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Correlation between stereoanomaly and perceived depth when disparity and motion interact in binocular matching

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Abstract. The aim of this study was to find out to what extent binocular matching is facilitated by motion when stereoanomalous and normal subjects estimate the perceived depth of a 3-D stimulus containing excessive matching candidates. Thirty subjects viewed stimuli that consisted of bars uniformly distributed inside a volume. They judged the perceived depth-to-width ratio of the volume by adjusting the aspect ratio of an outline rectangle (a metrical 3-D task). Although there were large inter-subject differences in the depth perceived, the experimental results yielded a good correlation with stereoanomaly (the inability to distinguish disparities of different magnitudes and/or signs in part of the disparity spectrum). The results cannot be explained solely by depth-cue combination. Since up to 30% of the population is stereoanomalous, stereoscopic experiments would yield more informative results if subjects were first characterized with regard to their stereo capacities. Intriguingly, it was found that motion does not help to define disparities in subjects who are able to perceive depth-from-disparity in half of the disparity spectrum. These stereoanomalous subjects were found to rely completely on the motion signals. This suggests that the perception of volumetric depth in subjects with normal stereoscopic vision requires the joint processing of crossed and uncrossed disparities.

1 Introduction

Our retinae receive slightly different two-dimensional (2-D) images of objects around us. We are able to retrieve the three-dimensional (3-D) layout of a scene from the spatial differences between the two retinal images, ie the binocular disparities. The computation of binocular disparities depends upon the correct identification of corresponding features of the two retinal images (eg Julesz 1971). This identification process is commonly referred to as the *matching problem.* Establishing correspondence is ambiguous when images contain excessive binocular matching candidates. For example, woods containing innumerable tree branches contain excessive matching candidates (eg Helmholtz 1867). For a long time now, researchers have tried to understand how the brain solves the matching problem (for a review see Howard and Rogers 2002).

A recent study by van Ee and Anderson (2001) on the role of orientation and motion in establishing binocular correspondence constitutes the basis for the present study. The subjects in that study estimated the perceived depth-to-width ratio (a metrical task) in a stimulus that consisted of an array of bars uniformly distributed inside a volume (mimicking a volume of tree branches in woods containing excessive matching candidates). Dependent variables were bar orientation, and both the direction and magnitude of motion. Van Ee and Anderson concluded that the visual system uses differences in orientation, motion direction, and speed to achieve binocular correspondence in ambiguous 3-D stimuli when a (volu)metrical task is

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employed.⁽¹⁾ Van Ee and Anderson explicitly demonstrated that their results could not be explained in terms of depth-cue combination (that is, a combination of depth-from-motion and depth-from-disparity), implying that there is an early interaction of motion and disparity in binocular matching. Physiological data have revealed that many cortical cells in V1 (Poggio and Talbot 1981), MT (Maunsell and Van Essen 1983; Bradley et al 1995; Bradley and Andersen 1998; DeAngelis and Newsome 1999), and MST (Roy and Wurtz 1990; Roy et al 1992; Eifuku and Wurtz 1999) that are tuned to binocular disparity are also tuned to orientation, motion direction, and speed. Van Ee and Anderson suggested that one of the functional roles of cells that multiplex orientation, motion direction, speed, and binocular disparity is to help solve the binocular-matching problem.

Here the study of van Ee and Anderson is extended by using stereoanomaly. In this regard, it is of interest to make a comparison with color-vision research where anomalous color perception (*color blindness*) has led to rapid advances in our understanding of puzzling inter-subject differences in color perception and has helped to unveil the underlying color processing mechanisms. My hope is that anomalous stereoscopic perception (*stereoanomaly*) will serve a similar purpose in the study of stereopsis. What is stereoanomaly? In the early seventies, it was reported that about 30% of the population is unable to discriminate the perceived depth elicited by—relatively large—crossed disparities from the perceived depth elicited by monocular stimuli, whereas others are unable to perceive depth from—again relatively large—uncrossed disparities (Richards 1970, 1971a). Such subjects were said to be *stereoanomalous*, whereas those who exhibited errors in depth judgments in all of the disparity categories (about 3% of the population) were classified as stereoblind. The defect is selective and can extend to small disparities (Richards and Kaye 1974). Although stereoanomalous subjects show normal stereopsis and good stereoacuity (Jones 1977; van Ee and Richards 2002) while making eye movements, researchers studying stereoanomaly should take steps to restrict subject's eye movements because these enable the subject to put a crossed stimulus in the uncrossed region (and vice versa).

Volumetric stimuli similar to those described in the previous study (van Ee and Anderson 2001), are here used to investigate to what extent motion facilitates binocular matching in normal and stereoanomalous subjects when they are required to estimate the depth of a volume containing excessive matching candidates. More specifically, I tested whether stereoanomaly correlates with the experimental results. The main part of this study is based upon two assumptions: first, that there is a matching problem—disparity on its own (without motion) is unable to provide sufficient information for the recovery of the 3-D structure within the stimulus—and, second, that the data cannot be explained simply by depth-cue combination. In control experiments I investigated whether these assumptions are valid.

Anticipating the main findings, we will see that the experimental results yield a striking correlation with stereoanomaly. I was particularly interested in the abilities of stereoanomalous subjects. Such subjects might be able to integrate disparity and motion in the part of the disparity spectrum that they are able to process correctly. They might also disregard the disparities and rely completely on the motion signals. We will see that the latter possibility describes the data best. Stereoanomalous subjects were found to rely completely on the motion signals, even though they are able to process

⁽¹⁾ A number of papers report that observers who fail to see depth in static stereo displays are indeed able to perceive depth when the stimulus consists of dynamic disparities (Braunstein et al 1986; Bradshaw et al 1987; Rouse et al 1989; Pong et al 1990; Tittle and Braunstein 1991, 1993; Cornilleau-Pérès and Droulez 1993; Bradshaw and Cumming 1997; Lankheet and Palmen 1998). However, following the line of discussion of Landy et al (1995, page 403), most (but not all) data can be explained by an interaction between depth-from-motion and depth-from-disparity, but not unequivocally as a facilitation of binocular matching.

either only crossed or only uncrossed disparities. This suggests that the perception of volumetric depth in subjects with normal stereoscopic vision requires the joint processing of crossed and uncrossed disparities.

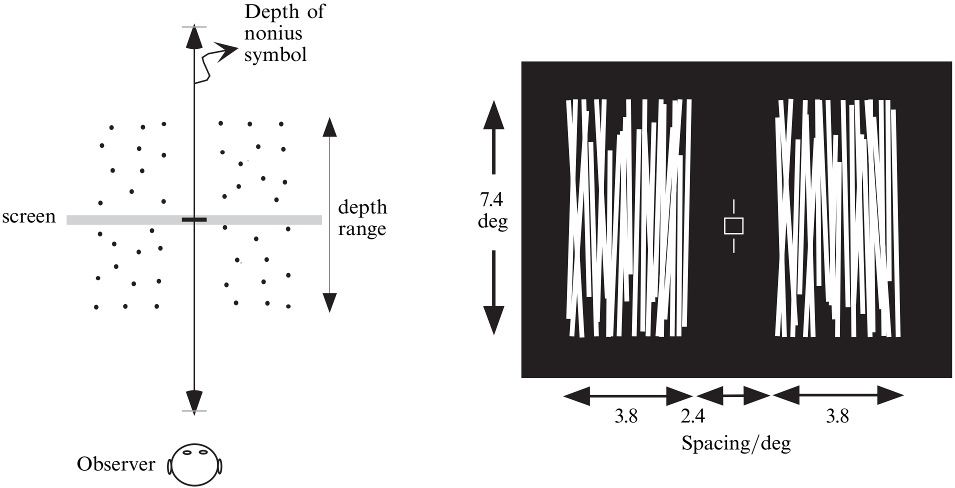
2 Methods

2.1 *Apparatus*

Subjects viewed stereograms that were back-projected onto a 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 the standard red – green anaglyph technique. The room was darkened. The incremental luminance (relative to the background and without anaglyph filters) of the red stimuli was 1.6 cd m^{-2}, and of the green stimuli was 2.2 cd m^{-2}.

2.2 *Stimuli*

The stimuli consisted of an array of bars uniformly distributed inside a 3-D volume that was divided into two subvolumes by a nonius symbol. The stimulus is schematically depicted in figure 1. Since I intended to examine to what extent differential bar motion facilitates binocular matching, relatively many bars were needed in order to create circumstances in which stereoscopic correspondence could not be established entirely without the aid of motion (the present stimulus resembled those of van Ee and Anderson as much as possible). There were 23 bars on either side of the nonius symbol. The horizontal angular width of the stimulus was 10 deg. The width of each collection of bars on either side of the nonius symbol was 3.8 deg and the horizontal gap between the two collections was 2.4 deg. The bars were arranged in a series of frontoparallel planes (no slant in depth). Bar orientations within a frontoparallel plane were chosen randomly from a range −4° to 4° relative to vertical (figure 1b). The individual bars had a width of 9.2 min of arc and a vertical length that was minimally 5.0 deg and maximally 7.4 deg (the bar length was jittered on either side, within a range of 1.2 deg).



(a) Top view (b) Frontal view

Figure 1. Viewing geometry of the experiment. To simulate ambiguous matching conditions, the stimuli consisted of an array of bars uniformly distributed inside a 3-D volume. (a) Top view of a cross section of the collection of bars in the horizontal plane. The depth range was either 0 or 100 cm at a viewing distance of 230 cm. (b) Frontal view which depicts how the volume was divided into two subvolumes by the nonius symbol. The nonius symbol was presented with a range of disparities. Each bar was positioned in a frontoparallel plane (no slant in depth) but the orientations varied randomly between −4° to 4° relative to vertical.

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. The volumetric set of bars was always presented symmetrically relative to the plane of the screen. This means that a depth of 50 cm (disparity range, 0.28 deg) was presented behind the screen and a depth of 50 cm (disparity range, 0.44 deg) in front. The disparity between 2 bars in neighboring depth planes was determined by the maximum disparity (100 cm depth) divided by the total number (46) of bars. In the zero-depth condition the bars were presented in the plane of the screen.

The collection of bars was always presented with a gradient of motion, such that the speed decreased systematically with the depth specified by the bar disparity. The bars underwent a square-wave oscillation (left – right in a frontoparallel plane) that reversed direction 3 times (2 cycles). Half a cycle was represented by 20 frames. The bar speeds(2) spanned the range of roughly 3 to 6 deg s^{-1}. Depth informations provided by motion and disparity were consistent in the volumetric condition but they were in conflict in the planar condition.(3) In the latter condition, an observer who is able to process the disparities correctly perceives transparent sliding bars that are more or less in one plane. An observer who is unable to process the disparities correctly derives his/her depth judgment from the monocularly present motion parallax (van Ee and Anderson 2001).

A nonius symbol was present in the center of the screen throughout a trial. The central binocularly visible square of the nonius symbol subtended 24 min of arc × 24 min of arc, the length of each of the vertical monocular parts was 36 min of arc, the width of a single line was 6.9 min of arc, and the gap between the monocular and the binocular portions was 9.2 min of arc. This configuration was chosen because dichoptic alignment measurements are quite precise for this configuration (Westheimer and McKee 1977; McKee and Levi 1987). The disparity of the nonius symbol varied randomly across trials, ranging between -1 and 1 deg (ie between 88 cm in front and 270 cm behind the screen). This means that for a number of nonius disparity conditions the set of bars was presented either entirely in front of nonius symbol (crossed disparity), or behind it (uncrossed disparity), ie in these conditions the complete volume of bars was presented off-horopter (extra-horopteral stereopsis—Blakemore 1970; McKee et al 1990).

2.3 *Task and procedure*

Subjects were instructed to judge the magnitude of the perceived depth of the volume subtended by the bars. This judgment was to be expressed in terms of the perceived depth-to-width ratio of the volume. This task is identical to the task used in preceding studies (van Ee and Anderson 2001; van Ee and Richards 2002). After the presentation of the bar stimuli, a 2-D symbolic display consisting of a rectangular box appeared on the screen. A schematic drawing of the symbolic display is depicted in figure 2. The box in the symbolic display represented a top view of the viewing geometry. One of the horizontal lines was fixed and represented the nearest part of the volume. The subject could manipulate the vertical location of the other horizontal line by moving the computer mouse. The vertical distance between the horizontal lines represented the perceived depth within the volume. The horizontal length of the movable line was equal to the width of the stimulus on the screen (10 deg). This was explained to the

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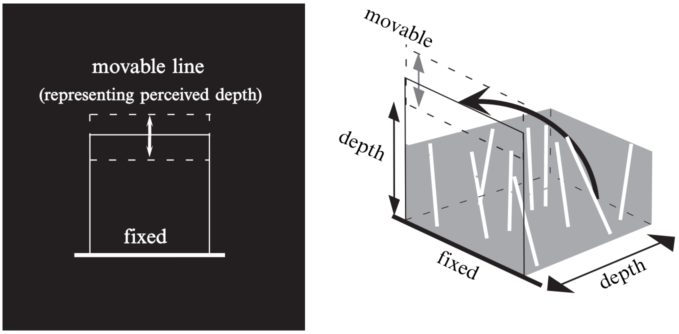
(2) Note that there is no zero motion plane and that the relative speeds of the targets on the screen are independent of the depth plane in which the eyes fixate.

(3) Motion parallax is in principle an ambiguous depth cue when it is presented in isolation: the same retinal motion is caused by an object whose near side moves faster as by an object whose far side moves faster. So, solely on the basis of motion parallax, the pivot point of the rotation of the volume might be perceived to be either behind or in front of the volume. The volumetric depth of both interpretations is, however, similar. So, if an anomalous observer is not able to disambiguate the motion cue by disparity, in monocular vision s/he perceives the same volumetric depth as the normals.



(a) Frontal view of 2-D symbolic display

(b) 3-D view

Figure 2. Matching the perceived depth-to-width ratio. Subjects were instructed to match the perceived depth-to-width ratio of the 3-D stimulus in a 2-D symbolic display. (a) Frontal view of the symbolic display that consisted of a rectangular box. The box represented a top view of the viewing geometry. One of the horizontal lines was fixed and represented the nearest part of the volume. The subject could manipulate the vertical location of the other horizontal line by moving the computer mouse. The vertical distance between the horizontal lines represented the perceived depth within the volume. (b) Mental operation that transforms the perceived depth range in 3-D into a 2-D representation on a frontoparallel plane.

subjects and they were therefore able to calibrate their depth estimates. The estimate 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. The resultant number represents the perceived depth-to-width ratio. Although the disparity range used was actually consistent with a volume receding 100 cm in depth (depth-to-width ratio is 2.5), observers reported that the perceived depth was almost always smaller than the perceived width of the volume (and never exceeded the values available to them).

This particular stimulus was selected so that the interaction of motion and disparity in binocular matching could be investigated when the bars were presented with disparities within a spectrum that is completely crossed, completely uncrossed, or both crossed and uncrossed. On the one hand, presenting bars that have well-defined disparities requires strict fixation, which usually means utilizing briefly flashed stimuli. A motion stimulus, on the other hand, requires a sufficiently long period of exposure for the motion to be effective, and therefore cannot be presented by means of a flash. A nonius symbol was presented while the stimulus consisting of bars was presented. The procedure was as follows: First the nonius symbol was presented on an otherwise empty screen. After the subject had 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 present for 2000 ms. Subjects were instructed to fixate the nonius symbol throughout the trial. Because the nonius symbol was relatively large, subjects had no difficulty with fixation. Subjects were instructed to set a negative ratio whenever the red and the green parts of the nonius symbol became out of vertical alignment by more than half the length of the horizontal side of the central square of the symbol. Several subjects were unable to fuse the disparate parts of the nonius symbol for disparities larger than 0.5 deg (this explains the absence of data points for R1 and T2 in figure 3). Trials that yielded a negative ratio setting were discarded. Eye posture was not measured objectively during the experiment. However, in a control experiment, five subjects were instructed to make scanning eye movements across the stimulus. The data in the scanning-eye-movement condition (presented in a subsequent section) reveal a characteristic that is fundamentally different from the characteristic

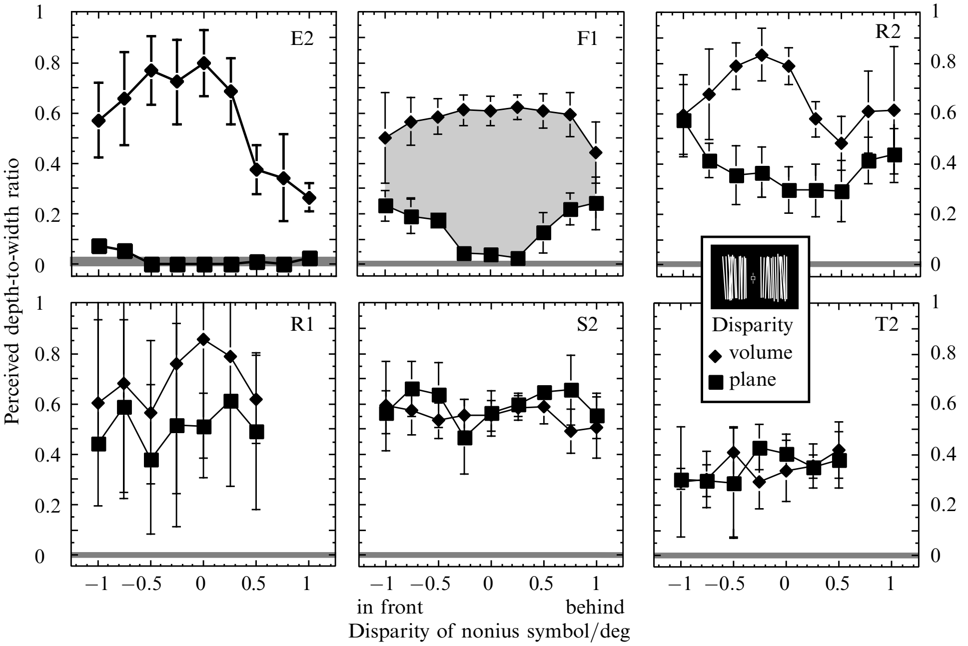


Figure 3. Integration of motion and disparity. Perceived depth-to-width ratios for six more or less typical subjects as a function of the nonius disparity. The icon depicts a schematic view of the stimulus. In the right part of each panel (positive disparity) the nonius symbol was presented behind the 3-D collection of bars. The black diamonds and squares represent conditions in which the disparity specified a volume and a plane, respectively. Motion was present in both conditions. The gray area (only for subject F1) highlights the difference between the two conditions. The difference between the conditions is more reliable in the top row than in the bottom row. The top row depicts the data for subjects who showed normal stereopsis in the stereoanomaly test (see figure 4). Subjects R1 and T2 were unable to keep the monocular parts of the nonius symbol aligned for nonius disparities larger than 0.5 deg. The error bars denote one standard deviation across five trials.

in the fixation condition. This finding is consistent with the notion that occasional unintended saccades did not contribute significantly to the results. The fixation disparity of the subjects was measured; for all subjects these disparities were insignificantly small ($<$ 3 min of arc) relative to the disparity range used (120 min of arc).

Clearly the 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 on a frontoparallel plane (figure 2b).(4) Prior to a test, subjects were informed about the range of possible perceived depths; they participated in five test trials and were allowed unlimited observation time. 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. To prevent these test trials from biasing subjects' responses (i) subjects were not told which of the randomly presented trials contained the maximum or minimum depth, and (ii) subjects received no feedback about their responses. Each experimental session consisted of five successive trial blocks, each consisting of eighteen

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(4) This metrical visual method is inspired by a method of measuring stereoscopically perceived slant estimates (van Ee and Erkelens 1996). Prior to recruitment of a subject, tests were made whether s/he was able to provide consistent depth range estimates. Of the nearly fifty subjects who participated in experiments in which this perceived depth-to-width ratio measure was used (van Ee et al 2000; van Ee and Anderson 2001; van Ee and Richards 2002) none reported any difficulties.

conditions. Within one block, every trial appeared once and each was presented in random order.

2.4 *Subjects*

Thirty subjects took part in the experiment. They were part of a laboratory community and were routinely involved in an assortment of vision experiments. All subjects had participated in a stereoanomaly test developed in a previous study (van Ee and Richards 2002). The subjects who participated in the current study reflect a biased set of the population. Many were asked to participate because they were classified as stereoanomalous in the stereoanomaly test (for this experiment, stereoanomalous subjects are more informative than normals). All subjects wore their corrective glasses. Except for subject E2, the author, they were naïve with respect to the purposes of the experiment.

2.5 *Results*

I will first concentrate on typical data characteristics of individual subjects and then will present an objective measure to compare the data of all subjects. Figure 3 depicts the perceived depth-to-width ratios for six subjects that represent more or less typical characteristics (in the group of thirty subjects).(5) The disparity labels for the abscissa reflect the locations of the nonius symbol with respect to the screen. The right side of each panel corresponds to crossed-disparity presentation of the collection of moving bars (fixation is then behind the collection of bars). On the ordinate, the depth scale reflects the perceived depth-to-width ratio, with '1' meaning that the depth and the width of the volume of bars were perceived equally large. Two conditions are indicated. The black diamonds and squares represent conditions where the disparity indicated a depth of 100 cm (volume) and 0 cm (plane), respectively. Stimulus motion was identical in both conditions.(6) The error bars represent one standard deviation across five trials. The difference between perceived depth ratios for the planar and the volumetric conditions is highlighted by the gray area in figure 3 (only in the panel that shows the data for F1).

Before analyzing the data in the disparity–motion integration experiment, let us look at the subjects' results in a recently developed stereoanomaly test. These results, depicted in figure 4, were reported previously by van Ee and Richards (2002).(7) Stimuli closer than fixation are on the right, whereas those with uncrossed disparity, located behind fixation, are in the left portion of each plot. Note that the disparity labels for the abscissa ('in front' and 'behind') are reversed relative to figure 3. They now reflect the disparity of the line pair with respect to the screen. This reversal in labeling makes figures 3 and 4 comparable in that the right side of each panel corresponds to crossed disparity presentation (with respect to fixation). The ordinate shows

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(5) A reviewer requested the average data for the thirty subjects to be presented in a separate graph. Because subjects differ considerably, such a graph would not really be informative. There would be large error bars and this would mask relevant details. The ordinate of the graph in figure 6 should be consulted for a characteristic of each individual subject's data.

(6) A reviewer stated that it is crucial to examine perceived depth for stereoanomalous subjects in the no-motion condition. The no-motion condition has actually been examined for the stereoanomalous subjects. But the results are not presented because they are not relevant for the current paper. If there is no motion, stereoanomalous subjects do not perceive reliable depth in both the no-disparity and the disparity conditions; much the same as when we look at figure 1b.

(7) In the stereoanomaly test subjects judged the depth-to-width ratio of two briefly (100 ms) flashed vertical bars relative to a centrally presented fixation symbol. Figure 4 contains an icon depicting the stimulus; the width of each bar was 9.6 min of arc, the length was 3.5 deg and the bars were presented at a horizontal eccentricity of ±5 deg. The data for the six subjects in figures 3 and 4 could also be compared with data for the same six subjects in another stereoanomaly test; see figure 4 of the volumetric test in the study by van Ee and Richards (2002).

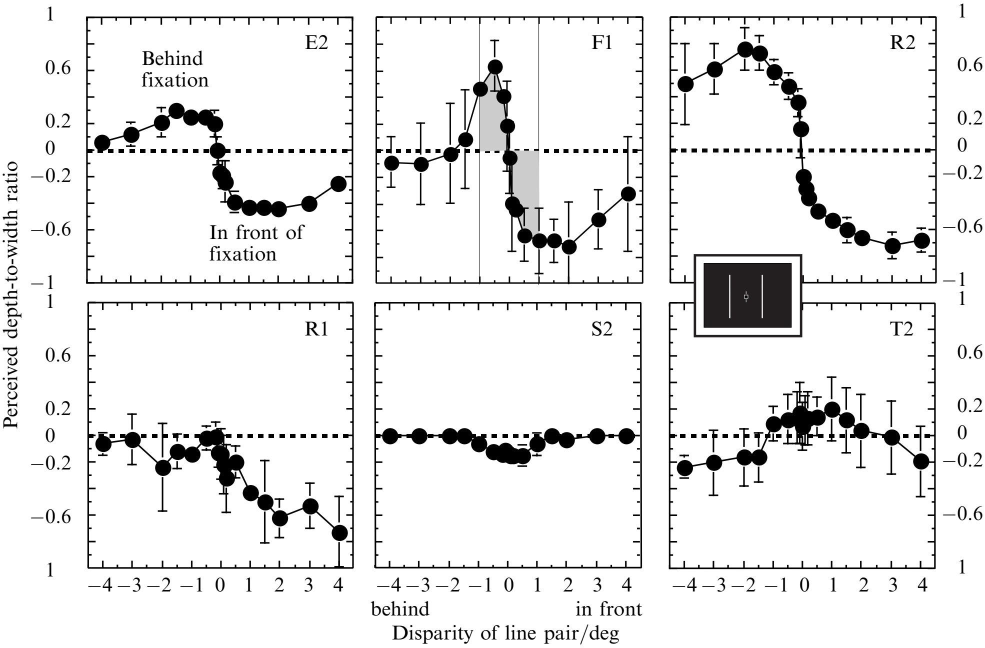

Figure 4. Results of the stereoanomaly test. The data shown are for the same six subjects whose data were depicted in figure 3. The icon depicts a schematic view of the stimulus used in the stereoanomaly test. The top row relates to normal subjects. Although the magnitudes of the depth settings vary across these subjects, they perceive the sign of the disparity of the pair of bars correctly. The bottom row relates to stereoanomalous subjects. Subject R1 perceives the sign of disparity correctly only for crossed disparities. For subject S2 the magnitudes of perceived depths are small. Subject T2 frequently reverses the magnitudes of perceived depth. The gray area (only for subject F1) represents the data that were used for further study. The error bars represent one standard deviation across five trials. Note that the disparity labels for the abscissa ('in front' and 'behind') are reversed relative to figure 3. They now reflect the disparity of the line pair with respect to the screen. These data have previously been reported by van Ee and Richards (2002).

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. Although the magnitudes of the depth settings vary across subjects, the subjects in the top row perceived the sign of the disparity of the pair of bars correctly. The bottom row represents stereoanomalous subjects. Subject R1 perceives the sign of disparity correctly only for crossed disparities. Although for subject S2 the magnitudes of perceived depths are small, the error bars are also small, so disparity stimuli clearly generate a depth signal (note, however, that half of the responses indicate the wrong depth direction). Subject T2 reverses the magnitudes of perceived depth for a number of disparities. The gray patch (shown only for F1) represents the area that was used for further study.

The top row in figure 3 represents subjects who were classified as normal in the stereoanomaly test (figure 4). Subject E2 perceives little depth in the planar condition for all of the nonius disparities, but perceives considerable depth in the volumetric condition, especially when fixation is in the center of the volume. The data for subjects F1 and R2 are similar to E2's data, in that they show a clear difference between the planar and the volumetric condition. Subject F1 perceives more depth in the planar condition when the stimulus is presented farther away from the horopter than when fixation is in the center (I will return to this issue when discussing control observations). Subject R2 shows an interesting characteristic in his responses: when the depth specified by disparity is zero, a marked depth for all nonius disparities is perceived. One can speculate that this characteristic is caused by the monocular occlusion cue [Braunstein et al (1986); partially occluding bars indicate that one bar is in front of the other].

The bottom row of figure 3 represents stereoanomalous subjects who were unable to distinguish disparities of different magnitudes and/or signs. There is very little difference between the data for subjects S2 and T2 in the planar and the volumetric conditions. These subjects disregard the disparity signals and in the recovery of depth rely completely on the motion signals. Subject R1, however, consistently perceived larger depth-to-width ratios in the volumetric condition than in the planar condition, but his error bars are very large. His perceived depth-to-width ratios are very noisy which might indicate that this ability, namely to use the detectable disparity spectrum, is not utilized routinely.

Interestingly, R1 is the subject who was clearly able to perceive crossed disparities in the stereoanomaly tests, and one could hypothesize that this ability helped him resolve the matching problem and see depth in the volumetric stimuli. The data in figure 5,

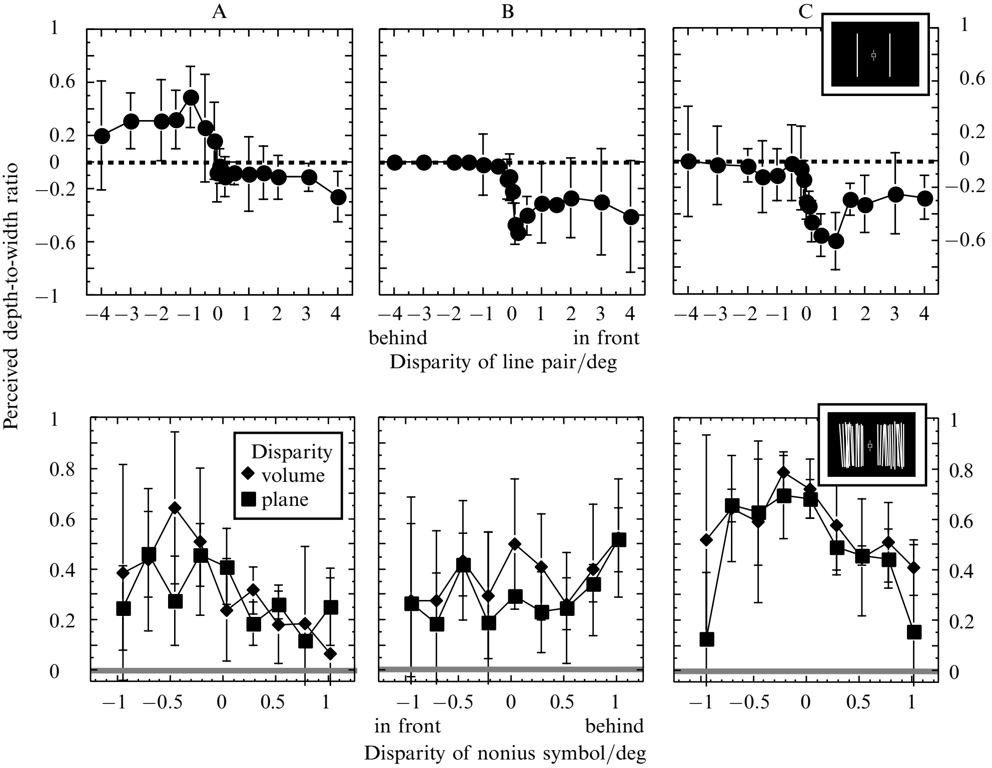

Figure 5. Results for three anomalous subjects. Depicted are the data for three subjects whose disparity-processing abilities were limited to only half the disparity spectrum. The top row represents the data of the stereoanomaly test; the bottom row the data of the motion – disparity integration experiment. The subject in column A was able to discriminate the uncrossed disparities but not the crossed disparities. The subjects in columns B and C were able to discriminate crossed disparities but not the uncrossed disparities. In the lower row of panels we see that none of the three subjects was able to reliably distinguish between the planar and volumetric conditions. These results suggest that stereoanomaly involves more than the inability to process part of the disparity spectrum. These results indicate that to perceive volumetric depth a subject needs to be able to compare pooled activities over the crossed and uncrossed disparity ranges. The error bars represent one standard deviation across five trials. The reversal in the disparity labels for the abscissa ('in front' and 'behind') makes the top and bottom rows comparable in that the right side of each panel corresponds to crossed-disparity presentation (with respect to fixation).

however, do not support this hypothesis. This figure depicts the data for three other subjects who in the planar stereoanomaly test (top row) exhibited results that were very similar to the results of subject R1. The subject in panel A was able to discriminate uncrossed disparities but not crossed disparities. The subjects in panels B and C were able to discriminate crossed disparities but not the uncrossed disparities. Contrary to the above-mentioned hypothesis, none of these three subjects was able to consistently—and reliably—perceive larger depth-to-width ratios in the volumetric condition than in the planar condition (bottom row) even for disparities that s/he was able to process.(8) These results are interesting because they suggest that stereoanomaly is a deficiency that involves more than an inability to process part of the disparity spectrum. It appears therefore that to perceive volumetric depth a subject needs to be able to compare pooled activities over the crossed and uncrossed disparity ranges.

To compare the results across all thirty subjects objectively, as a measure of primary interest use is made of the depth difference between the planar and the volumetric conditions. The area (sum of differences) between the planar and the volumetric conditions (as highlighted by the gray area for subject F1 in figure 3) was determined for every subject and divided by the number of disparities that spanned the gray area (nine for most subjects). The outcome of the calculation can be regarded as the disparity component used to make the depth-to-width ratio judgment.

Figure 6 depicts the individual results for all thirty subjects. The numbers along the vertical axis of the graph represent the disparity component used to make the depth-to-width ratio judgments in the motion–disparity experiment. The numbers along the horizontal axis represent a measure of perceived depth in the stereoanomaly

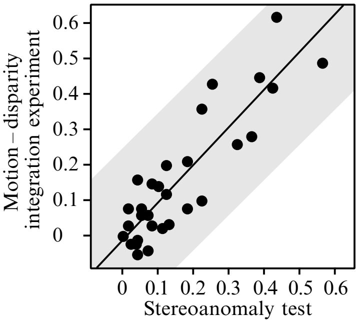

Figure 6. Correlation between the stereoanomaly test and the motion–disparity integration experiment. Each dot represents a subject. As noted in the text, this set of subjects included a higher percentage of anomalous individuals than would be found in a random sampling of the population. The data show that subjects with poor performance in distinguishing disparities of different sign and magnitude disregard disparities in the disparity–motion integration experiment. The numbers along the ordinate represent the disparity component in making the depth-to-width ratio judgment. To obtain these numbers, the area between the volumetric and planar curves (as highlighted in figure 3) was calculated and divided by the number of the presented disparities that spanned this area. The numbers along the abscissa represent a measure of perceived depth calculated by integrating depth magnitudes between -1 and 1 deg in the stereoanomaly test (as highlighted in figure 4). The solid curve shows the linear fit through the data points (with a slope of 1.07 and a correlation coefficient of 0.78).

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(8) In the various experiments conducted in our laboratory we encountered at least ten subjects who were clearly able to discriminate crossed disparities but not the uncrossed disparities, or vice versa. Generally, however, these subjects were unable to reliably perceive larger depth-to-width ratios in the volumetric condition than in the planar condition when they viewed stimuli as described in this paper, even for disparities that they were able to process.

test, calculated by adding together the depth magnitudes[9] between −1 and 1 deg (the gray area in figure 4), and dividing this sum by the number of disparities presented (nine).

Figure 6 also depicts the correlation of the data obtained in the motion – disparity integration experiment with the data obtained in the stereoanomaly test. There is a clear correlation between the results of the stereoanomaly test and the results of the motion – disparity integration experiment: Subjects who exhibited stereoanomalous behavior in the stereoanomaly test based their performance on the motion cue, but not on disparity. The solid curve in figure 6 represents a linear fit through the data points (with a slope of 1.07 and a correlation coefficient of 0.78).

3 Control observations

Two assumptions derived from the work of van Ee and Anderson (2001) underlie the study in this paper so far. The first assumption is that there is a matching problem in the bar stimulus; ie that disparity on its own (without motion) is unable to provide sufficient information for the recovery of the 3-D structure within the stimulus. The second assumption is that the results presented here cannot be explained simply by depth-cue combination (that is, combination of depth-from-motion and depth-from-disparity). According to these two assumptions there is an early interaction between motion and disparity in binocular matching of the stimuli used here. However, the assumptions could not be validated because stimulus motion was always present in the main experiment. Although van Ee and Anderson demonstrated that their binocular-matching results could not be explained solely by depth-cue combination, and although the stimuli used in the present experiment were similar to theirs, these assumptions were tested explicitly. I also assumed that subjects followed the fixation instruction; therefore I also examined the role of eye movements.

In all the control conditions, as in the conditions described previously, the disparity indicated either a plane or a volume that subtended 100 cm in depth. To examine depth-cue combination, it is vital to measure the perceived depth-to-width ratios that are produced by monocular processing of depth-from-motion. The monocular stimuli were presented in green (visible to the left eye only) and they were presented intermixed with the binocular stimuli. The additional control conditions were presented to five subjects who had shown normal depth discrimination of crossed and uncrossed disparities in the stereoanomaly test. Note that there is little point in presenting the additional control conditions to anomalous subjects, because their performance in the planar and the volumetric conditions (see figures 3 and 5) is not significantly different.[10]

In figure 7, the perceived depth-to-width ratios when bar motion was present (filled symbols), are compared to those when motion was absent (open symbols), and to those for monocular viewing (crosses). The disparity indicated either a volume (diamonds) or a plane (squares). The five subjects produced essentially identical data. Figure 7 gives the data for subject F1.

In the first control session (the left panel of figure 7) the number of bars was the same as in the main experiment (46). In fact, the data for the static condition were obtained in the same experimental session as the data for the motion condition, and they were presented randomly interleaved (note the black symbols are the same data as those presented in figure 3). The perceived depths in the volumetric-disparity

[9] In this calculation, the sign of the disparity was taken into account. For example, subject S2 in figure 4 is able to perceive depth in a reliable way from a number of disparities. However, about half of the responses are simply in the wrong direction, meaning that the aforementioned integrated area becomes almost zero. The results for this subject appear on the far left side in figure 6. The same applies to subject T2 in figure 4.

[10] In addition, previous data (van Ee and Richards 2002) indicated that stereoanomalous subjects are unable to perceive depth within static disparity-defined volumetric stimuli.

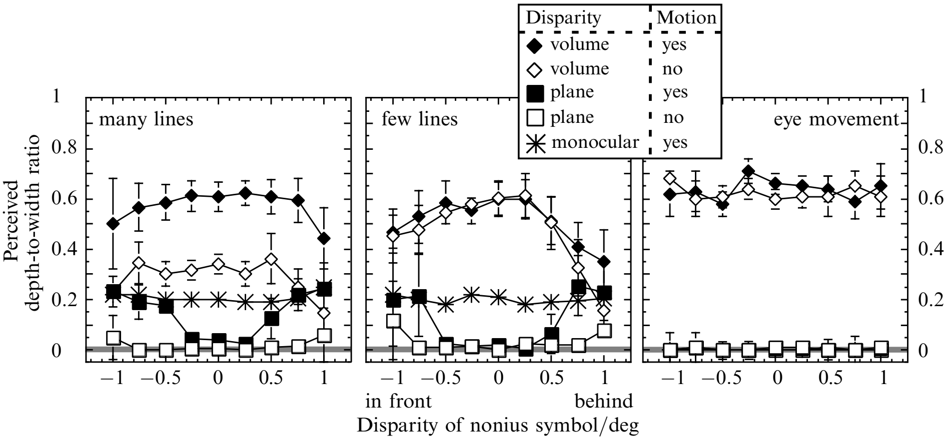

Figure 7. Control observations: roles of motion and monocular viewing. Compared are the perceived depth-to-width ratios when bar motion was present (filled symbols), when motion was absent (open symbols), and for monocular viewing (crosses). The disparity indicated either a volume (diamonds) or a plane (squares). In the left panel, 46 bars were presented; in the middle and right panels 10 bars were presented. In the left and the middle panels strict fixation was requested. In the right panel eye movements were unrestricted. Collectively, the data from the left and the middle panels show that the findings presented here cannot be due simply to depth-cue combination; a matching problem is critically involved. The data in the right panel show clear differences between the judgments for the planar and the volumetric condition and the motion signal is of little benefit. The data do not vary with the nonius disparity. The error bars denote one standard deviation across five trials. Note that the performance for zero nonius disparity does not differ significantly across the three panels when motion is present.

condition are clearly smaller without motion than with motion, indicating that motion aids perceived depth. On the assumption that motion facilitates binocular matching, one would expect the matching problem to become easier when the density of bars within the 3-D collection decreases. In the second control session the same experiment was repeated but now with only 10 bars. As in the conditions described previously, the disparity between two bars in neighboring depth planes was determined by the maximum disparity (100 cm depth) divided by the total number (10) of bars. And, as before, in the motion condition the collection of bars was presented with a gradient of motion, such that the speed decreased systematically with the depth specified by the disparity of the bar. The minimum and maximum bar speeds in this session were identical to those in the main experiment; the depth information provided by motion and disparity was therefore consistent in the volumetric condition. Note that 10 bars should be sufficient for the motion parallax cue to be effective: van Ee and Anderson demonstrated that only 2 bars are sufficient for reliably evoking depth. From the monocular data (crosses) in the left and middle panels it is clear that the motion parallax cue is equally effective for 10 and for 46 bars. The middle panel of figure 7 shows that when the number of bars is reduced from 46 to 10, the data obtained in the presence and absence of motion do become very similar.

Collectively, the data from the left and the middle panels of figure 7 show that (i) with 46 bars, motion aids image matching; and (ii) with 10 bars, matching is achieved without the aid of motion because there are fewer conflicting image matches. Motion might well have provided the same information as when there were 46 bars, but the information was not required. On the basis of depth-cue combination, one would expect the motion cue to be equally effective when either 10 or 46 bars are presented: I therefore conclude that depth-cue combination is not responsible for the findings reported here and that a matching problem is critically involved in the main experiment.

The right panel of figure 7 shows the data for a condition where subjects were instructed to make eye movements across the stimulus (again there were 10 bars and all other experimental factors were the same as in the main experiment). The data show a clear difference between the judgments for the planar and the volumetric condition, and the motion signal hardly helps to perceive depth. As one might expect, the data do not vary with the nonius disparity. The performance for zero nonius disparity does not differ significantly across the three panels when motion is present.

I was intrigued by the U-shape of the data curve for the normal subjects in the planar condition (where disparity indicated zero depth, represented by the black squares in the top panels of figure 3, and the left and middle panels in figure 7). The data indicate that perceived depth-to-width ratios increase when the collection of bars is presented off-horopter. The monocular data (crosses) show that this U-shape reflects a characteristic that is actually independent of binocular vision. The monocular curve is essentially independent of the nonius disparity. When observers fixate at larger disparities (with respect to the center of the stimulus), the data for the volumetric condition (black diamonds in figure 7) become almost identical to the data for the planar condition (black squares). Both sets of data resemble the data for the monocular motion condition. This means that the rising flanks of the U-shape reflect monocularly perceived depth engendered by the motion parallax cue.

4 General discussion

I have investigated to what extent binocular matching is facilitated by motion in both stereoanomalous and normal subjects when they are required to estimate the perceived depth of a 3-D stimulus that contains excessive binocular matching candidates. The main finding is that there is a clear correlation between the results of the stereoanomaly test and the subjects' performance in the experiment described in this paper. I have argued that these results cannot be explained solely in terms of depth-cue combination (ie a combination of depth-from-motion and depth-from-disparity, as opposed to an early interaction of disparity and motion in binocular matching). The present results, in combination with other recent findings,(11) demonstrate that results obtained with the stereoanomaly test correlate quite well with subjects' results in stereoscopic experiments.

One could say that these results reveal only what is obvious: stereoanomalous subjects make less use of disparity signals. Here, however, it is of interest to mention the commonly occurring, puzzling, and unexplained differences that occur across subjects in the results in stereoscopic experiments (eg Buckley and Frisby 1993; Frisby et al 1995; Bradshaw and Hibbard 2000; Buckley 2000). Thus, although it is not surprising that stereoanomalous subjects make less use of disparity signals, it is important to know whether there is a correlation between the results of the stereoanomaly test and disparity experiments.

It is particularly interesting to test stereoanomalous subjects in motion – disparity integration. Such subjects might be able to use motion signals to define disparities in the part of the disparity spectrum that they process normally. The results presented here, however, are described best by the hypothesis that stereoanomalous subjects rely entirely on the motion signal and disregard the disparities, even if they are able to correctly process more than half the disparity spectrum. These results suggest that

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(11) Van Ee and Richards (2002), relating to presentation duration in both planar and volumetric depth judgments; and van Ee et al (2000) on perceived 3-D-depth relief under monocular, binocular, and synoptic viewing conditions [as studied by Koenderink et al (1995)].

stereoanomaly involves more than simply being insensitive to part of the disparity spectrum. Apparently, to perceive volumetric depth—based on disparity—a subject needs to be able to compare pooled activities over the crossed and uncrossed disparity ranges.

The processing of both the magnitude and the sign of disparities is fundamental for our understanding of the cortical mechanisms that underlie our ability to recover the 3-D layout of our environment. As pointed out, it is interesting to extend the use of stereoanomaly in order to unveil processing mechanisms in stereopsis. Such an approach is not unguided, for we know that Richards has suggested that at least three separate 'pools' of neurons (crossed, uncrossed, and zero disparity neurons) underlie disparity processing (Richards 1970, 1971a). If depth from disparity is based upon the relative activities of pooled disparity signals, then the processing of stereoscopic disparity is somewhat analogous to the processing of color. Hence it is not surprising to find subjects who lack one of the pools for disparity processing. Indeed, this was the basis for Richards' original pool proposal. Many findings (Richards 1971b, 1973; Mitchell and Ware 1974; Breitmeyer et al 1975; Clarke et al 1976; Ferster 1981; Herring and Bechtoldt 1981; Birch et al 1982; Regan et al 1986; Manning et al 1987; Patterson et al 1995; Bussetini et al 1996; Kontsevich and Tyler 2000) are consistent with the separate processing of crossed and uncrossed disparities [see reviews in Mustillo (1985) and Regan et al (1990) for many more references]. It is of interest to make a distinction between the processing and the detection of disparities. Richards' pool hypothesis for *disparity processing* includes the possibility that there is a continuum of *disparity detectors*. Subjects pool many disparities—each with different spatial positions, magnitudes, and scale, but all of the same 'type'—prior to making depth judgments. Indeed there is a considerable body of findings that supports the existence of a continuum in disparity tuning (LeVay and Voigt 1988; Lehky and Sejnowski 1990; Stevenson et al 1992; Cormack et al 1993; Landers and Cormack 1997; Lee 1999).

Three previous studies are particularly relevant to the findings reported here. The first study reported that subjects are able to use both crossed and uncrossed disparities in a motion-parallax stimulus consisting of many random dots in order to recover depth (Bradshaw et al 1987). However, the subjects participating in that study were not necessarily stereoanomalous, and therefore it is not clear whether their results can be extended to stereoanomalous subjects. Another relevant study relates to the recovery of structure-from-motion in disparate stimuli that simulated wire frames constructed from at most 8 dots (Richards and Lieberman 1985). Although that study made use of stereoanomalous subjects, it did not include a matching problem. A third study that resembles the present one concerned the ability of observers to respond to constant disparity in the presence of either corresponding or conflicting motion parallax information (Rouse et al 1989). The display in that study simulated two slanted planes. The dihedral angle formed by these planes was either pointed toward or away from the subjects and their task was to indicate if the center was the nearest or the most distant part of the stimulus. In apparent contrast to current findings, the authors found that the presence of motion was sufficient to allow the stereo-deficient subjects to make accurate relative-depth judgments. For at least three reasons it is hard to compare their results with those reported here. First, stereo-deficient subjects were selected on the basis of clinical records (they were, for example, strabismic or amblyopic), but they were not tested for stereoanomaly in a test where subjects were asked to distinguish disparities of different sign and amplitude. Second, in their experiment the displays were presented for 15 s and fixation was not controlled, whereas it was in the present experiment. Third, the authors did not employ a metrical task.

Without the results of the stereoanomaly test, the results reported in this paper would not have made much sense. Stereoscopic experiments would be more valuable if subjects were first characterized with regard to their stereo capacities. For example, there is a noteworthy relationship between *fixation disparity* and stereoanomaly.(12) Fixation disparities have been extensively studied and classified by Ogle and colleagues (Ogle 1950; Ogle et al 1967). For any individual, these imbalances in fixation generally fall into one of four categories (defined and described as Type I to IV categories—Ogle 1950). Preliminary studies suggest a correlation between an observer's fixation disparity and types of stereoanomaly (Richards 1975). Furthermore, attempts have been made to discover whether stereoanomalous subjects are able to make eye movements to targets whose disparity is in the part of the disparity spectrum that is processed anomalously (Jones 1977). A number of subjects were found to exhibit anomalous vergence eye movements and "the presence of vergence-anomaly was always associated with the occurrence of stereoanomaly" (Jones 1977, page 621). Another interesting finding is that stereoanomalous subjects who were trained to discriminate between crossed and uncrossed disparities when the observation duration was unlimited, exhibited considerably reduced stereoanomaly when targets were flashed only briefly (Foley and Richards 1974). Furthermore, stereoanomaly can be specific to particular retinal locations (Richards and Regan 1973). Stereoanomalies can also be specific to the sign of luminance contrast; a number of anomalous observers who confuse either crossed 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).

Although stereoanomaly appears to be a potentially interesting condition by means of which one can study both inter-subject differences and underlying mechanisms, it has not been utilized frequently since the original test for stereoanomaly was developed. A possible reason is that stereoanomaly has been regarded (Newhouse and Uttal 1982; Patterson and Fox 1984) as a 'transient' phenomenon that shows up only when targets are presented for a short duration.(13) The results of a recent study (van Ee and Richards 2002) have shown that such statements must be qualified to make it clear that the presence or absence of eye movements can greatly influence the outcome. In the latter study it was concluded that stereoanomaly is not a 'transient' phenomenon. Another possible reason is that the original test for stereoanomaly was difficult to organize and was time-consuming (as was the case with the original color-matching procedures). The recently developed versions of the stereoanomaly test (van Ee and Richards 2002) have overcome these problems.(14)

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(12) When the two eyes converge onto a fixation point, neither eye necessarily orients the fovea directly at the target. Some observers fixate slightly behind the target, whereas others fixate slightly in front. The deviation is called fixation disparity.

(13) It has been concluded that "stereoanomalies are much rarer than has previously been suggested and deficiencies [in crossed or uncrossed disparities] are actually due to strategy or sequence effects rather than to neural deficiencies" (Newhouse and Uttal 1982, page 48). However, in Newhouse and Uttal's experiment the observation period was 2 min and eye movements were unrestricted, which enabled the subject to put a crossed stimulus in the uncrossed region (and vice versa). This means that their experiment did not test stereoanomaly. Others used afterimages in which the perceived depth of two features needed to be matched (Patterson and Fox 1984). Paterson and Fox found that 80% of the subjects characterized as stereoanomalous in a brief-exposure test showed normal stereopsis for longer exposure durations. However, a confounding factor is that in their afterimage experiment subjects could have performed the task monocularly on the basis of vertical alignment matching of the two features (instead of perceived-depth matching).

(14) The anomaly test, including software to download, can be found on the web: http://www.phys.uu.nl/~vanee

5 Conclusion

There is a clear correlation between the results of the stereoanomaly test and the results when motion and disparity interact in binocular matching. I have argued that the present results cannot be explained purely by depth-cue combination. I suggest that to perceive volumetric depth—based on disparity—a subject needs to be able to compare activities over the crossed and uncrossed disparity ranges.

Since up to 30% of the population exhibits anomalous behavior in stereoanomaly tests, stereoscopic experiments would provide us with more valuable information if subjects were first characterized with regard to their stereo capacities. Just as the use of color-blind subjects in color-vision studies has advanced our understanding of the underlying mechanisms of color processing, so the wider use of stereoanomaly is likely to give us fundamental insights into the underlying mechanisms of disparity processing.

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