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A planar and a volumetric test for stereoanomaly

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Abstract. Stereoanomaly is the failure to see differences in depth when the viewer is presented with stimuli having different magnitudes of stereoscopic disparity. In the absence of eye movements, everyone suffers from stereoanomaly for extremely large disparities. Typically, such disparities are seen at the same depth as monocular stimuli. However, about 30% of the population exhibit some form of stereoanomaly even for very small disparities, provided eye movements are avoided. In some cases, the sign of the disparity will be confused, and the perceived depth will be incorrectly seen as 'behind' rather than 'in front of' the fixation point, for example. Because anomalies provide useful information about perceptual mechanisms, tests that measure and quantify the extent of a blindness are important investigative tools for research. Here we offer two easy-to-administer tests for stereoanomaly. The first test is based on depth judgments of two bars relative to a fixation point. The second test involves judgments of volumetric stimuli, seen stereoscopically. In each case, subjects indicate depth by setting a rectangle (with fixed base) to match the perceived depth. Although both tests are correlated, some differences in stereo processing are seen, depending upon whether or not the stimuli are presented near the point of fixation.

1 Introduction

An important source of information for the recovery of the 3-D layout is the retinal disparity between the images seen by the two eyes. There is a large body of work showing that there are at least two mechanisms underlying the processing of disparities: one for crossed disparities lying nearer than the fixation point, and another for uncrossed disparities (for review see Howard and Rogers 1995; Mustillo 1985; Regan et al 1990). Support for this idea comes from neurophysiology (Clarke et al 1976; Ferster 1981; Poggio and Fischer 1977). Further evidence appears in several other disciplines: developmental studies show that infants exhibit different maturation rates for crossed and uncrossed disparities (Birch et al 1982). In the adult, we see a substantial body of evidence of quite different spatiotemporal response functions for crossed and uncrossed disparities (Finlay et al 1989; Patterson et al 1995; Richards 1972; Schor and Wood 1983). Finally, Ogle's studies of phorias show that individual differences in processing of uncrossed and crossed disparities can be divided into four categories (Ogle et al 1967). All of these results suggest that at least two different mechanisms underlie the processing of stereoscopic disparities. These differences might therefore be expected to have consequences for the perception of depth, which presumably occurs at a subsequent stage in information processing. In support of this possibility, it was reported in the early seventies that, in the absence of eye movements, a significant fraction of the population were not able to perceive correctly the 3-D location of brief presentations of a bar. Hints of this deficit had already appeared in a study of six subjects by Westheimer and Tanzman (1956) where one of their six subjects failed to meet criteria for localizing stereoscopic presentations. This subject performed well above the criterion

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over the uncrossed region of disparities, but near chance over the crossed region. Richards's studies of over a hundred subjects showed that about 30% of that population had similar deficits (Richards 1971). Specifically, for some subjects, stimuli presented with quite different uncrossed stereoscopic disparities were seen at roughly the same depth. Others reported approximately the same depth for stimuli with markedly different crossed disparities. In both these cases, the perceived depth was similar to that elicited by monocular stimuli (Richards 1970, 1971). Such subjects were designated as *stereoanomalous*, whereas those who exhibited errors in depth judgments in all of the disparity categories (about 3% of the population) were classified as stereoblind. These defects were selective to the sign of the disparity, and extended to small disparities (Richards and Kaye 1974).

Considering that a host of other properties are found correlated with stereoanomaly (eg Herring and Bechtoldt 1981; Manning et al 1987; Mitchell and Ware 1974; Regan et al 1986; see for review Mustillo 1985; and Regan et al 1990), it is a bit surprising that tests for depth perception with stimuli of varying disparity are seldom used as a basis for correlating individual differences in stereoscopic information processing. When color anomalies were discovered and made easy to diagnose, then the use of tests for color blindness rapidly advanced our understanding both of underlying processing mechanisms and of inter-subject differences in color perception. Hence our hope is that an easy-to-administer test for stereoanomaly can serve a similar purpose for stereopsis. Here we introduce two convenient tests. The first test is a modified version of Richards's original test: the judgment is of the depth of a frontal plane defined by two bars which are flashed for 100 ms in front (or behind) a fixation point. The second test requires a judgment of the apparent volume of a collection of bars, each with different disparity. We will refer to the first test as the "planar test" and to the second test as the "volumetric test". Although both tests give correlated results, each is not predictive of the other. Specifically, deficits in the ability to see significant depth of 3-D volumes presented in either the crossed or uncrossed region of disparity were highly correlated with deficits in the ability to see depth from brief presentations of two bars presented in the same region, but not vice versa.

2 Methods

2.1 *Apparatus*

Observers viewed stereograms, that were rear-projected onto a large flat screen (50 deg × 37 deg), at a fixed viewing distance of 230 cm. The projector (JVC DLA-G11E) was driven by a Mac G4. Every pixel subtended 2.3 min of arc × 2.3 min of arc. The refresh rate was 75 Hz. The stereograms were presented to the two eyes by means of the standard red – green anaglyph technique. The luminances of the red and green stereogram half-images were adjusted to appear equally bright when viewed through the red and green filters placed before the eyes (1.4 cd m^{-2}). The room was darkened. The incremental luminance (relative to the background and without filters in front of the eyes) of the red stimuli was 1.6 cd m^{-2}, and of the green stimuli it was 2.2 cd m^{-2}. There was no visible crosstalk between the half-images and photometric measurements showed that insignificant amounts of the green and red light leaked through the red and green filters, respectively.

2.2 *Stimuli*

The planar and the volumetric tests were very similar (figure 1). The perceived depth of the bars was governed by disparity. An identical nonius symbol was present in both tests. The central binocularly visible square of the nonius symbol subtended 24 min of arc × 24 min of arc, the lengths of the vertical monocular parts were 36 min of arc, the width of a single line was 9.6 min of arc, and the gap between the monocular

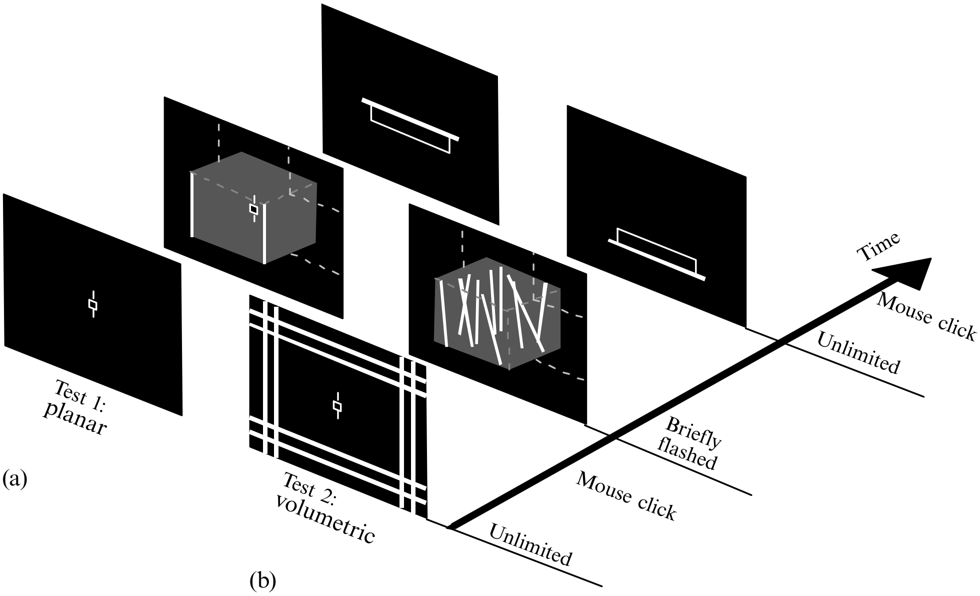


Figure 1. The planar and the volumetric stereoanomaly tests. (a) In the planar test, the subject fixates the nonius symbol which has zero disparity. After the subject decides that the eyes are properly fixating the nonius, the stimulus presentation is initiated by a mouse click. The stimulus consists of two eccentrically (± 5 deg) located vertical bars that have the same disparity so they are perceived in a frontal plane. The bars are flashed for 100 ms either in front or behind the nonius symbol and the subject's task is to judge the sign and the magnitude of the perceived depth between the bars and the nonius symbol. Subsequently a 2-D symbolic display is presented and the perceived depth is matched by setting a movable line (see figure 2 for details). After the subject is satisfied with the setting, s/he clicks the mouse and the next trial begins. (b) The volumetric test is similar to the planar test. However, now the disparities within the flashed stimulus are constant, representing a volume, but the disparity of the nonius symbol varies. The nonius symbol has either a positive or a negative disparity relative to the screen. The horizontal and vertical lines in the first frame have the same disparity as the nonius symbol and serve to stabilize fixation. The subject initiated the 150 ms flash of the volumetric stimulus and matched the perceived depth between the nearest and the farthest part of the volume by setting a movable line in the symbolic display.

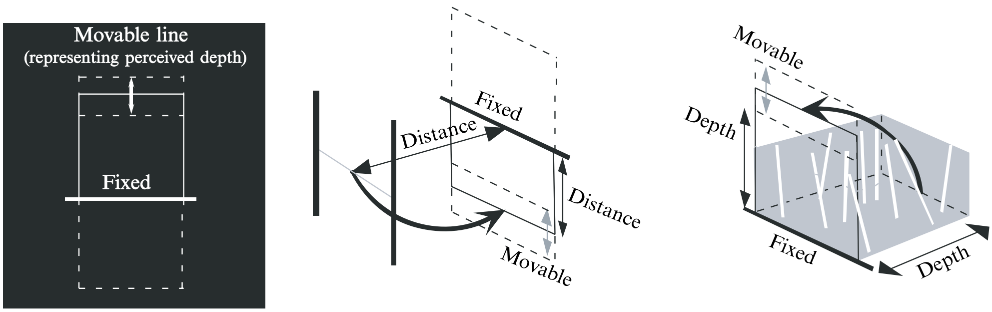
and the binocular portions was 9.6 min of arc. This configuration was chosen because dichoptic alignment measurements are quite precise for this configuration (McKee and Levi 1987; Westheimer and McKee 1977). When stimuli were presented monocularly, they were presented in green only.

In the planar test the disparity of the nonius symbol was zero with respect to the screen. In the volumetric test the disparity of the nonius varied with respect to the screen and the mean position of the volumetric display was held constant at 0 deg with respect to the screen.

2.3 *Task and procedure*

At the beginning of a trial, subjects fixated the nonius symbol. After the subject established stable fixation of the nonius symbol (by perceiving the monocular parts of the nonius to be vertically aligned), s/he clicked the mouse and the test stimulus was then flashed for either 100 ms or 150 ms, depending on the test. This duration was chosen to be sufficiently short so that vergence eye movements were minimal.

Subjects judged the perceived depth-to-width ratio of the bar stimuli by matching this ratio to the aspect ratio of a rectangular display (van Ee and Anderson 2001). After the bar stimuli were presented, a 2-D symbolic display was presented on the screen consisting of a box (figure 2). This display represented a top view of the viewing geometry. One of the horizontal lines was fixed and represented the screen. The vertical location of the other horizontal line could be manipulated by the subject through movements of the computer mouse. The vertical distance between the horizontal lines represented the perceived depth of the stimulus. Although some of the presented disparities were actually consistent with a depth-to-width ratio that was significantly larger than one, observers reported that the perceived depth was almost always smaller than the perceived width of the volume (and never exceeded the values available in the rectangular display). The horizontal length of the movable line was equal to the width of the stimulus on the screen (10 deg). This was understood by the subjects and provided a calibration of their depth estimates. The setting of the subject (in other words, the vertical difference between the two horizontal lines in the symbolic display) was divided by the width of the movable horizontal line. This number represents the perceived depth ratio, which is the dependent variable.



(a) Frontal view of 2-D symbolic display (b) Planar test (c) Volumetric test

Figure 2. (a) A 2-D symbolic display was presented on the screen in order to measure the perceived depth-to-width ratio evoked by the stimulus. The display consisted of a box. It represents a top view of the viewing geometry. One of the horizontal lines was fixed. The vertical location of the other line could be manipulated by the subject through movements of the computer mouse. The vertical distance between the horizontal lines represented the perceived depth. (b) In the planar test this fixed line represented the screen. Depicted is an example where the bars were flashed in front of the screen. (c) In the volumetric test the fixed line represented the nearest part of the volume.

Clearly this method of measuring the perceived depth range involves a mental operation that transforms the perceived depth range in 3-D into a 2-D representation onto a frontoparallel plane.[1] Prior to recruitment of a subject we tested whether s/he was able to provide consistent depth-range estimates. None of the subjects exhibited any problems in performing the task.

Each test consisted of five successive trial blocks (in the planar test there were 17 stimuli + 10 monocular controls, in the volumetric test 26 stimuli + 13 controls; disparities ranged from -4 to 4 deg, which will be described in more detail subsequently). Within one block, every trial appeared once and each was presented in random order. Prior to a test, subjects were informed about the range of possible perceived depths; they conducted five test trials with unlimited observation duration. It was explained to them that the five test trials in random order contained the minimum depth, the maximum depth, and three randomly chosen depths that they were to see in the particular session (there was no feedback though about their responses).

[1] This metrical method is inspired by a method of measuring stereoscopically perceived slant estimates (van Ee and Erkelens 1996).

2.4 *Subjects*

Twenty-eight subjects took part in the experiments. The subjects reflect a somewhat biased set of the population: almost all were asked to participate because they were part of a laboratory community and were routinely used for an assortment of vision experiments. All subjects wore their corrective glasses. Informed consent was obtained from the subjects after explanation of the nature and possible consequences of the study. The research followed the tenets of the declaration of Helsinki.

3 Test 1: Stereoanomaly with planar stimuli

3.1 *Methods*

A qualitative (eg Blakemore 1970; Ogle 1952; Westheimer and Tanzman 1956) and quantitative (Kaye 1978) sensation of depth exists with briefly flashed disparate stimuli even when double vision has already emerged. The planar test quantifies this sensation of depth. The stimulus used in the planar test consisted of two vertical bars and is schematically depicted in figure 1a. In the case of zero disparity, one bar was presented at an eccentricity of 5.0 deg, the other at -5.0 deg. When there was non-zero disparity the bars were presented at ± 5 deg $\pm$ disparity/2. The bar width was 9.6 min of arc and its length was 3.5 deg. After the subject decided that stable fixation was established, s/he clicked the mouse and two bars were flashed for 100 ms presentation duration. The disparity of the bars ranged from -4 to 4 deg (specifically, values of -4, -3, -2, -1.5, -1, -0.5, -0.2, -0.1, 0, 0.1, 0.2, 0.5, 1, 1.5, 2, 3, 4, thus sampling small disparities more densely than large). The disparities of the two bars were identical, so that the two bars represented a frontoparallel plane.

As a control condition we also presented the bars monocularly to either the left or the right eye. Their eccentricities were in the ranges -4 to -1 deg and 1 to 4 deg (specifically, values of -4, -3, -2, -1.5, -1, 1, 1.5, 2, 3, 4).

3.2 *Results*

Figure 3 shows the raw data (unprocessed perceived depth-to-width ratios) of six typical subjects. Stimuli closer than fixation are to the right, whereas those with uncrossed disparity, located behind fixation, are in the left portion of each plot. The ordinate shows the subjects' perceived depth with '1' corresponding to a perceived depth between the bars and the nonius that is identical to the perceived width subtended by the two bars. As shown by the white squares, although the magnitudes of the depth settings vary across subjects, the subjects in the top row perceive the sign of the disparity of the pair of bars correctly.(2) The error bars represent one standard deviation across the five trial repetitions. The bottom row consists of stereoanomalous subjects. Subject R1 perceives the sign of disparity correctly only for crossed disparities. Subject S2 shows similar data but the magnitude of perceived depth is very small. His error bars are very small, so disparity stimuli clearly generate a depth signal. Subject T2 generally reverses the magnitudes of perceived depth.(3)

The black squares represent monocular control conditions. In most subjects the monocularly perceived depth ratio at zero disparity (extrapolated) is the same as the binocularly perceived ratio. The gray patches represent the area that was used for further study.

(2) Larger diplopic disparities may not be judged on the basis of disparity. Subjects can make such depth judgments on the basis of dichoptic lateral distance separating the bars, ie a width judgment. When targets are fused, subjects cannot use this width cue effectively (McKee et al 1990).

(3) Stereoanomalies can be specific to the sign of luminance contrast; a number of anomalous observers who confuse either crossed-disparity or uncrossed-disparity stimuli, reverse the sign of perceived depth when the stimulus is changed from dark bars on a light background to light bars on a dark background (Richards 1973).

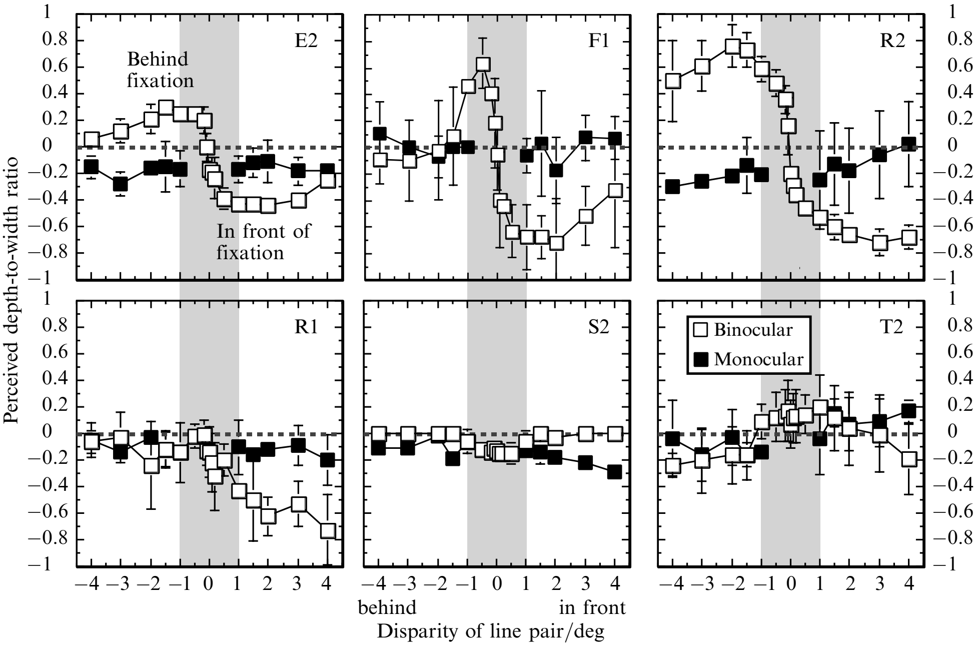


Figure 3. The results of the planar test. The data of six typical subjects are shown. The top row consists of normal subjects. While the magnitudes of the depth settings vary across these subjects, they perceive the sign of the disparity of the pair of bars correctly. The bottom row consists of stereoanomalous subjects. Subject R1 perceives the sign of disparity correctly only for crossed disparities. This subject does either not detect uncrossed disparities or he suppresses them. Subject S2 shows similar data but the magnitudes of perceived depth are very small. Subject T2 frequently reverses the magnitudes of perceived depth. Viewing was both binocular and monocular. The gray patches represent the area that we used for further study.

4 Test 2: Stereoanomaly with volumetric stimuli

4.1 *Methods*

The stimulus used in the volumetric test is schematically depicted in figure 1b. A visual frame consisting of horizontal and vertical lines was presented together with the nonius symbol to aid stable fixation. This frame had the same disparity as the nonius symbol. (The frame was absent in the planar test.) Since peripheral stimuli are effective in stabilizing (cyclo)vergence, we used the whole screen so that the frame subtended a large visual angle. (However, measurements on a small sample of subjects showed that the test can also be carried out on a normal computer monitor when the viewing distance is small.) The frame is depicted in figure 1b; its size was 50 deg by 37 deg. The eccentricity of the frame relative to the nonius symbol was 9.4 deg horizontally and 7.9 deg vertically. The distance between two neighboring frame lines was 3.7 deg. The line widths within the frame were 0.4 deg. No features were visible with another disparity than the frame and the nonius symbol. In contrast with test 1, where the nonius position remained at a fixed distance from the subject, here in test 2 the nonius symbol was presented with a range of disparities between −4 and 4 deg. A number of subjects, however, were not able to fuse the disparate parts of the nonius symbol for disparities larger than 1.5 deg (this explains the absence of data points for R1, R2, and T2 in figure 4). In these cases, the lack of fusion of the nonius was indicated by setting a negative ratio, and these trials were discarded. After the subject perceived the monocular parts of the nonius to be aligned s/he clicked the mouse and the test stimulus was then flashed for 150 ms.

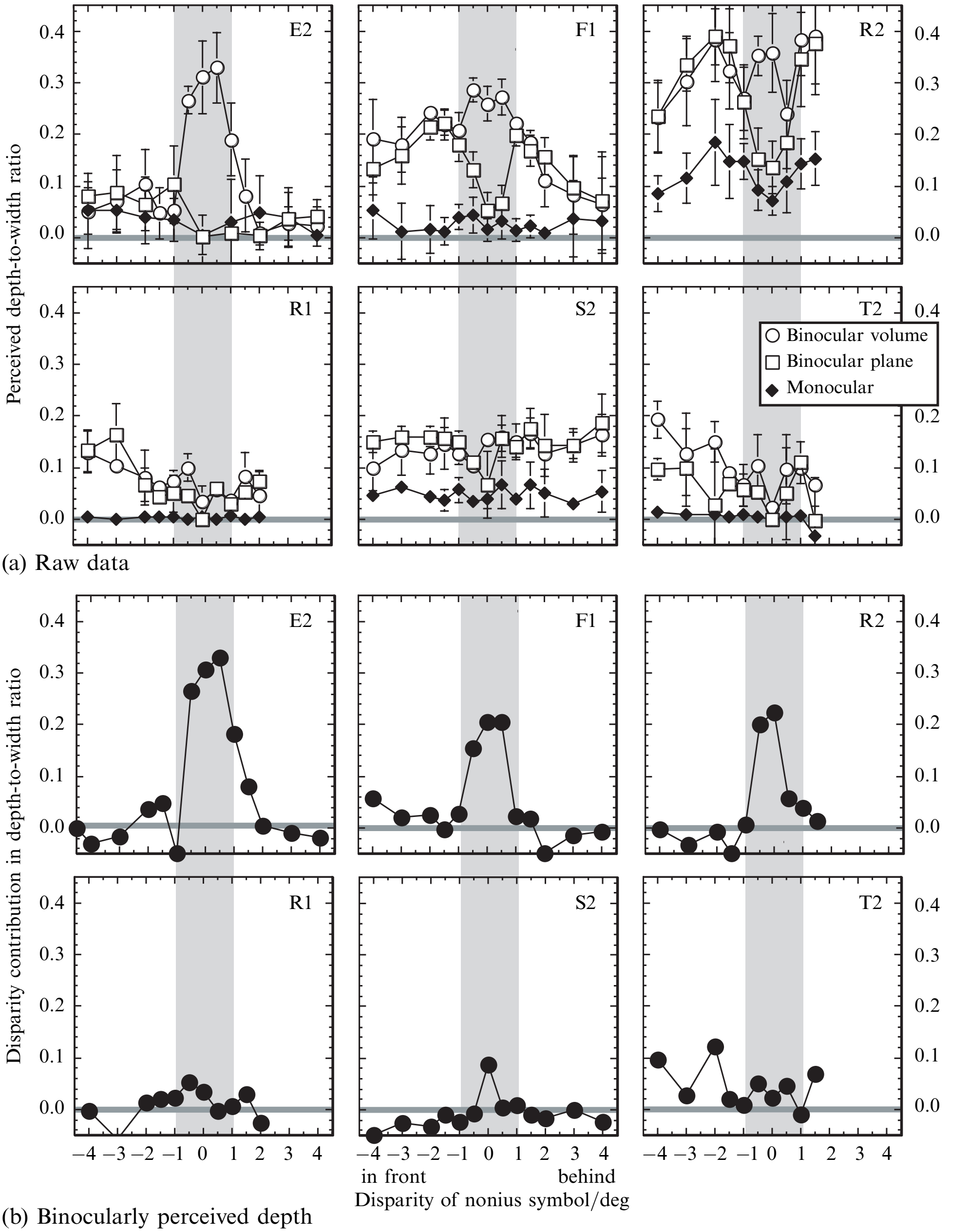


Figure 4. The results in the volumetric test of the same six typical subjects whose data were depicted in figure 3. (a) For the disparities within the gray region the normal subjects in the top row are clearly able to perceive a difference between the volumetric condition and the planar condition. Outside the gray region the normal subjects lose this ability. For the stereoanomalous subjects there is no significant difference between the volumetric and the planar binocular conditions in all of the disparity conditions. The area between the two binocular curves within the gray region is used for a comparison with the results in the planar test. Viewing was also monocular (black diamonds). The data in this condition can be regarded as a bias that is present in both binocular conditions. (b) In order to articulate the differences in judgments between the volumetric and planar binocular conditions we subtracted the data in the two conditions. This difference can be regarded as a disparity component in perceiving ratios of the volumes. The normal subjects exhibit very similar data with marked peaks near zero disparity, whereas the anomalous subjects all have essentially flat curves with little or no disparity gain.

The test stimulus consisted of ten frontoparallel bars with orientations randomly chosen from a range between −20 and 20 deg. Figure 1b depicts an example of the set of bars. The set of bars subtended 10.0 deg by 5.0 deg on the screen. The width of a single bar was 9.6 min of arc. There were three conditions randomly mixed: one monocular (stimuli were presented in green only) and two binocular conditions. In the monocular condition, the bars were presented solely to the left eye. The disparities within the set of bars represented a 3-D volume that subtended either 0 (planar condition) or 100 cm (volumetric condition) in depth. In the 100 cm condition the disparity between two neighboring bars was determined by the maximum disparity (at 100 cm depth) divided by the total number of bars. The volumetric set of bars was always presented symmetrically relative to the plane of the screen. For the 0 cm depth condition this means that they were presented in the plane of the screen. For a depth of 100 cm this means that a depth of 50 cm was presented behind the screen (disparity range = 0.28 deg) and a depth of 50 cm was presented in front of the screen (disparity range = 0.44 deg). Note that in a number of conditions the complete volume of bars was presented off-horopter (extra-horopteral stereopsis—Blakemore 1970; McKee et al 1990).

Using the method of matching the perceived depth-to-width ratio (van Ee and Anderson 2001), we measured the perceived depth elicited by the volume of bars. After the bar volume was presented, the 2-D symbolic display was visible and the subject moved the mouse to indicate the perceived ratio as in test 1.

4.2 *Results*

Figure 4 reports volumetric data of the same six subjects whose data were depicted in figure 3. Three conditions are indicated: depth judgments for the volume of bars (open circles); depth judgments for a plane of bars (open squares); and the monocular condition (black diamonds). The error bars represent one standard deviation across the five trial repetitions. Note the disparity labels for the abscissa ('in front' and 'behind') are reversed relative to figure 3. They now reflect the positions of the nonius with respect to the screen. This reversal in labeling makes figure 3 and figure 4 comparable in that the right side of each panel corresponds to crossed-disparity presentation (with respect to fixation). On the ordinate, the depth scale reflects the perceived depth-to-width ratio.

4.2.1 *Disparity condition.* The first interesting result is highlighted by the gray region. For disparities ranging between −1 and 1 deg, the subjects in the top row are clearly able to perceive a difference in the ratios between the volumetric condition (white circles in figure 4a) and the planar condition (white squares). Outside the gray region these subjects lose this ability, as shown by the overlap in the white circles and squares. Four of our subjects showed these kinds of results.

The lower panel of figure 4a shows results for three subjects. Notice that now the white circles and squares overlap over the entire range of disparities. Hence this fraction of our subject pool reported similar volumes regardless of whether the stimuli were planar or filled a 3-D volume. We can make this loss in depth discrimination ability clearer by subtracting the volumetric (white circles) and the planar (white squares) depth judgments. This difference is shown in the lower panels (figure 4b). One set of subjects, those from the top panels in figure 4a, exhibit very similar data with marked 'gains' (eg the peaks) near zero disparity, whereas the remaining set of subjects all have essentially flat curves with little or no disparity 'gain'.

4.2.2 *No disparity condition (monocular stimuli).* Returning again to the six upper panels in figure 4a, the black diamonds show results for the monocular control condition. These data reveal biases in reporting depth when only monocular stimuli are presented. For large disparities, such biases are common, and appear to some degree for all observers. We speculate that this bias is caused by the occlusion cue that is present because our stimulus consists of bars which partly occlude one another.[(4)] Subject R2 explicitly noted that a monocularly presented set of bars evoked a clear percept of relative depth. When the monocular data are subtracted from the rest of the data, R2's results are very similar to the results of E2 and F1 (figure 4b).

5 Results

5.1 *Stereoanomalies*

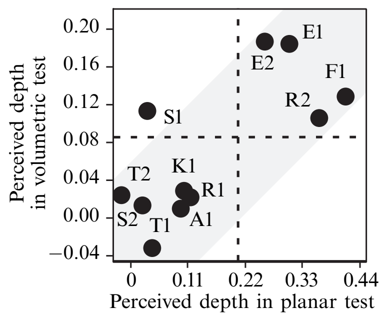
Our results further reinforce the observation that individuals differ markedly in how much depth is seen for a given stimulus disparity. For some individuals, a high gain relation is seen between depth and disparity—ie even a small disparity can elicit a large depth magnitude. For others, it is the opposite: over the entire range of disparities, essentially little depth is seen regardless of the magnitude of the stimulus disparity. However, of special interest is that this relation between depth and disparity may also differ within the same individual, depending upon whether a crossed or uncrossed range of disparities is explored. In other words, for a small fraction of the population, some individuals have a high gain relation between depth and disparity over, say, the crossed region of disparities, but a low gain relation over the uncrossed range—ie little depth is seen regardless of the magnitude of uncrossed disparity presented (see panel 4a). Thus we know that the depth – disparity gain characteristic need not be the same function over the entire disparity range, suggesting that the crossed and uncrossed stereoscopic mechanisms may be distinct.

5.2 *Relation between planar and volumetric tests*

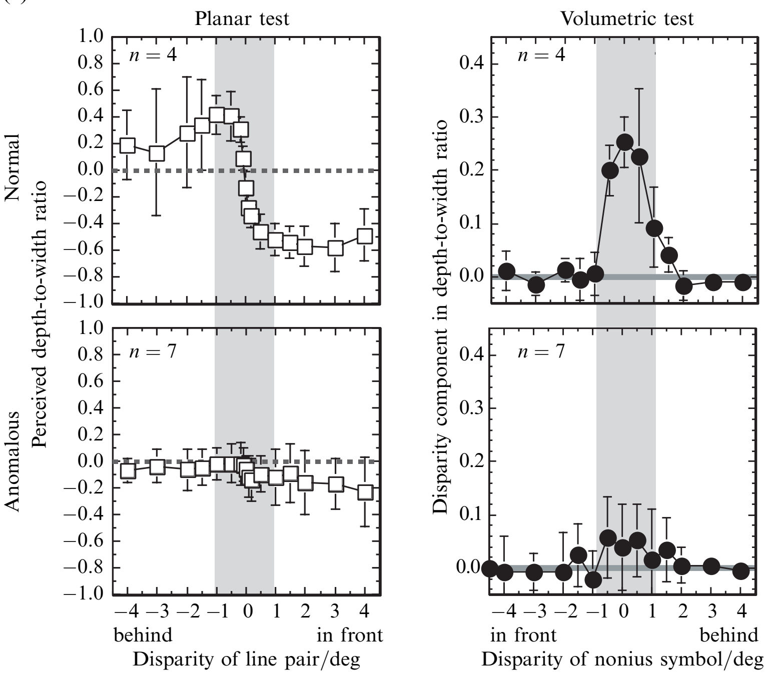
A second finding concerns the relation between the planar and volumetric tests (figure 5). Eleven subjects participated in both tests; by intention, this set included subjects that showed poor depth on the planar task. For those subjects in this group that had a low-gain depth – disparity relationship across all disparities in the planar test, a low-gain response was also observed in the volumetric test (eg figure 5b, lower panels). This correlation occurred for all of the seven subjects found with low gain on the planar test, and for none for four subjects that had a high gain on the planar test. (A criterion of 0.2 was used on the planar test and 0.08 on the volumetric test.) Note that the reverse relationship was not valid: namely, subjects with low gain over one region of the planar test need not 'fail' the volumetric test (eg S1). Presumably this non-reciprocality between the two tests is due to the volumetric test being more sensitive for the ± 1 deg region near the fixation point, where both crossed and uncrossed disparity mechanisms could come into play (Richards 1971).

Figure 5 shows the mean results for the form of the depth – disparity relationship of all eleven subjects who participated in the two tests. Subjects were divided into two groups based on the volumetric test, using a criterion of 0.08 (see figure 5b). The panels on the left-hand side represent the planar test. The right panels show the results in the volumetric test. The striking difference between the two groups again strongly suggests that individuals may have categorically different stereo mechanisms.

[(4)] In order to prevent occlusion, one could use vertical bars. However, vertical bars lead to matching problems known as wallpaper effects. Subjects might match a bar in one eye's image with an uncorresponding bar in the other eye's image which leads to an incorrect bar depth; in volumetric stimuli consisting of vertical bars, perceived depth is diminished when false matches degrade the establishment of correct correspondence (van Ee and Anderson 2001).



(a) Correlation



(b) Comparison of mean results

Figure 5. Comparison between the planar and the volumetric stereoanomaly test. (a) Correlation between the planar and the volumetric stereoanomaly tests. The numbers along the two axes represent a measure of perceived depth, which was calculated by adding absolute depth magnitudes divided by the number of presented disparities within the shaded bounds of figure 3 and figure 4. (b) The mean form of the depth – disparity relationship of all the normal and anomalous subjects who participated in the two tests. The panels on the left hand side represent the planar test. The right panels show the results in the volumetric test.

6 Discussion

There can be no doubt that there are marked individual differences in stereoscopic information processing. These differences appear not only among individuals, but within the same individual. For example, left and right hemispheric processing may differ (eg Breitmeyer et al 1975; Julesz et al 1976; Richards and Foley 1971). Even more striking are differences in stereoscopic information processing within a hemisphere, as revealed by regions of scotomata to bars moving in depth (Richards and Regan 1973). The issue, then, is the nature of the defect when failures occur.

First, there is abundant evidence that the presence or absence of eye movements can greatly influence the ability to see stereoscopic displays, especially when depth – disparity gains are very low (see appendix) or when correlations are hard to extract, such as when fine random-dot stereograms are presented (Julesz 1971). In some cases, longer durations can improve stereo abilities and acuities (Kumar and Glaser 1994; McKee et al 1990; Ogle and Weil 1958; Westheimer 1979), even in the absence of eye movements. However, neither eye movements nor stimulus duration can explain the wide variations among individuals seen in our subject pool. For eye movements to explain the differences, we would require that when depth – disparity gain is high, eye movements occurred. But the volumetric test shows that these movements would have been limited to about ± 1 deg disparity from fixation. Yet the planar test shows that large gains can be seen with disparities as large as 2 or 3 deg. However, more damaging to any eye-movement hypothesis is that in some cases, including that of Westheimer and Tanzman (1956), the depth – disparity gain for the planar task is large for, say, crossed but not for uncrossed disparities. A more parsimonious interpretation in these cases is that the mechanism underlying the extraction of depth from uncrossed disparities is impaired but the crossed-disparity mechanism is not. This same argument rules out the hypothesis that it is stimulus duration, and stimulus duration alone, that creates reduced depth – disparity relationships for some individuals (Patterson and Fox 1984). At the very least, one needs different spatiotemporal characteristics for stereo processing over crossed and uncrossed ranges of disparity, which again leads to the more parsimonious conclusion that there are at least two separate mechanisms. Indeed, the spatiotemporal characteristics of these depth – disparity mechanisms have been estimated and are found different (Finlay et al 1989; Patterson et al 1995; Richards 1972; Schor and Wood 1983).

For those interested in understanding the relation between depth perception and stereoscopic disparity, our two tests complement each other nicely. The planar test permits the experimenter to explore the depth – disparity relation over a wide range of isolated disparities, especially away from fixation, whereas the volumetric test seems more appropriate in the ± 1 deg region near the fovea. In the former, we have a better chance of isolating and studying the crossed and uncrossed mechanisms throughout the visual field, whereas the latter is more likely to explore how the two mechanisms are used together to estimate spatial extent.

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Appendix: Role of stimulus duration and eye movements

Figure A1 shows depth seen with 100 and 2000 ms stimulus presentations in the planar test on nineteen subjects. Eye movements were minimized by requiring fixation on the nonius. Similar to test 1, an average performance measure was calculated over the −1 to +1 disparity interval by summing up the absolute depth magnitudes and then dividing by the number of presented disparities. (The interval is the shaded region in figures 3 and A2.) The figure shows clearly that subjects with poor performance in

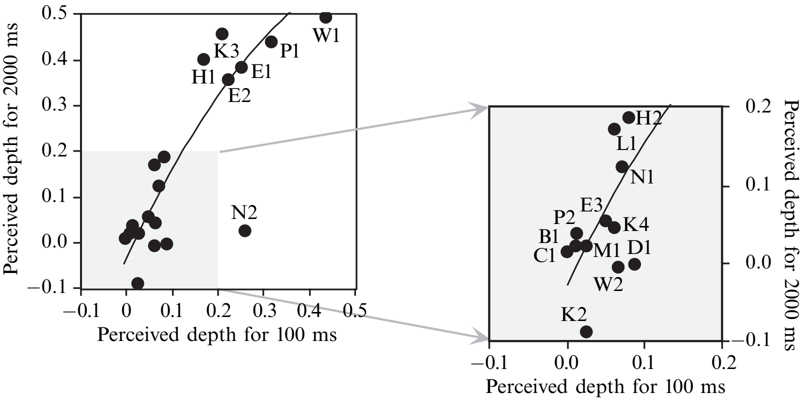

Figure A1. Correlation of the performance in the planar tests at 100 ms and 2000 ms for nineteen subjects. Each dot represents a subject. Subjects with poor performance in the 100 ms test also show poor performance in the 2000 ms test. The solid curve shows the best fit spline through the data points.

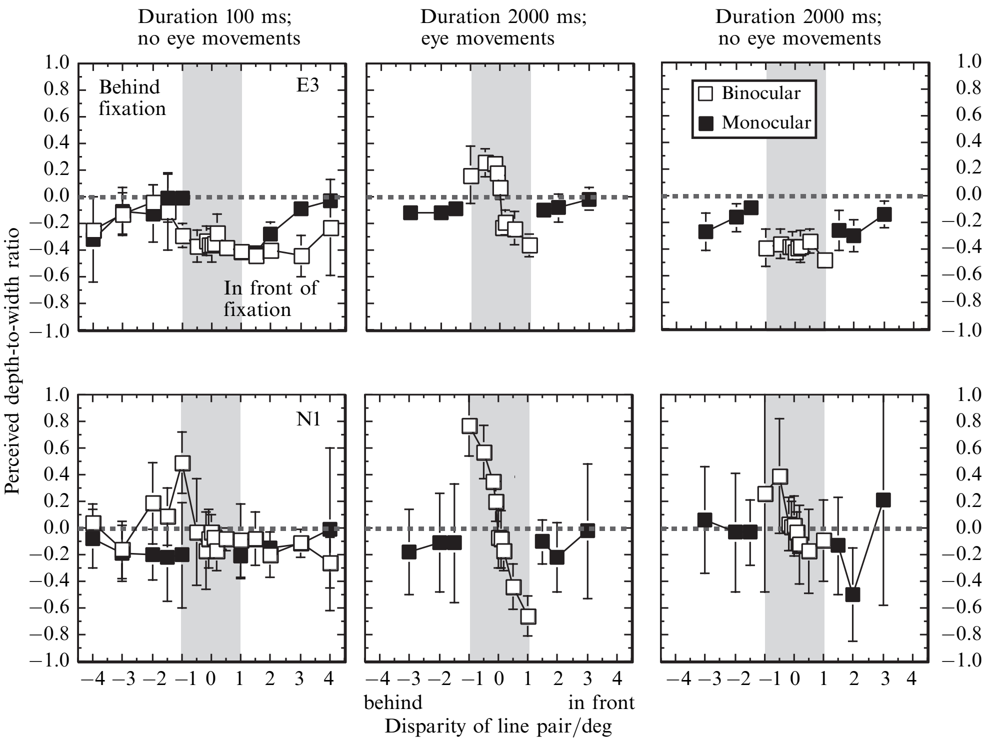

Figure A2. The left panels show the data in the 100 ms anomaly test of two anomalous subjects. The middle panels show that performance becomes normal with 2 s duration and free eye movements. In the right panels we see that behavior is poor when eye movements are not allowed at a duration of 2 s.

the 100 ms test also showed poor performance in the 2000 ms test. This relationship is nonlinear. The solid curve shows the best fit spline through the data points (with a correlation coefficient of 0.84).

Two of the subjects with poor depth – disparity gains (and hence who were classified as anomalous on the 100 ms presentation) were then allowed to make eye movements. Figure A2 shows these results. The middle panel of the figure shows that, when eye movements are permitted with a 2 s presentation duration, both anomalous subjects now correctly report both the sign and magnitude of disparity. This finding is in agreement with previous results (eg Jones 1977; Newhouse and Uttal 1982; Patterson and Fox 1984). On the other hand, with no eye movements but with the stimulus presented for a long duration (right-most panel), the anomalous behavior again is present. These latter results look very similar to those found for the short 100 ms stimuli. Although we did not objectively measure eye posture during the experiment, note that any occasional unintended vergence movements would clearly go against the hypothesis being tested. Furthermore, note that the free viewing results have taken on a character different from the results in both fixation conditions, which are similar to one another. These findings are consistent with the notion that occasional unintended saccades did not contribute significantly to the results. We conclude that eye movements, not stimulus duration, is the more critical factor in the failure to observe stereoanomalies in experiments with bar-like stimuli.