Stereo-Discrimination between Diplopic Images in Clinically Normal Observers

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When retinal disparity exceeds the limits for fusion, the resulting images are perceived as diplopic. In a stereo test that allowed comparison of crossed and uncrossed disparity sensitivities, 74% of the subjects perceived convergent disparities more readily than divergent disparities. This asymmetric sensitivity to disparity did not appear to be related to measurements of phoria, vergence amplitudes, or clinical measurements of stereo acuity. Invest Ophthalmol Vis Sci 25:1316–1320, 1984

Ogle1 divided binocular depth perception into patent stereopsis and qualitative stereopsis. Both forms of stereopsis depend upon retinal disparity to create the sensation of depth, but in patent stereopsis the disparities must be small, the two images must be similar so that they can be fused, and the sensation of depth is a monotonic function of disparity. In qualitative stereopsis, the disparities are large,2,3 the sensation of depth does not necessarily increase with increasing disparity,1 image similarity is not required,4 and the object is seen diplopicallly.1–3

Richards5 has extended our understanding of qualitative stereopsis further by the discovery that some observers are unable to appreciate some classes of disparity. This discovery was made possible by a new paradigm of stereo-discrimination. Earlier studies investigating qualitative stereopsis2,3 required observers to discriminate between crossed and uncrossed disparities. Richards5-6 hypothesized that if qualitative stereopsis involved two independent mechanisms, one mechanism tuned to crossed disparities and the other to uncrossed disparities, the standard discrimination test would not reveal any abnormalities because the disparity corresponding to the missing mechanism could be deduced correctly by exclusion. Thus, Richards introduced a third stimulus, a pair of lines presented to only one eye of the binocularly fixating observer. These two lines appear identical to disparate diplopic images in every sense, except that they are generally localized to the zero disparity fixation plane by a normal subject.7,8 With this stimulus added to the crossed and uncrossed disparity stimuli, observers were asked to discriminate among the three stimuli. Richards found that most observers could perform the discrimination. However, a minority of observers confused the monocular stimuli with either crossed disparities or confused monocular stimuli with uncrossed disparities. These observers were called, respectively, crossed anomalous and uncrossed anomalous observers.

The purpose of this investigation was to determine whether stereo-anomaly was accompanied by other abnormalities of stereo vision, as measured by standard clinical tests of binocular visual function.

Materials and Methods

Stimuli

Figure 1 shows the stimulus display. The photographically created targets were either 10° × 4.3° lines or 21°-diameter dots projected on an aluminum coated screen. Polarization of the images was achieved by placing orthogonally oriented polarizing chips over each image of the stimulus pair, and when viewed through orthogonally oriented polaroid goggles allowed only one eye to see one member of the stimulus pair. When the left eye saw the right image and the right eye saw the left image, the stimulus was seen in crossed disparity. When the left and right eyes saw the corresponding images, the stimulus was seen in uncrossed disparity. Monocular targets used to simulate zero disparity were seen by only one eye. The dot stimuli had disparities of 1, 2, 3, and 4 deg while the line stimuli had a disparity of 1.6 deg. In all cases, the stimuli symmetrically flanked the fixation target. The luminance of the 28-deg square screen

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1316
was 430 cd/m², which was sufficient to mask cross-talk between images seen by right and left eyes. The target luminance was 1700 cd/m². The continuously present 10'-square fixation target was flanked by vertical nonius lines to aid fixation.

Subjects

Subjects were recruited from the staff of Bascom Palmer Eye Institute and the parents of patients brought to the Childrens’ Eye Clinic. Most subjects were given a complete ophthalmologic examination, which included the measurement of their visual acuity, phoria, vergence amplitudes, and stereo acuity.

Procedures

Subjects were positioned in a head and chin rest and viewed the fixation target through polarizing eye pieces. Subjects were instructed to report vertical misalignment of the nonius lines. A trial was initiated with a warning tone, followed by a 100-msec exposure of the stereo stimulus. The subject then chose one of the two possible responses by pushing a button associated with the response choice. Entering the response also initiated the next trial. For the line stimuli, there were three blocks of 60 trials. In each block of trials, the subject discriminated between a pair of stimuli: crossed/uncrossed, crossed/monocular, or uncrossed/monocular stimuli. For the dot stimuli, there were two blocks of trials, crossed/monocular and uncrossed/monocular, with the disparity magnitudes in random order.

The subjects were given a box with two buttons. One button was labeled “near” and the other button was labeled “far.” In any given block of trials, one type of stimulus was perceived as closer than the other. Thus, in the crossed/monocular stimulus block, stimuli perceived in front of the fixation plane (crossed stimuli) were perceived as closer than the monocular stimuli. In this case, subjects were instructed to press the “near” button when the stimuli appeared closer and the “far” button when the stimuli appeared on the screen. When the stimulus pair were uncrossed/monocular stimuli, subjects pressed the “near” button for stimuli appearing to fall on the plane, while stimuli appearing behind the screen required a “far” response.

Data Analysis

The percent correct scores for a block of trials was converted to d’ using the table of Elliot.9 This procedure rescales the scores so that a chance level of performance (50% for a two alternative forced choice (2AFC) experiment) corresponds to zero sensitivity10 (ie, d’ = 0). The two d’ values associated with the crossed/monocular and the uncrossed/monocular tasks were converted to a ratio to permit the assessment of the asymmetry of the observer’s sensitivity to crossed and uncrossed disparities. The numerator of the ratio was chosen so that it was always smaller than the denominator. Thus the ratio always varied between zero and one. If the uncrossed measurement was in the numerator, the ratio was given a positive sign to distinguish it from the case where the crossed measurement was in the numerator. A positive ratio indicates a relative lack of sensitivity to uncrossed disparities, while a negative sign indicates insensitivity to crossed disparities.

Some subjects found the stereo test difficult, especially when the dot stimuli were used. Twenty-three out of 49 subjects tested with dots were excluded from the results since their identification scores were not significantly (P < .05) greater than chance. When line stimuli were used, only 7 out of 71 subjects were excluded for the same reason. Stereo ratios obtained from the dot stimuli results were averaged across disparity magnitudes for each included subject.

Results

The data of the 64 subjects who discriminated the depth direction of lines are shown in Figure 2. The left graph shows the percent correct for each of the
Fig. 2. Results for 64 subjects who discriminated between lines of crossed and uncrossed disparity. The left-hand graph shows the present correct scores for all subjects performing significantly above chance for at least one of discrimination tasks. The right graph shows the corresponding stereo ratios for each subject. A ratio of one indicates that the subject perceived crossed and uncrossed disparities equally well. Stereo ratios plotted to the right of the unity line indicate better detection of crossed disparities, while ratios plotted to the left of the line, indicate superior performance for perceiving uncrossed disparities.

subjects for both the uncrossed/monocular targets (left) and the crossed/monocular targets (right), while the right graph shows the corresponding stereo ratios. The stereo ratio is a measure of the asymmetry of sensitivity to the two types of disparity. The positive ratio indicates greater sensitivity to crossed disparities while the negative ratio indicates relatively more sensitivity to uncrossed disparities. The ratios of more clearly show asymmetric sensitivity because they rescale the percent scores so that chance detection levels are zero. The addition of a large constant unrelated to sensitivity, as is the case in a percent correct score for 2AFC experiments, tends to cause their ratio to converge to unity.

Inspection of the stereo ratios in Figure 2 indicates that most subjects perceive crossed disparities better than uncrossed disparities. When the targets were dot stimuli, subjects were, on the whole, also more sensitive to crossed disparities. However, a greater percentage of the subjects who were tested with dots were excluded from analysis. This is because many more subjects detected both crossed and uncrossed stimuli at chance. In this case, stereo ratios would be meaningless since division by zero and near zero values of \( d' \) would result. Comparing the exclusion rate of 9.9% of subjects for line stimuli to 47% of subjects for dot stimuli suggests that line stimuli are more robust in evoking depth sensations. However, since dot stimuli involved disparity values ranging from 1–4 deg, it is useful to consider an analysis of relative stereo sensitivity for crossed and uncrossed disparities broken down by disparity magnitude. Figure 3 shows the results of such an analysis averaged across subjects with like signed stereo ratios. The top part of the figure shows the results for subjects more sensitive to uncrossed disparities, while the bottom shows subject more sensitive to crossed disparities. The figure shows that the disparity asymmetry holds for all values of disparity. The result suggests that stereo ratios for the line stimuli are not simply a consequence of two disparity functions having noncoincident peaks.

If the stereo scores of subjects for both experiments are analyzed together, then it is obvious that the majority (74%) of subjects perceived crossed disparities more clearly show asymmetric sensitivity because they rescale the percent scores so that chance detection levels are zero. The addition of a large constant unrelated to sensitivity, as is the case in a percent correct score for 2AFC experiments, tends to cause their ratio to converge to unity.

Fig. 3. Average percent scores broken down by disparity magnitude for dot stimuli. Top graph shows average scores for those subjects who perceived uncrossed disparities better than crossed disparities, while the bottom graph shows scores for subjects who performed better with crossed disparities. Note that performance for the poorly perceived disparity is uniformly depressed for all disparity values.
better than uncrossed disparities. The binomial test was used to decide whether this asymmetry is significant. The null hypothesis can be rejected with a risk of error of less than 0.00006 (N = 87, z = 5.23, two-tailed).

Since most subjects are more sensitive to crossed disparities, and since many of these subjects are "stereo-anomalous" by Richards' definition,5 we wanted to know whether our subjects were anomalous in other aspects of binocular function. Neither measures of phoria (cover test) or stereo acuity (Titmus stereo plates) showed a corresponding asymmetry. The mean phoria for all subjects was less than 1 prism diopter, while the stereo acuity scores were essentially equal for crossed and uncrossed disparities. The results of measurements of vergence amplitudes for base in and base out prism are shown in Table 1, in juxtaposition with the measurements obtained by other investigators.11-13 There is evidently no appreciable difference between our measurements and those of other investigators.

### Discussion

In our experiment, the stimulus disparity spanned the midline, and disparity processing required exchange of information between the cerebral hemispheres. For this condition, Richards5 finds that the probability that the depth of a crossed stimulus is appreciated is 0.63, while we find that the probability is 0.90. Our data are in closer agreement when the stimuli are uncrossed; we find the probability is 0.49 while for Richards5 the probability is 0.54. The latter difference is probably not significant, but the difference between our data and Richards' for the crossed disparity stimuli is noteworthy. As mentioned in the results, we find that our subjects' tendency to better perceive crossed disparity targets is statistically very significant. This difference between our results and Richards' results may be a consequence of the difference in which we implemented his paradigm. Richards tested the discrimination with a simultaneous, three-way presentation of stimuli. Normally, however, a three alternative forced choice experiment is only used when three conditions are met. First, it is assumed that the three alternatives are orthogonal (non-overlapping) alternatives. Secondly, the three alternatives are chosen so that there is not likely to be any preference for any of the three alternatives. Finally, the stimuli associated with the three alternatives are equally detectable. Clearly these three conditions do not apply to all subjects. For example, for those subjects who confuse uncrossed and monocular stimuli, the three-way discrimination involved only two orthogonal sensory alternatives. Given that there were still three response alternatives, response bias would take unpredictable forms. Since the forced choice paradigm is chosen to avoid response bias problems, we chose to present the discrimination task in a set of three different stimulus pairings.

Our subjects' greater sensitivity to crossed disparity stimuli, which is much more pronounced than in Richards' subjects, is not readily explainable. It has been suggested that subjects know that no object can be behind the opaque screen, and hence the cue of a solid surface overrides the disparity cue. The problem with this explanation is that subjects also knew that the images were flashed on a flat screen and thus knew that the images could not be in front of the screen. Yet most subjects had no trouble in seeing such images. In addition a few subjects had difficulty only when they were presented with crossed-disparity stimuli.

The major finding of this study is that there is no evidence that stereo-anomalous depth perception is accompanied by other abnormalities of binocular visual function measured by clinical tests. However, this result contrasts with that of Jones14 who explored the relationship between stereo-anomaly and the observer's ability to make vergence eye movements in the correct direction when presented with diplopic images. He found that all normal observers, as classified by Richards' test, made appropriate vergence eye movements, but not all subjects classified as stereo-anomalous made in appropriate vergence eye movements. It is possible that the clinical tests lacked the sensitivity to detect vergence anomaly, or Jones' sample was more homogenous than our sample.

While our methodology departs from that of Richards5 in separating the discrimination tasks into a pair of two discrimination tasks, we retained the practice of taking ratios of d', partly in order to facilitate comparison with his results. However there is a compelling theoretical reason for taking ratios of

### Table 1. Mean vergence amplitudes (prism diopters)

<table>
<thead>
<tr>
<th></th>
<th>Convergence</th>
<th>Divergence</th>
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<tbody>
<tr>
<td>Near</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>23 ± 9.6*</td>
<td>13 ± 4.6*</td>
</tr>
<tr>
<td>(2)</td>
<td>38</td>
<td>16.5</td>
</tr>
<tr>
<td>(3)</td>
<td>26.42</td>
<td>13.62</td>
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<tr>
<td>(4)</td>
<td>22.18</td>
<td>12.04</td>
</tr>
<tr>
<td>(1)</td>
<td>11.6 ± 5.2*</td>
<td>7 ± 2.6*</td>
</tr>
<tr>
<td>(2)</td>
<td>14.1</td>
<td>5.82</td>
</tr>
<tr>
<td>Far</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3)</td>
<td>17.68</td>
<td>7.97</td>
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<tr>
<td>(4)</td>
<td>18.29</td>
<td>9.00</td>
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<tr>
<td>(5)</td>
<td>18-20</td>
<td>14-16</td>
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* Standard Deviations. (1) Our data; (2) Berens, Losey and Hardy11; (3) Mellick12; (4) Mellick13; and (5) Tait14.
d'. It can be shown* that the stereo ratio is equal to the product of the ratio of the crossed and uncrossed signal means and a ratio of the crossed and uncrossed signal standard deviations. This product of ratios is of some interest since it indicates that an asymmetry in sensitivity can be due to two separate causes: in one case the sensitivity of one mechanism is greater than the other, while in the other case the noise in one mechanism is greater than in the other. By generating Receiver Operating Characteristics\(^{10}\) (ROC), these two hypotheses can be differentiated by inspecting their slopes when the ROCs are plotted on normal deviate coordinates.\(^{15,16}\)

We are not alone in finding that crossed-disparity stimuli are predominant. Others have noted asymmetries favoring crossed disparities, including the development of vergence movements in infants\(^ {17}\) and in the perception of random dot stereograms.\(^ {18}\)

However, in the latter study, the stimuli were of necessity fused and the effect disappeared when continuous viewing was permitted. Since, as Ogle observed,\(^ {1}\) the depth effects of diplopic images, which were employed in this study, also disappeared under continuous viewing, the results of Patterson and those of Richards.\(^ {5}\) Our results are consistent with Richards’ hypothesis that for large disparity stereopsis, there are two mechanisms. Fine stereopsis presumably would require at least one further mechanism.

**Key words**: stereopsis, qualitative stereopsis, diplopia, phoria, stereo acuity, vergence amplitudes

**References**


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* The derivation, assuming equal variance Gaussian distributions is:

\[
d'_c = \frac{m_c}{SD_c} d'_u = \frac{m_u}{SD_u} \\
\frac{d'_c - d'_u}{SD_c - SD_u} = \frac{m_c}{SD_c} - \frac{m_u}{SD_u} = \frac{m_u - m_c}{SD_c} - \frac{m_u - m_c}{SD_u} \\
\text{Eq. 1}
\]

where \(m_c\) = mean of crossed stimulus decision variable, \(m_u\) = uncrossed mean and \(SD\) = standard deviation.

By assumption, \(SD_c = SD_u\), so equation 1 reduces to a ratio of means. When \(SD_c \neq SD_u\) the situation is more complicated since \(SD_c\) and \(SD_u\) are variables that now reflect the variances of both the signal (crossed or uncrossed disparities) and noise (monocular) distributions, but the ratio will reflect an asymmetry in noise variances in the two mechanisms.