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Measuring the depth induced by an opposite-luminance (but not anticorrelated) stereogram

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Abstract. The same-sign hypothesis suggests that *only* those edges in the two retinal images whose luminance gradients have the same sign, known as same-sign edges, can be stereoscopically fused to generate a perception of depth. If true, one would expect that the magnitude of the depth induced by an opposite-luminance stereogram (eg one where the figure in one stereo half-image is black and the figure in the other is white) should be determined by the disparity of the same-sign edges. Despite the considerable work on the same-sign hypothesis this prediction has yet to be verified. Here we confirm this prediction for a particular opposite-luminance stereogram and discuss possible reasons why it is not true for opposite-luminance stereograms that are presented briefly or where each stereo half-image contains many elements.

1 Introduction

Whittle (1963) has suggested that *only* those edges in the two retinal images whose luminance gradients have the same sign can be stereoscopically fused to generate a perception of depth. This is now known as the same-sign hypothesis (Cogan et al 1995) and is generally accepted as valid (for a review see Howard and Rogers 1995), providing the stereograms are not presented briefly—on the order of 150 ms (Cogan et al 1995). Figure 1a shows a schematic of an anticorrelated stereogram. Here the left eye sees a black bar, and the right eye a white bar, both on a gray background. According to the same-sign hypothesis only those edges whose luminance gradients have the same sign, referred to as same-sign edges, can be stereoscopically fused. Consequently, it is predicted that there are two possible ways to stereoscopically fuse this stereogram. Either the right edge of the black bar could fuse with the left edge of the white bar, since these are same-sign edges, to form the percept shown in figure 1b; or the left edge of the black bar could fuse with the right edge of the white bar to form the percept shown in figure 1c.

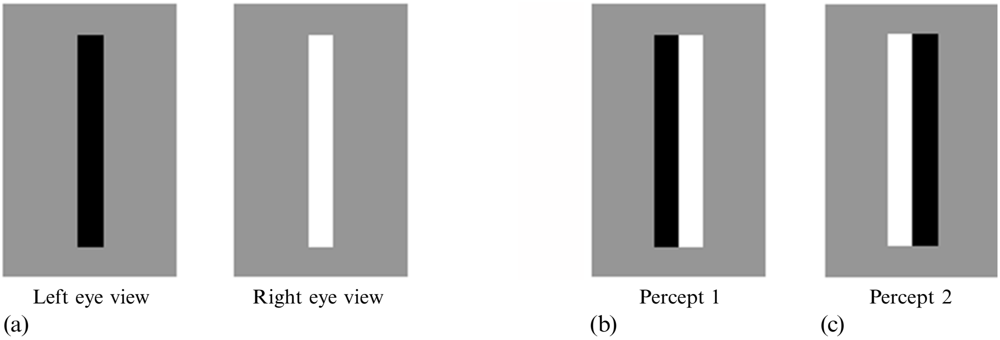

Figure 1. (a) An anticorrelated stereogram. (b) One of the percepts predicted by the same-sign hypothesis. (c) The other possible percept predicted by the same-sign hypothesis. Although this stereogram is readily fusible with a haploscope, many people find it hard to free fuse.

Initially we attempted to measure the magnitude of depth induced by an anticorrelated stereogram similar to that shown in figure 1a, which subjects viewed through a haploscope for as long as they wished. Subjects found that the perceived percept was unstable and would alternate between the two possible percepts shown in figures 1b and 1c. Consequently we found that it was impossible to make accurate measurements of the induced depth.

One way to resolve this difficulty would have been to present the stereograms briefly, so that subjects would have had time to perceive only one of the two possible percepts. However, we did not do this, since, as described further in section 5, there is evidence that the same-sign hypothesis does not apply to briefly presented stereograms (Cogan et al 1995).

Instead, we altered the stereogram so that the same-sign hypothesis would predict only a single possible percept. We did this by converting the bars in figure 1a into ellipse halves, as shown in figure 2a. The left eye saw the left half of a black ellipse, and the right eye the right half of a white ellipse. Figure 2b shows the single percept predicted by the same-sign hypothesis.

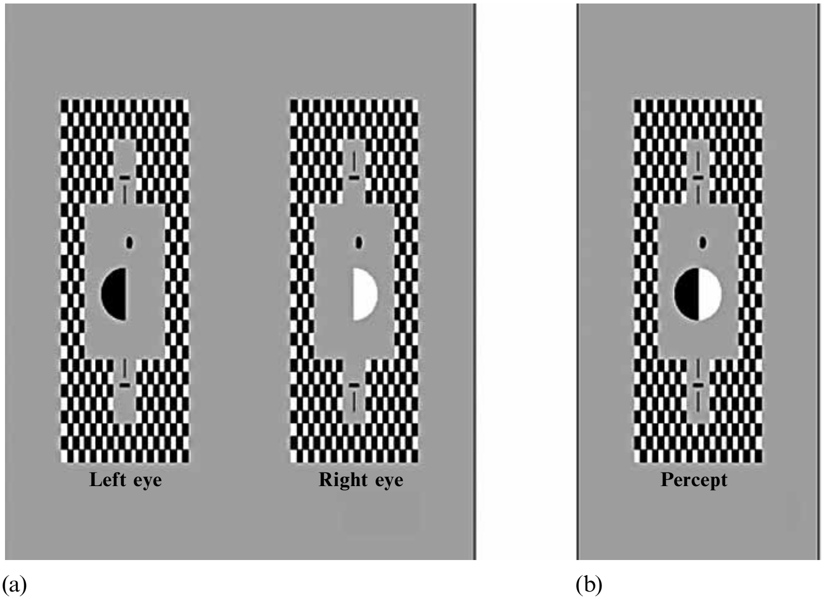

Figure 2. (a) The stimulus shown to the subjects in the first experiment. The left and right eyes are presented with ellipse halves of opposite luminance-polarity—one is black and the other is white—the vertical edges of which have luminance gradients of the same sign. (b) The percept predicted by the same-sign hypothesis. In particular, it is predicted that the magnitude of the perceived depth of the ellipse should be determined by the disparity of the vertical edges of the two ellipse halves.

It should be stressed that the stereogram shown in figure 2a cannot be described as anticorrelated, since the ellipse halves in the two stereo half-images are not identical in shape, being mirror images of each other. To stress this fact, we describe this stereogram as opposite-luminance as this term does not necessarily imply anticorrelation, even though anticorrelated stereograms are generally also opposite-luminance (but not always; see Albert and Nakayama 2002).

It would seem to follow from the same-sign hypothesis that the amount of depth induced by this stereogram should be determined by the disparity of the fused same-sign edges. However, it should be noted that, other than the fused edges, the rest of the ellipse halves are seen monocularly. Furthermore, it is well known that monocular objects tend to be perceived to lie in the fixation plane (Krol and van de Grind 1983). There might therefore be a conflict between these two opposing tendencies, and so the degree of depth induced by the stereogram shown in figure 2 might be less than that predicted on the basis of the disparity of the fused same-sign edges. Despite the large number of studies on the same-sign hypothesis (Helmholtz 1909/1962; Treisman 1962; Kaufman and Pitblado 1965, 1969; Levy and Lawson 1978; Krol and van de Grind 1983) this issue had yet to be addressed and so was the focus of our study.

2 Experiment 1

2.1 *Apparatus and stimuli*

Stimuli were generated by a Matlab™ routine and displayed on a 19-inch SuperScan Mc 801 RasterOps monitor at a setting of 1920 × 1080 pixels with a refresh rate of 75 Hz. They were viewed in a darkened room through a mirror-type haploscope at a distance of 85.8 cm. The subject's left eye was presented with the left half of a black ellipse and the right eye with the right half of a white ellipse, the two ellipse halves therefore having opposite luminance. The background for both was mid-gray. A dot, which functioned as a test probe, was placed above the ellipse halves at a position that was randomized between trials. Both ellipse halves were surrounded by a checkerboard frame which subjects found easy to fuse and which defined the plane of zero disparity. The stimulus is shown in figure 2a and had the following dimensions: the checkerboard frame was 7.1 deg wide by 3.4 deg high, each check subtending 19.4 min of arc × 7.3 min of arc, each ellipse half 2.1 deg × 1.2 deg; the circular test probe had a radius of 6.7 min of arc, and the nonius lines were 1.0 min of arc wide. Subjects reported that it was very easy to notice any misalignment of the nonius lines that was equal to or greater than their width. Following the example of Nakayama and Shimojo (1990), we consequently estimated that fixation was maintained to within the width of the nonius lines (ie to within 1.0 min of arc). The luminances of the white, gray, and black areas of the display were 70.2 cd m^{-2}, 24.3 cd m^{-2}, and < 0.5 cd m^{-2}, respectively.

2.2 *Procedure*

Each ellipse half had a single vertical edge whose luminance increased from left to right. The same-sign hypothesis predicts that subjects can stereoscopically fuse these same-sign edges to produce a perception of depth. To verify this, we asked four subjects to adjust the depth of a probe to match the perceived depth of the bicolor ellipse using the conventional staircase method. According to this method, the subject would repeatedly indicate whether the test probe (the dots above the ellipse) was closer or further away than the ellipse. The computer would then alter the depth of the probe in the perceived direction of the ellipse by a predetermined step size. Every time the subject perceived the probe to have gone past the ellipse (which was indicated by the subject giving an opposite response to that given immediately previously), the step size (which was initially 3.9 min of arc) would automatically be decreased by 40%, ensuring that the test probe rapidly converged to the depth of the ellipse. After six of these passings, the trial was terminated and the computer estimated the perceived depth of the ellipse as the average of the disparity at which the previous two passings had occurred. Each trial lasted approximately 2 min during which time the stimuli were viewed continuously.

In this article, the term 'ellipse disparity' is used to refer to the disparity of the vertical edges of the two ellipse halves. The perceived depth was estimated at least twice for each ellipse disparity, once with the probe starting much closer than the ellipse and once with the probe starting much further away. For each subject, the perceived depth for seven ellipse disparities was measured, resulting in at least 14 (and sometimes 28) measurements. In addition to this, the subject practiced estimating the depth for 4 ellipse disparities before data were collected.

2.3 *Subjects*

Four subjects (three male and one female) participated in the first experiment having given informed consent. All were experienced stereoscopic observers and had either normal or corrected-to-normal vision. Two were the authors (TW and PH) and the other two were naïve as to the purposes of the experiment (AH and IM).

2.4 *Results*

All subjects reported seeing a complete ellipse as depicted in figure 2b. Curiously, one of the reviewers of this article reported that when he/she fused the stereogram he/she perceived the ellipse to be bent with the monocularly viewed edges appearing to lie nearer the fixation plane. However, in the experimental stimulus setting described in section 2.1, all the subjects perceived the ellipse to be flat with the monocularly viewed edges of the two ellipse halves being seen at the same depth as the binocularly viewed vertical edge, consistent with Gogel's (1965) findings. The results for all four subjects are shown in figure 3, with the crosses indicating the perceived depth of the ellipse and the lines indicating the expected position of these data if stereoscopic matching of the vertical edges of the ellipse halves occurred. For these graphs, the term 'perceived disparity' means the disparity of the test probe when it was perceived to lie at the same depth as the ellipse. Since virtually all data points are well described by the straight lines (to within the estimated fixation error), we can conclude that the same-sign hypothesis can accurately account for the magnitude of the depth perceived in this opposite-luminance stereogram.

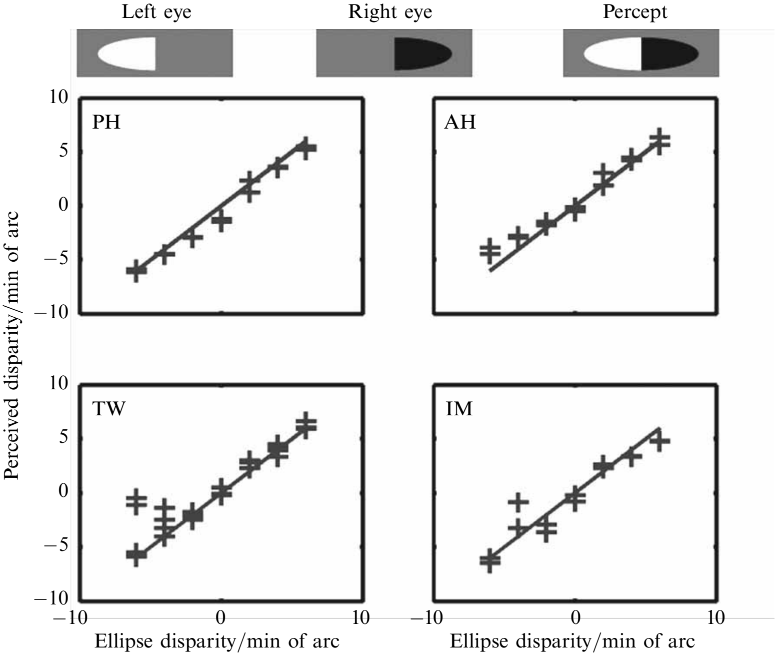

Figure 3. The results from experiment 1 in which the luminance gradients of the vertical edges had the same sign, even though the ellipse halves had opposite luminances. The crosses denote the subject's data and the straight lines the expected position of these data if stereoscopic fusion of the vertical edges of the ellipse halves occurred, which is what the same-sign hypothesis predicts in this case. The data for all four subjects are well described by the straight lines, indicating that the same-sign hypothesis can account for these data.

3 Experiment 2

Experiment 2 used the same apparatus and procedure as experiment 1 but was designed to further test the same-sign hypothesis by investigating whether, for a same luminance-polarity (but not correlated) stereogram, edges whose luminance gradients have opposite sign can be stereoscopically fused. This time the background was white, and the ellipse halves were black and gray with luminances of 70.2 cd m^{-2}, < 0.5 cd m^{-2}, and 24.3 cd m^{-2}, respectively. The vertical edges of these ellipse halves therefore had luminance gradients of opposite sign, so the same-sign hypothesis would predict their stereoscopic fusion to be impossible. Three subjects from the previous experiment participated (IM, PH, TW) and a fourth subject (SK), who was an experienced male stereoscopic observer and had normal vision, gave informed consent and was naïve as to the purposes of the study.

On fusing this stereogram, a reviewer of the article experienced a tendency for the edges whose luminance gradients have opposite sign to repel each other and in doing so alter his/her fixation. It therefore needs to be stressed that in this experiment, and also in the other two experiments, subjects made depth judgments only when the nonius lines were aligned. This ensured that fixation was maintained to within the width of the nonius lines (ie to within 1.0 min of arc; Nakayama and Shimojo 1990). Figure 4 shows the results for the four subjects. Clearly, the data are not well described by the straight lines, confirming the prediction of the same-sign hypothesis that stereoscopic depth perception is impossible in this case.

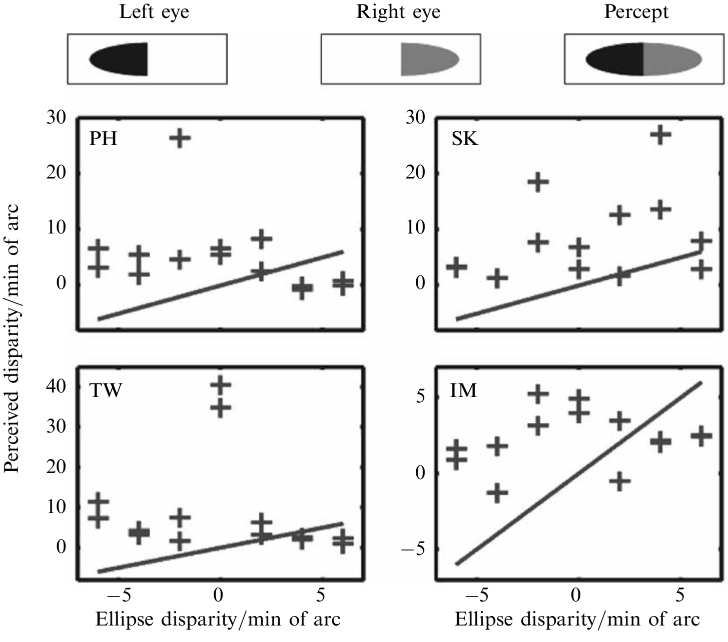

Figure 4. The results from experiment 2 in which the luminance gradients of the vertical edges did not have the same sign, even though the ellipse halves themselves had the same luminance polarity. The data for all four subjects are not well described by the straight lines, indicating that stereoscopic fusion of the vertical edges of the ellipse halves did not occur, which is in accord with the same-sign hypothesis.

4 Experiment 3

The third experiment used the same stimuli as the first, except that now both ellipse halves were black. The vertical edges of these ellipse halves therefore had luminance gradients of opposite sign but now the *magnitude* of the contrast of each edge was

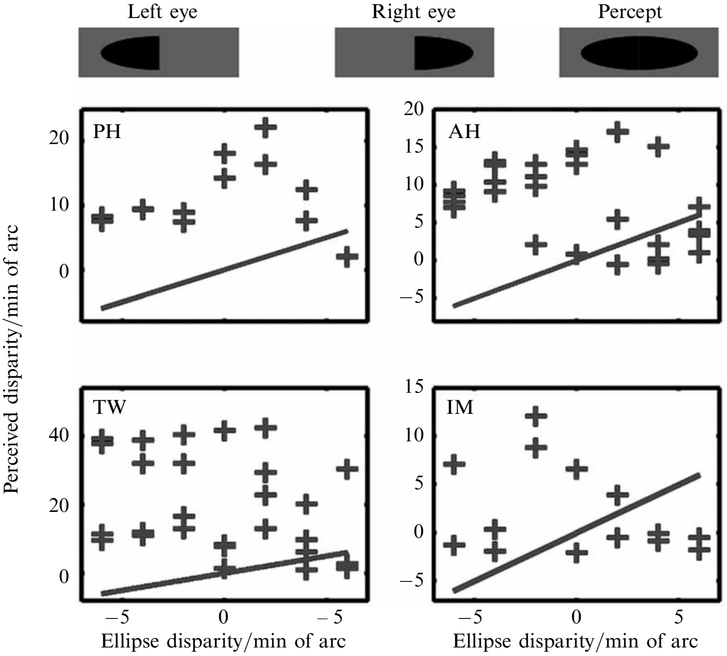

Figure 5. The results from experiment 3 in which, as in experiment 2, the luminance gradients of the vertical edges of the ellipse halves did not have the same sign. Now, however, the magnitudes of their contrasts are the same. The data for all four subjects are still not well described by the straight lines, indicating that, in agreement with the same-sign hypothesis, stereoscopic fusion of the vertical edges of the ellipse halves still did not occur.

the same. The four subjects from the first experiment participated. Again, the data are clearly not well described by the straight lines, confirming the prediction of the same-sign hypothesis that stereoscopic fusion is impossible in this case (figure 5).

5 Discussion

These three experiments have demonstrated that, consistent with the same-sign hypothesis, for the stereograms considered in this study, stereoscopic fusion was possible only when the luminance gradients of the vertical edges in the two stereo half-images had the same sign. Furthermore, in the case that stereoscopic fusion was possible, the magnitude of the induced depth was well described by the disparity of the fused same-sign vertical edges.

It should be stressed that the above results do not appear to apply to anticorrelated stereograms that are presented transiently on the order of 150 ms (Cogan et al 1995; for related studies see Cumming et al 1998; Pope et al 1999). A reason for this was suggested by Pope et al (1999), who proposed that there are two stereopsis systems, one responding preferentially to transient stimuli and the other preferentially to sustained stimuli, and that the transient system does not obey the same-sign hypothesis, being able to fuse edges whose luminance gradients have opposite sign.

It should also be noted that complex anticorrelated stereograms (ie those where each stereo half-image contains many elements), even when they are presented for long or short durations, do not induce the degree of depth that would be expected on the basis of their disparity (Julesz 1971; Howard and Rogers 1995). This might be because complex stereograms cause false matches, where in the context of an anticorrelated stereogram a false match is considered to be the fusion of same-sign edges that correspond to different objects. Although the visual system seems to be able to suppress false matches that arise in complex correlated stereograms, Cumming et al (1998) proposed that the visual system might not be able to suppress those false matches that arise in complex anticorrelated stereograms.

For the opposite-luminance stereograms employed in this study, each stereo half-image contained only a single vertical edge. There was therefore no possibility of a false match. The suggestion of Cumming et al (1998) is therefore consistent with our observations that, for the stereograms considered in this study, the magnitude of the induced depth is determined by the disparity of the same-sign edges.

In summary, this investigation has presented what we believe to be the first example of an opposite-luminance stereogram for which it was shown that the magnitude of the perceived depth was determined by the disparity of the same-sign edges, a prediction that follows from the same-sign hypothesis and is known not to be true for anticorrelated stereograms that are complex or presented transiently.

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