Vertical disparity detection: is there an induced size effect?

Gerald Westheimer

Horizontal, vertical, and over-all size differences were introduced in the retinal images of the two eyes of normal subjects during brief presentations of simple foveal targets. Horizontal disparities, whether accompanied by vertical disparities or not, induced the appearance of a rotation of the target around a vertical axis out of the frontal plane, according to the expectation from geometry, but vertical disparities had no effect. Over-all size changes in one eye induced the effect of the horizontal component. Threshold experiments showed that even with practice and error feedback, vertical disparity detection has at most only one-tenth the sensitivity of horizontal disparity detection. Although at variance with findings on the induced size effect obtained under more complex observation conditions, these results confirm that the processing of horizontal disparity plays a special role in the integration of the signals coming from the two eyes.

Key words: disparity, induced size effect, stereoscopic vision

In the 1930's Ogle described a new binocular phenomenon which he termed the "induced size effect." It had its origin in the influence of small interocular differences of spectacle lens magnification on stereoscopic space perception, a subject which under the name of "aniseikonia" enjoyed some popularity a generation ago.

Basic to the effect is the well-understood relationship between differences in the horizontal retinal images in the two eyes and the apparent tilt of targets out of a frontoparallel plane. If two vertical lines are shown with different horizontal separations for the two eyes, i.e., if they have a different retinal disparity, one of the lines will be seen farther from the observer than the other (Fig. 1). The phenomenon is in full accord with the geometrical basis of stereoscopic space perception and has been termed the "geometrical size effect." Specifically, when horizontal magnification is introduced in the left image, the left line is seen farther away.

Ogle used more complicated targets than just lines and also employed a method of measurement in which the observer nulled out the apparent tilt of a plane target by rotating it around a vertical axis to make it appear frontoparallel. Measurements agreed with the geometrical predictions.

Now Ogle placed an optical device before one eye which magnified only in the vertical meridian. (This might happen if a patient wore a + cylinder spectacle lens axis 180 before the right eye and none before the left,
and indeed Ogle's interest in the subject was sparked by publications of early American ophthalmologists on space perception side effects of prescribing such lenses.) Strangely, vertical magnification seemed to induce a horizontal change, i.e., an apparent tilt of a frontoparallel target around a vertical axis, but now in the opposite direction from that in horizontal magnification: vertical magnification in one eye mimicked horizontal meridional magnification in the other eye. Specifically, vertical magnification in the left eye made the left edge of the target appear nearer than the right. This is the induced size effect.

In addition, Ogle reported that an over-all magnification of one eye had no effect on the apparent tilt of a frontoparallel target; it was as if the geometrical size effect due to the horizontal magnification, which has a legitimate basis in the physiology of stereoscopic space perception, were canceled by the induced size effect.

For animals with horizontal eye separations, only horizontal disparities are useful as depth cues. That the direction of vertical disparities can be discriminated, whatever the manifestation of this discrimination, runs counter to many experiments on stereoscopic vision, going back to Hering. Ogle's psychophysical results, however, have generally withstood the test of time; those on the induced size effect are particularly thoroughly documented. Although ignored by researchers in the field of binocular vision, the induced size effect with its implication of a mechanism for detection of vertical disparity might be a significant pointer for the ongoing search for the physiological basis of binocular space perception. It is here subjected therefore to an analysis more in line with the abstract geometrical approach that constitutes one (though not the only) tradition in binocular vision research. The separation of simple geometrical parallax concepts from the many and varied other influences on human space perception seems an essential analytical approach, but one which Ogle did not carry through completely in his studies on the induced size effect. It was done more rigorously in the experiments described here with, as will be seen, different results.

**Methods**

Patterns with differing horizontal and vertical disparities were created under computer control on two Tektronix 602 display units with P4 phosphor. There was a screen for each eye, and the two were seen superimposed by a beam splitter; the complete separation of the two eyes was accomplished by suitable high-quality polaroid filters before the screen and the eyes. The patterns were made of dots, generally 1 min of arc apart. At the observation distance of 2.5 m, each dot subtended somewhat less than 0.5 min of arc at the eye, but placement of dots could be controlled in units of 2 sec of arc. The pattern was white, of medium photopic luminance (equivalent to about 10 millilamberts) seen against a dark background. A presentation, lasting 500 msec, was given every few seconds, and the subject had to make a binary decision. No feedback was given. In the intervals between presentations, the subject saw a square of 40 min of arc side length outlined by its four corners, in the center of which the pattern appeared. Runs of about 250 presentations constituted a session. When results are given as percentage of yes
Table I. Percent yes responses to forced-choice question “Does the right edge of the target appear farther to you than the left edge?” for binocular observation of target I in Fig. 2a

<table>
<thead>
<tr>
<th>Subject</th>
<th>Larger vertically</th>
<th>Smaller vertically</th>
<th>Larger over-all</th>
<th>Smaller over-all</th>
<th>Larger horizontal</th>
<th>Smaller horizontal</th>
<th>Equal</th>
</tr>
</thead>
<tbody>
<tr>
<td>G. W.</td>
<td>54.6</td>
<td>44.7</td>
<td>3.2</td>
<td>97.8</td>
<td>3.4</td>
<td>93.5</td>
<td>34.1</td>
</tr>
<tr>
<td>B. J.</td>
<td>54.6</td>
<td>36.1</td>
<td>3.6</td>
<td>89.8</td>
<td>5.8</td>
<td>93.0</td>
<td>29.5</td>
</tr>
<tr>
<td>M. H.</td>
<td>53.9</td>
<td>22.5</td>
<td>16.1</td>
<td>81.8</td>
<td>18.9</td>
<td>90.3</td>
<td>60.6</td>
</tr>
</tbody>
</table>

*Percentages are based on at least 100 responses in each case.

Table II. Percent yes responses to forced-choice question “Does the right edge of the target appear farther to you than the left edge?” for binocular observation of target II in Fig. 2a

<table>
<thead>
<tr>
<th>Subject</th>
<th>Larger vertically</th>
<th>Smaller vertically</th>
<th>Larger over-all</th>
<th>Smaller over-all</th>
<th>Larger horizontal</th>
<th>Smaller horizontal</th>
<th>Equal</th>
</tr>
</thead>
<tbody>
<tr>
<td>G. W.</td>
<td>38.2</td>
<td>51.5</td>
<td>0</td>
<td>99.3</td>
<td>1.6</td>
<td>96.9</td>
<td>44.7</td>
</tr>
<tr>
<td>B. J.</td>
<td>78.7</td>
<td>60.1</td>
<td>1.8</td>
<td>98.8</td>
<td>0</td>
<td>98.1</td>
<td>64.4</td>
</tr>
<tr>
<td>M. H.</td>
<td>50.0</td>
<td>50.4</td>
<td>5.6</td>
<td>93.9</td>
<td>5.3</td>
<td>97.4</td>
<td>56.9</td>
</tr>
</tbody>
</table>

*Percentages are based on at least 100 responses in each case.

responses, they are based on at least 100 responses for each data point for each subject. When thresholds are given, each value here presented is based on probit analysis of between 300 and 500 responses, which also allows the computation of the standard error of the mean. Although most experiments were conducted in a dimly-lit room, all results held up when the room was completely dark and the patterns free of any visual context.

The author and two students served as subjects, and salient features were also replicated on two other experienced psychophysical subjects. Observation was binocular with natural pupils, with optimal correction of any refractive error.

Results

All experiments tested the effects of vertical and horizontal disparities on the apparent tilt of a pattern out of the frontoparallel plane around a vertical axis.

In the first experiment, the right eye was always shown a square of 24 min of arc side length. Simultaneously, the left eye was shown, randomly interspersed, one of the following patterns:

1. Rectangle 24 min wide, 25 min high; 4.1% vertical disparity (L > R)
2. Rectangle 24 min wide, 23 min high; 4.1% vertical disparity (R > L)

The percentage of yes responses to the forced-choice question “Did the right edge of the pattern appear farther than the left?” are given in Table I. They are based on about 100 responses each and hence have a standard error of at most 5 percentage points.

The horizontal changes, introducing as they do crossed and uncrossed disparity differences, led to the expected stereoscopic spatial effects which manifested themselves by an apparent tilt of the square around a vertical axis, away from the observer on the side of the eye with the larger image. The “equal” condition indicated some observer bias, but the strength of the stereoscopic stimulation was such that it gave on the order of 90% correct responses.

Contrary to Ogle’s finding on the induced
size effect, however, there was no reversed effect for vertical disparities. They did not seem to be able to be distinguished from each other or from the equal condition, at least as far as their effect on apparent tilt of a pattern around a vertical axis is concerned. Finally, over-all change in pattern size in one eye led in these experiments to the spatial effect expected from the horizontal disparity component. The vertical disparity had no effect and certainly did not counteract the effect of the horizontal disparity.

The horizontal disparity of 1 min of arc was nearly 10 times threshold for observers G. W. and B. J., but the responses seemed to show more errors than would be expected. This seems to have its origin in the fact that there were horizontal lines connecting the two vertical bars whose disparities furnished the clue for the psychophysical response. The experiment was therefore repeated with a pattern which, although retaining all the features necessary for the detection task, maintained a clear separation of the two features whose relative distance from the observer had to be determined.

In the experiment whose results are shown in Table II, the right eye always saw a pair of parallel vertical lines, 24 min of arc high, separated by 24 min of arc. At the top and bottom of each line was a horizontal cross bar, 8 min of arc long, which constituted a clear feature for any detection of vertical disparity. The left eye saw a similar target, except that the height and/or separation of the two vertical lines was changed in a manner identical to that shown in the list above. That is, seven conditions were randomly interspersed: vertical, over-all and horizontal increases and decreases, respectively, in the size of the left eye’s pattern, and equality. Table II shows results that are similar to those in Table I and even more conclusive. Horizontal disparity led to the expected geometrical space effect; over-all disparity showed up by its horizontal component only; vertical disparity alone did not manifest itself significantly in a horizontal tilt, nor was there a consistent ability to distinguish vertical magnification from minification.

These results, verified on two other observers, leave no doubt that under the conditions here tested there is no induced size effect, i.e., no influence of vertical disparity on stereoscopic space change induced by horizontal retinal disparities. The tests were carried out with a 4.1% difference between the two eyes, in the middle of the range that Ogle found to be operative for the induced size effect. Such preliminary tests as I carried out do not show the above time, luminance, size, and disparity parameters to be critical variables in this demonstration of lack of vertical disparity effects.

The experiments so far described were designed to ascertain the responses for fixed horizontal, vertical, and over-all disparity. The stimulus parameters were chosen for optimal display of the effects of pure retinal disparity, with as little influence of other perceptual factors as could be arranged. Under these conditions, horizontal disparity manifests itself strongly, but vertical disparity does not. The 4.1% size change, 1 min of arc disparity, is well above the threshold, but it may be that vertical disparity needs to be larger than 1 min of arc to manifest itself. For this reason, two experiments were designed that allowed the determination of vertical and horizontal disparity thresholds as they relate to the apparent tilt of a simple geometrical pattern.

In the first of these threshold experiments, the right eye was shown three vertical lines 30 min of arc long and 20 min of arc apart. Two short horizontal lines, 8 min of arc long, crossed the middle vertical lines, and these were separated vertically by 20 min of arc. The other eye saw the same pattern with one of two changes: (1) with the vertical dimension of all features of the pattern randomly 0, 5.3%, 10.7%, or 16% larger or smaller or (2) with the horizontal separation of the three
Fig. 2. Patterns used in the four experiments, whose results are shown in Tables I to IV, drawn to scale. I, Square, 24 min of arc side length. Left eye's pattern was increased or decreased in vertical dimension, horizontal dimension, or both. II, Two I beams, 24 min of arc high and 24 min of arc apart. Cross bars each 8 min of arc wide. Left eye's pattern was increased or decreased in vertical dimension, horizontal dimension, or both. III, Pattern modeled after Ogle's horopter apparatus. Three vertical lines 20 min of arc apart and 30 min of arc high. Center line had two cross bars 8 min of arc long and vertically separated by 20 min of arc. Left eye's pattern was increased or decreased in either vertical dimension, or horizontal separation of three lines. Both changes were used in method of constant stimuli to measure threshold of disparity detection in horizontal and vertical directions. IV, Pattern that is fully symmetrical in horizontal and vertical dimension and in which symmetrical changes were made in the two eyes for measurement of threshold of disparity. Outline of pattern is 26 min of arc, individual lines are always 8 min vertical lines randomly 0, 6, 12, or 18 sec of arc wider or narrower. These two conditions, vertical magnification and horizontal disparity, were run together in a randomly interdigitated fashion, without error feedback. The subject's task was simply to judge whether the pattern appeared tilted toward him on the right side or not. According to the standard geometry of binocular parallax (Fig. 1), an increase in horizontal separation of the vertical lines in the right eye will cause the pattern to appear tilted away from, and a reduction toward, the observer's right. By fitting the psychometric function (proportion of yes responses vs. disparity) with a probit, a threshold disparity can be defined as half the disparity extent between 25% and 75% yes responses.

The target was patterned after one described by Ogle: a horopter apparatus, i.e., vertical rods which are moved back and forth to make them appear in a frontoparallel plane, and a fixation rod on which beads are arranged with vertical separation of about 0.5 degree. According to Ogle (ref. 2, p. 196), this arrangement will also demonstrate the induced size effect; that is, vertical magnification of the right eye will mimic horizontal minification of the same eye in the sense of making a frontoparallel plane appear tilted away at the left.

Table III gives the results of threshold disparity (magnification) for a response of an apparent target tilt. This was seen to be 10 sec of arc disparity or less, which for a base distance of 20 min of arc, is less than 1%. Under identical conditions, even a 20% difference in vertical dimension of the target did not yield a reliable indication of an induced horizontal change.

The target in the above experiment has the disadvantage of not presenting a configuration that is symmetrical for horizontal and vertical size changes. To obviate this possible objection, threshold vertical and horizontal
Table IV. Disparity threshold (sec of arc) for target IV in Fig. 2, with apparent rotation of pattern around a vertical axis used as criterion

<table>
<thead>
<tr>
<th>Subject</th>
<th>Horizontal disparity (sec of arc)</th>
<th>Vertical disparity* (sec of arc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G. W.</td>
<td>28.7 ± 2.3</td>
<td>-182 ± 107</td>
</tr>
<tr>
<td>B. J.</td>
<td>22.1 ± 1.5</td>
<td>-452 ± 3670</td>
</tr>
<tr>
<td>M. H.</td>
<td>29.8 ± 3.0</td>
<td>-559 ± 977</td>
</tr>
</tbody>
</table>

*Negative values for vertical disparity signify that vertical magnification of left eye gives appearance of rotation away from subject at right. The values are, however, not significantly different from zero and indicate insensitivity to changes in this variable.

disparities were obtained with target IV illustrated in Fig. 2—four corner brackets made of lines 8 min of arc long, outlining a square 26 min of arc in side length. Two conditions were run randomly interspersed: (1) increase in horizontal separation of brackets of one eye coupled with a decrease in the other eye by -24, -16, -8, 0, +8, +16, or +24 sec of arc, i.e., 0, 16, 32, or 48 sec of arc crossed or uncrossed disparity difference between the right and left eyes' set of brackets; and (2) similar changes in vertical dimensions with a somewhat larger module of change (0, 19.2, 38.4, or 57.6 sec of arc vertical disparity, right eye larger and left eye smaller, or vice versa).

A pattern belonging at random to one of the two ensembles was presented every 3 sec, and the subject had to make a response to the question “Does the right set of brackets appear to be nearer to you than the left?” but there was no feedback to confirm the correctness of the response. By the method of probits, threshold disparities were determined, and they are shown in Table IV. Horizontal disparities gave the appearance of tilt expected on geometrical grounds, although the threshold is now higher than in the experiment in Table III.

In accord with the original formulation, the subject had to respond to the direction of apparent tilt of the pattern around a vertical axis. The results show that this gave a threshold of 22 to 30 sec of arc disparity, i.e., 1.4% to 1.9% magnification difference, when it was in a horizontal direction, whereas even 10 times larger vertical differences still did not give a reliable indication of such an apparent tilt.

The question of vertical disparity detection in general is, however, not finally answered here, although an answer is brought closer by the following variation of the experiment IV. The pattern was shown to one subject in ensembles containing only vertical disparities, and feedback was provided to help him develop criteria, of whatever nature, to distinguish the direction of vertical disparity (right image larger than left, or vice versa). Even after 1,000 responses with error signaling, probit analysis showed that within a range of 200 sec of arc of disparity, the subject still responded by chance. A similar experiment with ensembles of only horizontal disparities gave a threshold more or less like that in Table IV. The figures of Table IV, since they are replicated even with error feedback, may therefore be accepted as a denial of a subject's capability of correctly identifying the direction of vertical disparities when presented in this form. Or more precisely stated: If there is detection of direction of vertical disparity, even after 1,000 trials with feedback, its threshold is no less than 10 times larger than that for horizontal disparity under strictly comparable observation conditions. Whether a subject could eventually develop vertical disparity discrimination is, of course, left open.

Discussion

The results show unambiguously that under abstract observation conditions, vertical disparity does not have any influence on the depth effects of horizontal disparities. In particular, when there is horizontal disparity, whether accompanied by vertical disparity or not, there is the expected apparent tilt of the target out of the frontal plane around a vertical axis. Such tilts are not seen with vertical disparity alone.

The difference between the findings reported here and those in the publications of the Dartmouth Eye Institute, from which Ogle's work originated, must therefore lie in the procedures and observation conditions. Here: simple geometrical patterns, presented for 0.5 sec with foveal vision, binary
forced-choice responses to many hundreds of stimuli without error feedback, and random interspersal of direction and sign and finally even of magnitude of disparity. There: complex large patterns, unlimited observation time and fixation conditions, and adjustment of a real target plane to appear coincident with the frontoparallel plane. It is surprising that even such gross test and procedural differences could yield such differences in results: detection of vertical disparity there, none here; over-all disparity showing no effect there, the effect of the horizontal component here. One can only speculate on the reasons for the differences. When two oblique lines in the frontal plane are seen with vertical disparity, i.e., magnification or minification only in the vertical direction in one eye, the stereoscopic displacement is that of a horizontal magnification or minification of the other eye. This has a simple geometrical basis well illustrated on p. 248 of Ogle's book and was used as the substrate of clinical tests for vertical magnification differences in the space eikonometer. Although Ogle's targets did not usually contain a set of explicitly oblique lines, diverse contours could have conceivably acted in that capacity implicitly. It is to be noted that the two targets used here for which there was a slight hint of an induced effect were the squares (Table I) and the brackets outlining a square (Table IV), each of which can possibly be thought of as containing an implicit set of oblique lines—the diagonals.

Another possible reason for the differences between Ogle's results and those in this paper relates to the absolute magnitude of the image size differences, rather than their relative magnitudes. Threshold horizontal disparity differences are a few seconds of arc. But magnification differences of a few percent can amount to image size differences of many minutes of arc, and these may readily be discernible directly as size changes if seen with one eye only. For example, a rectangular target 24 by 26 min, when presented alone, can be identified as not being a square. But the capability of judging the size of the image in one eye is not the basis of disparity tests and does not, for example, account for the low horizontal disparity threshold in Table III.

In the end, however, one is led to the conclusion that Ogle's findings and those reported here differ because the design of the experiments makes the respective responses depend predominantly on different levels of cortical processing. Brief, essentially context-free presentations with randomized test parameters and requiring only a yes/no answer presumably minimize the influence of perceptual, experiential factors and thus tend to display properties of the more basic apparatus for processing binocular disparities. If asked to guess, one would place this within the first few synapses of the central visual projection. At higher levels of processing, it may be quite reasonable to work with such postulates as adaptive scale modification of the images of the two eyes relative to each other, even though they may as yet lack roots in a persuasive neural model.

In demonstrating the ineffectiveness of the more basic human binocular apparatus in dealing with vertical disparities, the present findings are in accord with previous negative results as regards vertical disparity detection. They also allow a more singular view of the mechanism underlying stereoscopic depth discrimination. Whatever the apparatus by which the two uniocular images are projected to and routed in the cortex and whatever processes may be at play by which size, location, and feature quality are assigned to a retinal stimulus, there is something special about the binocular interaction detecting horizontal disparity, for it alone can yield thresholds of a few seconds of arc.

REFERENCES