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Measuring the depth perception invoked by a simple, sustained, polarity-reversed 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 can be stereoscopically fused to generate a perception of depth. If true, one would expect that the magnitude of the depth induced by a polarity-reversed stereogram (i.e. one where the corresponding figures in the two stereo half images have opposite luminance polarity) should be determined by the disparity of the same-sign edges. Here we present a simple, sustained, polarity-reversed stereogram which we believe to be the first example of a polarity-reversed stereogram where this prediction is shown to be true. We conclude by discussing possible reasons why this prediction fails for other polarity-reversed stereograms.

Key words: Depth perception Stereopsis Polarity-reversed stereogram Same-sign hypothesis

I. 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 conventional stereograms. However, previous investigations have indicated that the depth perception induced by transient polarity-reversed stereograms, where the corresponding figures in the two stereo half images have opposite luminance polarity, cannot be accounted for by the stereoscopic fusion of same-sign edges. This indicates that the same-sign hypothesis cannot be applied to such stereograms (Cogan et al 1995, for related studies see Cumming et al 1998; Pope et al 1999).

It also appears that the same-sign hypothesis does not apply to polarity-reversed stereograms that are sustained but complex i.e. those where each stereo half image contains a large number of potentially fusible edges. In particular, the same-sign hypothesis cannot explain why such stereograms produce little or no depth perception (Julesz 1971; Howard and Rogers 1995) as in such cases the hypothesis would appear to predict that a strong sensation of depth should arise from the stereoscopic fusion of same-sign edges.

Previous investigations as to whether the same-sign hypothesis applies to sustained polarity-reversed stereograms that are simple (Helmholz 1909; Treisman 1962; Kaufman and Pitblado 1965; Kaufman and Pitblado 1969; Levy and Lawson, 1978; Krol and van de Grind 1983) are conflicting but do not appear to disprove it (for a review see Howard and Rogers 1995). However, none of them tried to ascertain whether for such stereograms the magnitude of the perceived depth was determined by the disparity of the same-sign edges. This prediction follows from the same-sign hypothesis and, for the reasons mentioned above, is known not to be true for polarity-reversed stereograms that are either transient or complex.
Testing this prediction for a particular simple, sustained, polarity-reversed stereogram was the main purpose of this investigation.

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 by 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 Fig. 1a and the dimensions are as follows: the checkerboard frame was 7.1° wide by 3.4° high, each check subtending 19.4 by 7.3 arcmin, each ellipse half 2.1° by 1.2°; the circular test probe had a radius of 6.7 arcmin and the nonius lines were 1.0 arcmin wide. Subjects reported that it was 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 estimated that fixation was maintained to within the width of the nonius lines (i.e. to within 1.0 arcmin). The luminances of the white, gray and black areas of the display were 70.2 cd/m², 24.3 cd/m² and <0.5 cd/m² respectively.

Fig. 1. (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 perceived depth of the ellipse should be determined by the disparity of the vertical edges of the two ellipse halves.
2.2. Procedure

Each ellipse half had a single vertical edge whose contrast polarity, reading from left to right, was dark-to-light. The same-sign hypothesis would predict that since the two vertical edges had the same contrast polarity (i.e. their luminance gradients had the same sign) the subjects can fuse them to see an edge in depth. It has previously been reported that a monocularly viewed object tends to be perceived at the depth of the nearest binocularly viewed object (Gogel 1965). We would therefore expect the non-vertical edges of the ellipse halves, being perceived monocularly, to be perceived at the depth of the stereoscopically fused vertical edge. Consequently, we would predict subjects to report a flat, complete bicolor ellipse at a depth determined by the disparity of the vertical edges of the two ellipse halves. 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 dot 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 pre-determined 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 arcmin) 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 disparity at which the previous two passings had occurred. Each trial lasted approximately two minutes during which time the stimuli were viewed continuously.

![Fig. 2](image-url)  
Fig. 2. 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 luminance polarity. The crosses denote the subject's data and the straight lines the expected position of this 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 this data.
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 probe starting much further away. For each subject the perceived depth for seven ellipse disparities was measured resulting in at least fourteen (and sometimes twenty-eight) measurements. In addition to this the subject practiced estimating the depth for four ellipse disparities before data was collected.

2.2. 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 (T.W. and P.H.) and the other two were naïve as to the purposes of the experiment (A.H. and I.M.).

![Fig. 3](image1.jpg)

**Fig. 3.** 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 describe 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.

2.3. Results
All subjects reported seeing a flat, complete ellipse as depicted in Figure 1b i.e. the monocularly-viewed edges of the two ellipse halves were seen at the same depth as the binocularly-viewed vertical edge consistent with Gogel (1965). The results for all four subjects are shown in Fig. 2 with the crosses indicating the perceived depth of the ellipse and the lines indicating the expected position of this 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 polarity-reversed stereogram.

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 this type of stereogram edges of opposite contrast polarity can be matched. This time the background was white and the ellipse halves were black and gray with luminances of 70.2 cd/m², <0.5 cd/m² and 24.3 cd/m² respectively. The vertical edges of these ellipse halves therefore had opposite contrast polarity so the same-sign hypothesis would predict their stereoscopic fusion to be impossible. Three subjects from the previous experiment participated (I.M., P.H., T.W.) and a fourth subject (S.K.) who was an experienced male stereoscopic observer, had normal vision, gave informed consent and was naïve as to the purposes of the study. Figure 3 shows the results for the four subjects. Clearly the data is not well described by the straight lines, confirming the prediction of the same-sign hypothesis that stereoscopic fusion is impossible in this case.

![Graphs showing percept disparity vs. ellipse disparity for Experiment 2 subjects PH, AH, TW, IM.](image)

Fig. 4. 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 magnitude 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.

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 opposite contrast polarity but now the magnitude of the contrast of each edge was the same. The four subjects from the first experiment participated. Again, the data is clearly not well
described by the straight lines, confirming the prediction of the same-sign hypothesis that stereoscopic fusion is impossible in this case (Fig. 4).

5. Discussion

These three experiments have demonstrated that, for the polarity-reversed 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 and, in the case that stereoscopic fusion was possible, the magnitude of the induced depth was determined by the disparity of these same-sign vertical edges. Both results are consistent with the same-sign hypothesis. There seem to be two possible reasons why the same-sign hypothesis is not applicable to most other polarity-reversed stereograms.

First, Pope et al (1999) 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. This would explain why the same-sign hypothesis cannot be applied to polarity-reversed stereograms that are presented transiently (Cogan et al 1995, for related studies see Cumming et al 1998; Pope et al 1999), while also being compatible with our observation that the same-sign hypothesis is applicable to those that are both simple and sustained.

Second, we note that complex stereograms may cause false matches, where in the context of polarity-reversed stereograms 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 conventional (i.e. polarity-not-reversed) complex stereograms, Cumming et al (1998) proposed that the visual system might not be able to suppress those false matches that arise in complex stereograms that are polarity-reversed. Such a failure might be the cause of the reduced depth perception in complex, sustained, polarity-reversed stereograms that is reported (Julesz 1971; Howard and Rogers 1995).

For the polarity-reversed 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 same-sign hypothesis is applicable.

In summary, this investigation has presented what we believe to be the first example of a polarity-reversed 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 polarity-reversed stereograms that are complex or transient.

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