% level of performance over the zero and crossed disparity range reflects chance behavior. The middle graph in Fig. 1 shows similar data for another stereoblind observer, AE, who performs above chance only for stimuli that have crossed disparities. Over the full range of uncrossed disparities, the performance is a little less than 40%—reduced from the expected 50% level by a tendency to respond crossed to all stimuli.

The data shown in Fig. 1 are typical of the kind of individual differences that may be seen often among a large sample of subjects. (A more sophisticated analysis of discriminability is presented in Ref. 5.) Typically, when a discrimination is clearly made, the optimal disparity lies near $\pm 1°$, as it does for the subjects shown in Fig. 1. Presumably, this disparity activates the greatest number of disparity detectors. Typical, also, is the result that when an individual falls to chance performance, then he remains at chance over a wide range of disparities. Thus, as shown in Fig. 1, when both MW and AE have difficulty in identifying
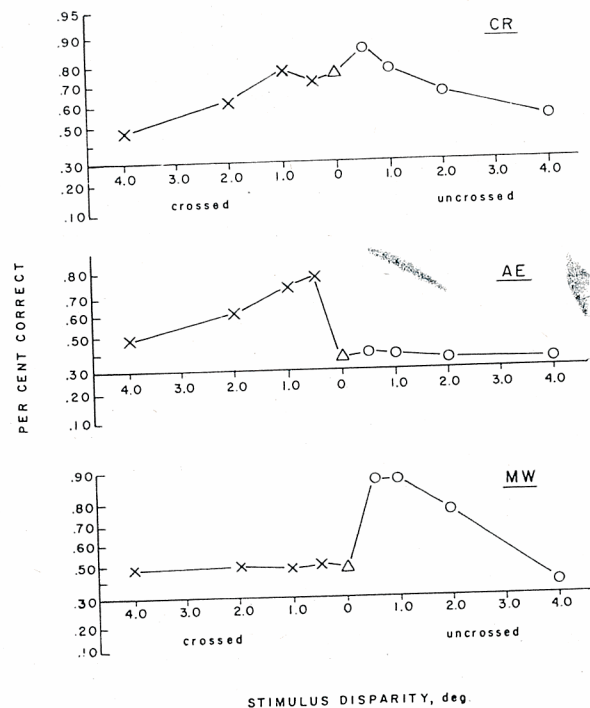

FIG. 1. Percent of correct responses to stimuli of different disparity. See text for details of scoring procedure. Each graph is based upon about 150 trials. The top graph is typical of a normal observer, the lower two graphs show typical anomalous data.

a particular disparity, the difficulty occurs for all crossed or all uncrossed disparities. This important result provides the major link with the data obtained by the second, independent method for assessing stereoscopic mechanisms.

PROCEDURE II: DEPTH MATCHING

The forced-choice procedure described above requires only that the subject indicate the direction (or sign) of the disparity. The second method requires the observer to indicate the magnitude of the depth judgment elicited by a given disparity. The stimulus conditions used were identical to those described above, except that the lines were slightly smaller (6′ by 75′) and were seen at 250 cm. Once again, each stimulus had a disparity with respect to the fixation cross, with the disparity chosen from the range 4° crossed to 4° uncrossed, centered on the fixation point. All stimuli were presented in 80-ms flashes only when the subject was fixating the cross.

After seeing the flashed lines several times in succession, the observer then attempted to match the apparent depth of the lines by setting a probe to the same position in space. This matched-depth setting was made with free eye movements in a disparity-rich environment. The probe was a 1-cm-diam black disk seen against a light background, approximately 4° to the left of the fixation cross. Movement of this probe
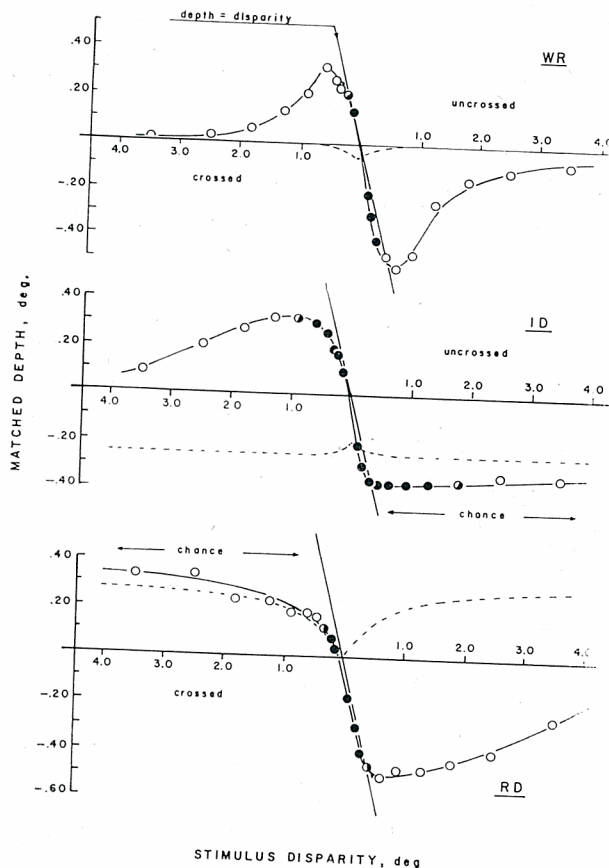
FIG. 2. Matched-depth settings (made with free eye movements) indicating the apparent depth of stimuli with different disparities relative to the fixation position, as shown on the abscissa. The top graph is typical of a normal observer, the lower two graphs show typical anomalous data. A filled circle indicates that the binocular stimulus appeared as single; the open circles show which stimuli appeared double. The dashed lines show the apparent depth of the monocular stimuli. The regions indicated by the arrows show where the anomalous observers respond at chance on the forced-choice test.

DEPTH-MATCHING RESULTS

Figure 2 shows the matched-depth settings (ordinate) made by each of three observers for various stimulus disparities (abscissa). Positive matched-depth values indicate that the flashed lines appeared in front of the fixation plane; negative values indicate matches to stimuli that appeared behind the plane of fixation. The solid line at $-75°$ through the origin indicates the locus where matched depth equals stimulus disparity. The top graph shows the results obtained from a stereonormal observer (WR), whereas the lower two graphs show settings made by two anomalous observers (ID, RD). The data are representative; these observers have been chosen to indicate the three clearest types of variations found to date among the present sample of fourteen observers. Four subjects were similar to WR; four similar to ID; three similar to RD; and the remaining three subjects generated two other types of curves, one of which will appear later. (The type not included is similar to that of WR, but with depth matches $\frac{1}{10}$ as large.)

For the normal stereo-observer (WR), matched depth first increases as disparity increases, and then falls back toward zero as the stimulus disparity exceeds $±1°$. For some observers, the rate of decrease of depth with disparity is not quite so sharp as that indicated here. The important characteristic, however, is that the complete depth-matching curve consists of two lobes, one associated with cross-stimulus disparities, and the second associated with uncrossed disparities. In contrast, the anomalous observers (ID, RD) generate only one of the customary two lobes seen in the complete depth-matching curve. For example, the matches to crossed disparities made by RD (lower graph) do not show the characteristic decrease in the depth matches for disparities greater than $+1°$; instead, RD's curve continues to rise over the region where the curve for the normal observer has fallen back almost to zero. This difference between matches made by WR and RD illustrates the principal finding: Each half of the matched-depth curves may be described in terms of one of two characteristic shapes: Either they assume the form of a distorted $\cap$ or $\cup$ over the entire crossed or uncrossed range, or, alternately are flat or rise slowly as the stimulus disparities exceed $±1°$. These characteristics are seen clearly in Fig. 2, when the data of ID and RD (lower two graphs) are compared with those of WR (upper graph).

Figure 2 also provides some data on the relation between single binocular vision and depth. Stimuli that appeared single are indicated by the filled circles. Note that maximum depth was often obtained from stimuli that appeared double. Even though many experiments have demonstrated that single binocular vision is not necessary for depth perception,[8] it has not been generally recognized that maximum depth may be achieved under conditions of doubling. This

was controlled by a reversible Bodine motor.[7] Because of space limitations, the probe could not be used to indicate the apparent depth of the flashed lines when uncrossed disparities were used, which placed the lines behind the projection screen. Therefore, when uncrossed test stimuli were presented, the probe was seen by reflection from a mirror placed on the screen. The test stimuli were randomized within a given stimulus category (crossed or uncrossed), but not between categories, except for the monocular stimuli, which were interspersed with the disparate stimuli. The lines were flashed as often as necessary (with fixation restricted to the cross), until the subject considered the probe to lie in the same frontal plane. The final probe settings, made with free eye movements, were then converted to disparities. Thus, the dependent variable, matched depth, has the units of degrees of equivalent disparity (with respect to the fixation plane).

finding suggests that depth perception is partly dissociable and separate from single binocular vision.

DISCUSSION

Some of the similarity between the results presented in Figs. 1 and 2 is not entirely fortuitous. In each figure, the two stereoanomalous observers (lower two graphs) generate curves that are monotonic or approximately flat over half the range of the stimulus disparities presented. Over these regions where the depth matches made by the anomalous observer depart from those of the stereonormal, the forced-choice discriminations are at the chance level, as indicated by the arrows labeled chance. Not surprisingly, this is the region where the apparent depth of the monocular stimuli almost matches the depth perception elicited by the disparate, binocular stimuli (dashed lines in Fig. 2). For observer ID (middle graph), the monocular stimuli are seen as possessing $-0.25°$ disparity behind the plane of fixation, whereas the disparate, uncrossed stimuli have roughly $-0.35°$ of disparity. Apparently this difference of $0.10°$ is not sufficient to enable ID to discriminate between the monocular and uncrossed stimuli in the forced-choice task, for his performance over this region is at chance, as indicated on Fig. 2. Similarly, where observer RD (lowest graph) fails to discriminate between the crossed and monocular stimuli in the forced-choice task, the depth matches for both the monocular and crossed disparities are found to be almost equal. To generalize, when an observer responds at a chance level on the forced-choice task, our results to date suggest that all stimulus disparities will appear at roughly the same depth over the range of disparities not discriminated, and that this depth will be close to that seen with monocular stimuli.

Any further interpretation of the shape of the curves shown in Figs. 1 and 2 must be somewhat tenuous and speculative at this time. However, the relation between depth and disparity over the range of discriminable disparities deserves comment. In the case in which depth appears to increase and then to fall with disparity ($\cap$-shaped curve), one possible explanation seems obvious: Matched depth would be expected to increase with disparity, as it does, but stimuli with very extreme disparities (i.e., $\gg8°$) would certainly be expected to exceed the physiological limits for disparity detection and would thus be treated as two monocular stimuli. For WR, and presumably for all normal observers, monocular stimuli are localized near or on the plane of fixation,[9] and hence matched depth must return to zero as the stimulus disparity is made excessively large. The unexpected finding is that the matched-depth settings for many observers decrease rather slowly to zero as the maximum value is exceeded, instead of abruptly collapsing. A given magnitude of depth may therefore be elicited by at least two stimulus disparities, one large and the other small. Thus, there

can be no one-to-one relation between depth and disparity. Without such a simple one-to-one relationship, it becomes implausible to consider depth to be simply a matter of which disparity detector is optimally stimulated. In order to create ambiguity in the relation between depth and disparity, it appears necessary in some cases for two such detectors to signal the same depth even though they may respond optimally to entirely different regions of the disparity spectrum. One possible mechanism for satisfying this constraint is to create a pool of the activities of many different disparity detectors, and to let the total activity of the pool be the correlate of the magnitude of the depth sensation.[10] Under such a scheme, stimuli with very large disparities will elicit little activity in the pool because the physiological limits for binocular integration and disparity detection will be exceeded. Similarly, it is also conceivable that if there are only a relatively few number of binocular units responding to small stimulus disparities, then small disparities will also elicit little activity. An intermediate disparity, in the neighborhood of $\pm\frac{3}{4}°$ according to Fig. 2, would then be the most effective binocular stimulus, driving the greatest number of binocular units and thereby creating the largest amount of binocular activity in the pool.

If depth depends upon the pooling of binocular activity elicited by a stimulus, then the depth-matching curves generated by the anomalous observers suggest that there must be at least two dissociable and independent kinds of pools. Observer ID makes roughly normal depth matches to the crossed disparities, but fails to show any distinction between the majority of uncrossed disparities. Instead, the normal relation between depth and disparity seems to be missing over the range of uncrossed disparities. Alternately, we may interpret this abnormal relation to indicate the absence of the normal mechanism for creating or pooling the binocular activity over this range of disparities. Because such abnormalities, when present, occur over the full range of either uncrossed (i.e., AE or ID) or crossed (i.e., MW or RD) disparities, we infer that the crossed and uncrossed binocular activities are created or integrated by separate, independent mechanisms. We propose to identify the two kinds of binocular activity suggested by the results of Figs. 1 and 2 as the crossed pool and the uncrossed pool of binocular activity.

THREE BINOCULAR POOLS

How many such independent pools of binocular activity might there be? A preliminary answer, based upon data obtained from 75 individuals using only the forced-choice procedure,[5] suggests that there may be as few as three basic pools. In addition to the crossed and uncrossed pools of disparity inferred from anomalous observers who fail to discriminate between crossed or uncrossed disparities of different magnitude, there is a third type of anomaly that confuses the sign of the
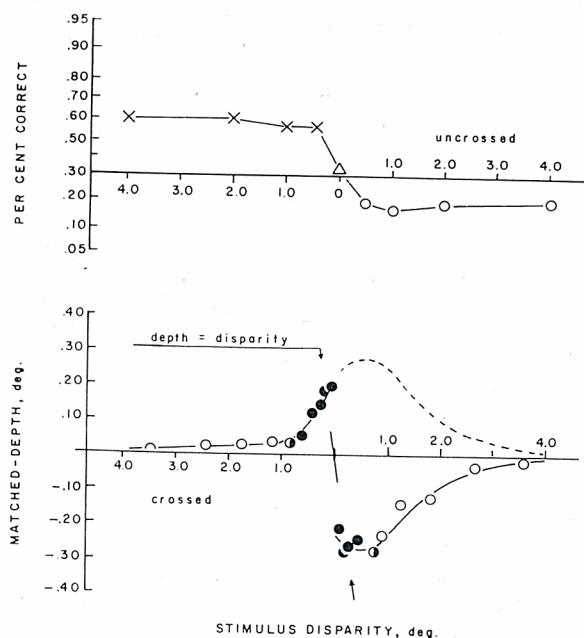
FIG. 3. The top graph shows the percent of correct responses to stimuli of different disparity for a third kind of anomalous observer. The observer cannot differentiate between crossed and uncrossed disparities, both of which always appear in front of the plane of fixation.

disparity, but not its magnitude. Unfortunately, there are several types of response strategies that these anomalous observers may use to perform the forced-choice discrimination. Figure 3 (top) shows the percent of correct responses vs disparity for one observer who represents this type of anomaly. Note that the crossed disparities are seen correctly approximately 60% of the time, whereas the uncrossed disparities are seen correctly only 20% of the time—well below chance. The explanation for this curve is that the monocular or null condition is consistently reported as being behind the plane of fixation, whereas the stimuli with either crossed or uncrossed disparities are reported as appearing in front of the fixation plane. Thus, with the present scoring method, 60% of his responses of crossed are, in fact, correctly assigned to the crossed disparities, whereas only very few uncrossed responses are to the uncrossed stimuli.

The lower portion of Fig. 3 shows the depth-matching data for the same observer. These data are somewhat misleading because the forced-choice judgments indicate that the uncrossed disparities actually appear as crossed (i.e., in front of the plane of fixation). Thus, the perceptually equivalent disparities for this observer would be indicated more accurately by inverting the uncrossed portion of the data so that all the depth matches would be positive. The dotted line represents

such an inversion, emphasizing the surprising finding that it is the smallest binocular disparities in the neighborhood of $-\frac{1}{3}°$ that have the greatest depth for this type of anomalous observer.[11]

To summarize, the present data suggest that normal or complete stereoscopic depth perception may be reduced to at least two, and possibly three, basic mechanisms. When such reductions occur, observers become stereoanomalous and differentiate among disparities only over limited regions of the normal range of disparities. The nature of the reductions suggests that there are at least three such regions, roughly corresponding to the crossed, uncrossed, and near-zero disparities. In order to interpret the nonmonotonic relation between depth and disparity, it is proposed that there is a pooling of the activities of the disparity detectors that sample any one of these regions of disparity. Thus, the magnitude of the depth sensation would be based upon the (relative) activity in one or more of the three pools of binocular activity: crossed, near zero, or uncrossed. Anomalous stereoscopic depth perception would result if one or more of these pools were absent.

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[11] Both the short duration and the length of the lines might be important factors contributing to this unusual result, in which small disparities elicited the greatest depth. Otherwise, we would have to conclude that the subject possessed a clear fixation disparity. However, under the experimental conditions, marked esotropia was probably not present, for then the two nonius lines above and below the fixation cross would have appeared misaligned.