Monocular symmetry in binocular vision

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Human vision is highly sensitive to bilateral symmetry in 2-D images. It is, however, not clear yet whether this visual sensitivity relates to symmetry of 3-D objects or whether it relates to symmetry of the 2-D image itself. We used a stereoscopically presented stimulus and a 3-D bisection task that enable us to dissociate object symmetry from image symmetry. The bisection stimulus consisted of three parallel lines, of which two lines were located in one depth plane and the third line in another. Bisection judgments were different for horizontal and vertical lines, which can be explained by taking into account the distinct viewpoints of the left and right eyes for either of the visible sides of the 3-D object. Image symmetry from a monocular vantage point predicts 3-D bisection better than object symmetry. We conclude that observers use either of the two monocular 2-D images separately but not a single cyclopean view—nicely dovetailing with what they do when they assess both 3-D visual direction and 3-D shape—to assess 3-D symmetry.

Keywords: binocular vision, bilateral symmetry, 3-D bisection

Citation: Erkelens, C. & van Ee, R. (2007). Monocular symmetry in binocular vision. *Journal of Vision, 7*(4):5, 1–9, http://journalofvision.org/7/4/5/, doi:10.1167/7.4.5.

Introduction

Human vision, whether monocular or binocular, is highly sensitive to the presence of bilateral or mirror symmetry (Barlow & Reeves, 1979). The reason for this perceptual salience is unclear, but it has been argued that bilateral symmetry is significant for biological functions such as discriminating living beings from inanimate objects (Tyler et al., 2005) and selecting attractive mates (Moller, 1992; Johnstone, 1994; Swaddle & Cuthill, 1997). These explanations suggest that sensitivity for bilateral symmetry has been developed for recognizing the symmetry of 3-D objects. Our knowledge on symmetry perception, however, has mainly been obtained from studies on symmetry in 2-D images. Mirror symmetrical objects, animals, and human beings will generally not create a symmetric image on the retina. Symmetric 3-D objects create symmetric images only if the optical axis of the eye is lying in the plane of object symmetry. This combination of object symmetry and image symmetry occurs in particular viewing conditions, known as accidental views. One may ask the question: Why would our visual system have developed sensitivity for image symmetry that is experienced only in exceptional conditions? The biological significance may be that image symmetry alerts the viewer that an object is approaching. Image symmetry may also have social significance in telling viewers that a person is gazing at them and, therefore, deserves their attention. Several studies have shown that the processing of face view and gaze direction is fast and automatic and that it may use specialized neural circuitry (Emery, 2000; Kleinke, 1986; Langton, Watt, & Bruce, 2000; Perrett et al., 1985; von Grünau & Anston, 1995). It is clear that detection of image symmetry could be a useful component of such a hardwired mechanism.

There are studies in the literature whose results are suggestive for the hypothesis that human beings are sensitive to image symmetry. Indeed, a few studies have reported that when subjects viewed asymmetric 2-D images that represented symmetric objects viewed from a skewed angle, symmetry detection dropped dramatically with increasing skewing angle (Gerbino & Zhang, 1991; Locher & Smets, 1992; Wagemans, van Gool, & d'Ydewalle, 1991, 1992). The result may be interpreted as that humans are more sensitive to image symmetry than object symmetry. However, an aspect of the used method that makes our interpretation inconclusive thus far is that image symmetry and object symmetry have not been pitted against each other. In fact, independent manipulation of object symmetry and image symmetry is not possible if one uses 2-D images because human beings do not interpret symmetric images as representing asymmetric objects. Manipulation of image symmetry independent of object symmetry is straightforward if one uses real 3-D objects or stereograms.

Here, we use stereograms for which image symmetry and object symmetry make different, easily verifiable predictions. We use the bisection task because human subjects can perform bisection with great accuracy (Klein & Levi, 1985; Westheimer, 1979). Figure 1A shows monocular views of two of the bisection stimuli, with the left stimulus containing three horizontal lines embedded in

doi: 10.1167/7.4.5 Received June 16, 2006; published March 15, 2007 ISSN 1534-7362 © ARVO

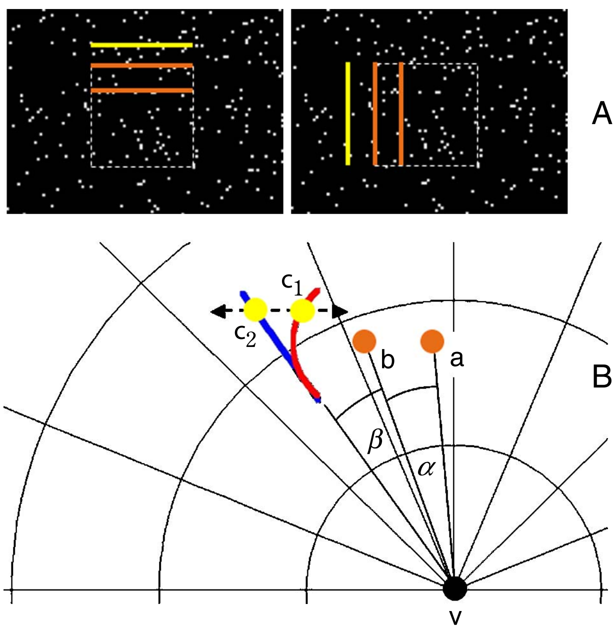

Figure 1. Stimuli and predictions for bisection settings. (A) Monocular, frontal views of two of the stimuli. The dashed squares (invisible in the actual stimuli) indicate the area within which the dots and two fixed lines (orange) have disparity relative to that of both the background dots and the movable third line (yellow). Subjects' task was to position this third line (movable up–down in the left stimulus, left–right in the right stimulus) so that the central line bisected the outer two lines. (B) Figure representing both the right-side view of the left stimulus of Panel A and the top view of the right stimulus. Orange dots **a** and **b** represent the fixed lines, and **v** denotes the viewpoint. Yellow dots $\mathbf{c}_1$ and $\mathbf{c}_2$ are two settings of the movable line (the arrows indicate its path of displacement). $\mathbf{c}_1$ is the prediction for object symmetry, and $\mathbf{c}_2$ is the prediction for image symmetry (for which $\alpha = \beta$). Colored lines indicate the predictions for object symmetry (red) and image symmetry (blue) for a range of disparities of **c** relative to **b**.

dots and the right one containing three vertical lines. Two lines were placed in one depth plane together with the dots, making up the central square (foreground), whereas the third line and the remaining dots were placed in another depth plane (background). The dots were included to guarantee good stereopsis and, thus, to ensure single vision of the lines. Dot density was varied to investigate the influence of half-occlusions on bisection. The subjects' task was to position the line in the background such that the central line appeared to bisect the outer lines. Figure 1B shows the predictions for object symmetry (red line) and image symmetry (blue line). For one specific disparity between foreground and background, the lines of the bisection stimulus (**a**, **b**, and $\mathbf{c}_1$) constitute a symmetric object if the background line is placed at location $\mathbf{c}_1$. The circular path through $\mathbf{c}_1$ (in red) indicates locations of the background line for which object symmetry exists for a range of disparities. The plane of object symmetry is oriented perpendicular to the plane depicted in Figure 1B. It includes the central line of the stimulus (**b**) and bisects $\mathbf{ac}_1$. The plane of object symmetry depends on the disparity of the lines, but it is independent of viewpoint **v**. Contrastingly, image symmetry depends on **v**. The lines of the bisection stimulus (**a**, **b**, and $\mathbf{c}_2$) constitute a symmetric image for the viewer **v** if the background line is placed at location $\mathbf{c}_2$. The radial path through $\mathbf{c}_2$ (in blue) indicates locations of the background line for which the retinal image is symmetric for a range of disparities. The axis of image symmetry coincides with the central stimulus line **b** oriented perpendicular to the plane of Figure 1B. The red and blue line segments in Figure 1B show that object symmetry and image symmetry make different predictions, particularly for uncrossed (far) disparities.

One may hypothesize that image symmetry and object symmetry are simultaneously available for perceptual judgment; that is, subjects can easily select between the 2-D and 3-D interpretations of symmetry. However, this may not be the case. Examples[1] from the literature show that judgments of 2-D shapes and angles as they are in the plane of a picture depend on their 3-D interpretation. The "turning the table" illusion described by Shepard (1990) shows that the drawn 2-D shape of a tabletop depends on the 3-D orientation of the table. Nundy, Lotto, Coppola, Shimpi, and Purves (2000) showed that identical 2-D angles between lines in a picture are perceived quite differently dependent on the 3-D context of the lines. Here, we will show that, different from the judgments in these examples, bisection concerns the 2-D rather than the 3-D interpretation of images. This result suggests that image symmetry represents significant information by itself and is not just the by-product of object symmetry.

We will exploit a geometric difference between bisection of horizontal (Figure 1A, left image) and vertical lines (Figure 1A, right image). When bisecting horizontal lines, the interocular axis is aligned with the lines and, therefore, vertical distances between the lines are identical in both eyes' images. For vertical lines, the viewpoints have an interocular separation of about 6.5 cm. As a consequence, horizontal distances between the lines differ in both eyes' images. Comparison of settings for horizontal and vertical lines will show whether image symmetry is a quality of the stereoscopic image or is related to symmetry of one of the two eyes' images.

Methods

Subjects

Six subjects participated in the experiments. None of them showed any visual or oculomotor pathology other than refraction anomaly. All had normal or corrected-to-normal visual acuity. They were checked for normal stereopsis under strict fixation (van Ee & Richards, 2002). Four subjects were naïve with respect to the purpose of the experiments.

Visual stimuli

Random-dot patterns were presented in red and green on a LaCie (22 in.) CRT monitor (resolution: 1,280 × 1,024 pixels; refresh rate: 100 Hz). Pixel resolution was 2 min (of arc) at the viewing distance of 50 cm. Custom-made red and green filters (Bernell, Belgium; light separation, better than 99%) were used to make each image exclusively visible to one eye. The patterns consisted of bright (18 cd/m^2) dots (size, 4 × 4 min) that were distributed on a dark (0.3 cd/m^2) background. The stereograms embedded a square (8° × 8°) that was centered at a rectangular background (36° wide × 27° high). The square floated either in front or behind the background (crossed or uncrossed disparity). Disparity between square and background was varied in seven equidistant steps between −30 min and 30 min. Three lines (8° × 4 min) were binocularly visible. Two lines were placed on the square: one at its edge and the other line at a fixed distance of twice the disparity between square and background from the first one. The third line was placed in the background. Subjects could displace this line in the background's depth plane using keys. The experiments were run in a darkened room in which the monitor was the only visible object.

Procedure and design

Subjects were instructed to fixate the central line while they judged its distance relative to the two outer lines. They displaced the outer line lying in the background until the central line was judged to bisect the two outer lines. The initial position of the movable line was randomly chosen such that the distance to the central line was between 0.5 and 1.5 times the distance between the two fixed lines. Trials were grouped in four blocks in which the central line was placed at the left, right, upper, or lower edge of the square. At the left/right locations, subjects judged horizontal separations between vertical lines, whereas they judged vertical separations between horizontal lines at the top/bottom locations. Each block contained 140 trials among which dot density of the random dot pattern varied across four levels (0%, 1%, 3%, or 9%) and disparity across seven levels (−30, −20, −10, 0, 10, 20, and 30 min). In the 0% dot-density stimulus, square and background were invisible so that the stimulus contained only three lines: two lines at the same depth and one line at another. As a consequence, the 0% dot-density stimulus did not contain any half-occlusions caused by dots in either the square or the background. Disparity was defined as positive if the square was in front of the background. Stimulus parameters (dot density, disparity) were varied in random order, and each combination was presented five times. To investigate the effect of eye movements, we repeated the experiment. This time, the subjects were free to look wherever they liked. The results of the study are based on a total of 7,620 settings.

Analysis and statistics

Coordinates of the three lines on the monitor were converted into two sets of directions (one set relative to the left eye, the other relative to the right eye). Distances between the lines were expressed in viewing angles. One set of angles (α_L in the left eye and α_R in the right eye) indicated the angular separation between the fixed lines (**a** and **b** in Figure 1B). The other set (β_L and β_R) indicated the angular separation between the central line (**b**) and the movable line (**c**). The (vertical) angular separation between horizontal lines **b** and **c** was computed as $\beta = \beta_L = \beta_R$. The mean (horizontal) angular separation between vertical lines **b** and **c**, for which $\beta_L \neq \beta_R$, was computed as $\beta = (\beta_L + \beta_R)/2$, which implies that the cyclopean eye was used as the reference. In addition, the horizontal disparity (d) between lines **b** and **c** was computed as $d = |\beta_L - \beta_R|$. All angles between **a**, **b**, and **c** were taken to be positive to allow easy comparison between the bisection settings collected from the various edges of the central square of the stereogram. The disparity of **c** relative to **a** and **b** was assigned a positive (negative) sign for locations of **c** in front of (behind) the screen.

Whether mean bisection results were different from the predictions was established with *t* tests. Differences between dot-density conditions and disparity conditions were tested with within-subject, two-way ANOVAs (Dot Density × Disparity) on the bisection settings for each condition. An effect of dot density would indicate that visual directions depend on the presence of half-occlusions.

Results

The bisection settings are presented as values of $\alpha - \beta$ (Figure 1B) as a function of disparity. Figure 2 shows the mean bisection judgments for horizontal and vertical lines made by one subject. As Figure 2 shows, the bisection results were different for horizontal and vertical lines and for crossed and uncrossed disparities. The absolute differences between α and β were much larger for vertical than for horizontal lines. For uncrossed disparity, $\alpha - \beta$ was always positive, which means that the angle between the more distant line and the central line was set at smaller values than the angle between the lines having equal distances to the viewer. For crossed disparity, $\alpha - \beta$ was negative for horizontal lines and positive for vertical lines. For horizontal lines, $\alpha - \beta$ showed a linear relationship

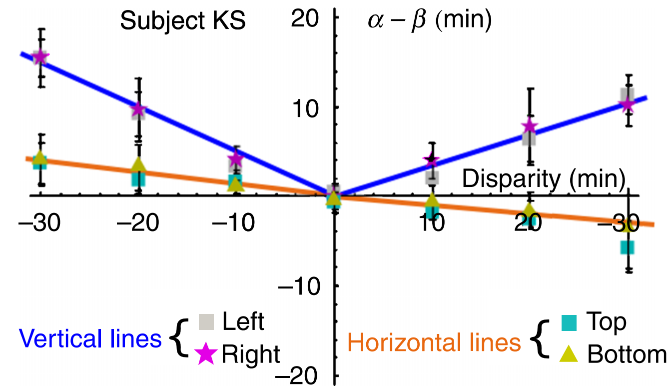

Figure 2. Bisection results for vertical and horizontal lines. Data points represent the means of $\alpha - \beta$ and their standard deviations as a function of disparity between the lines for one representative subject. Linear fits of the data (blue and orange lines) illustrate that bisection judgments are different for vertical and horizontal lines.

with disparity (orange line). For vertical lines, $\alpha - \beta$ was always positive (blue lines), which implies that angles between lines at unequal depths (β) were always set smaller than angles between equal-depth lines (α).

Figure 3 shows the mean bisection judgments for horizontal and vertical lines across the six subjects. The small standard deviations across subjects show that the subjects interpreted the task similarly and executed it in consistent ways. We report separately the results for horizontal and vertical lines. For horizontal lines, two-way ANOVAs (four Dot Densities × seven Disparities) revealed no main effect of dot density in any of the subjects, upper edge: $F(3, 139) < 1.76$, $p > .15$; lower edge: $F(3, 139) < 2.45$, $p > .06$. There was a significant effect of disparity in five of the six subjects, upper edge: $F(6, 139) > 8.82$, $p < .001$; lower edge: $F(6, 139) > 20.95$, $p < .001$. For the horizontal lines, the mean slope of the bisection judgments as function of disparity was −0.18.

Figure 3 also shows the mean bisection results for vertical lines across six subjects. Two-way ANOVAs revealed, again, no main effect of dot density in any of the subjects, left edge: $F(3, 139) < 1.92$, $p > .13$; right edge: $F(3, 139) < 2.27$, $p > .08$. Separate t tests showed that the means of $\alpha - \beta$ were significantly different from zero for each dot density ($p < .05$). There was a main effect of disparity, left edge: $F(6, 139) > 11.51$, $p < .001$; right edge: $F(6, 139) > 56.32$, $p < .001$. Separate t tests showed that $\alpha - \beta$ was significantly different from zero for disparities of −30, −20, 10, 20, and 30 min ($p < .05$) but not for disparities of 0 and 10 min ($p > .12$). Means of $\alpha - \beta$ were positive for all disparities but slightly less positive for positive than negative disparities.

Bisection results that were obtained under the instruction of free eye movements were very similar to those measured during fixation. Despite some individual differences, mean results were similar to those shown in Figure 3. Statistical tests on mean difference ($p > .18$) and variance ratio ($p > .07$) indicated that it was not unlikely that both data sets were drawn from the same population.

Discussion

Monocular viewpoints

The bisection results were clearly different for horizontal and vertical lines. A potential cause for the difference is that the eyes are positioned at an identical eccentricity for bisection judgments at the horizontal edges (of the horizontal lines) but at different eccentricities for judgments at the vertical edges (of the vertical lines). Figures 2 and 3 show that, for all nonzero disparities, angles between vertical lines positioned at unequal depths (β) were always set smaller than angles between equal-depth lines (α). The question, then, is, how can different

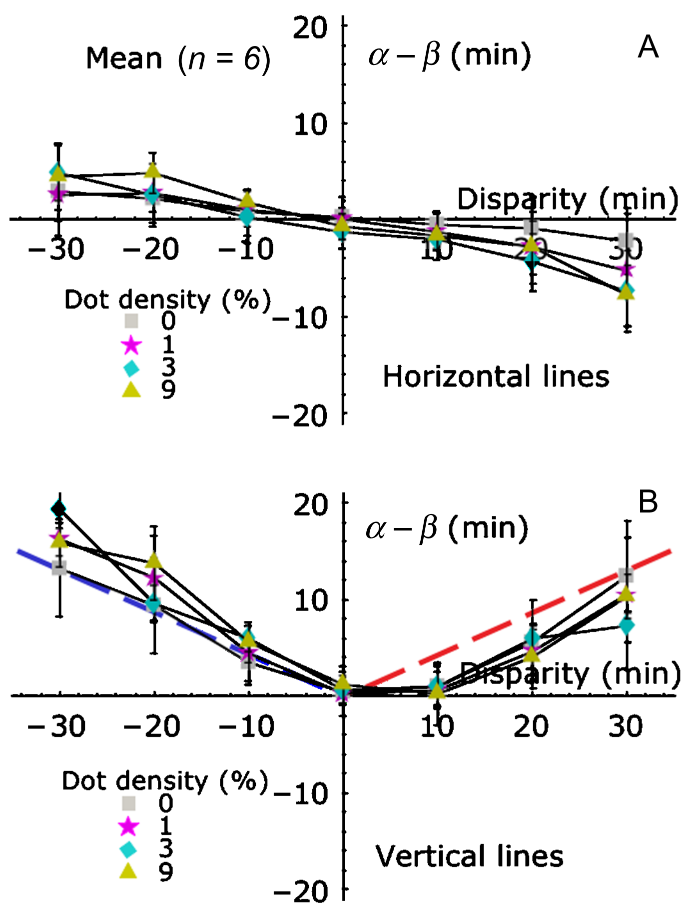

Figure 3. Means of $\alpha - \beta$ and their standard deviations across six subjects as a function of disparity between the lines. (A) Bisection results for horizontal lines. (B) Bisection results for vertical lines. Data are separately shown for different dot densities of the stereograms. The blue and red lines indicate $\beta = \alpha - |d/2|$, where d is horizontal disparity.

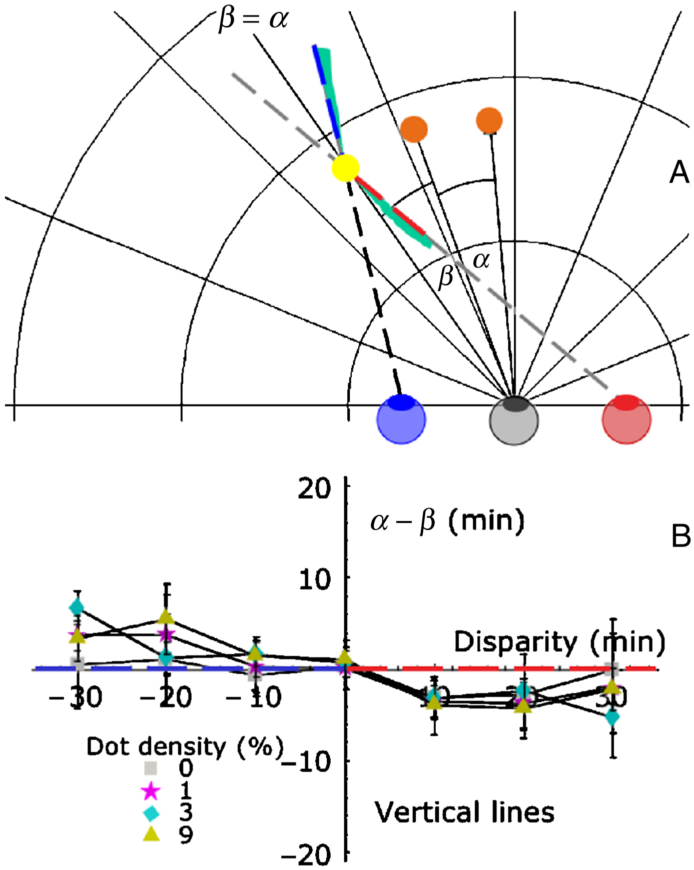

Figure 4. Reinterpretation of the bisection results for vertical lines. (A) Top view (dimensions not to scale) of the bisection stimulus, the left eye (blue), the right eye (red), and the cyclopean eye (gray). The blue and red dashed lines are defined by $\beta = \alpha - |d/2|$ (see Figure 3), which implies that either β_L or β_R is constant. Positioning of the movable stimulus line in these directions is associated with image symmetry in the left or right eye. The green regions roughly indicate the locations of the movable line for the bisection results of Figure 3B. (B) The bisection results of Figure 3B recomputed relative to the blue and red lines, which implies that either the left eye ($\beta = \beta_L$) or the right eye ($\beta = \beta_R$) is taken as the viewpoint.

viewpoints explain this finding? In the computations of $\alpha - \beta$, we assumed the cyclopean eye to be the viewpoint. However, if, instead, the subjects used the left or right eye as the reference, our computations must be adjusted to reflect their bisection judgments. Figure 4A shows the translation of the equation $\beta = \alpha - |d/2|$ from the $\alpha - \beta$ against the disparity plot of Figure 3B into direction and distance coordinates. The relationship $\beta = \alpha - |d/2|$ is equivalent with $\alpha = \beta_L$ if $d < 0$ and with $\alpha = \beta_R$ if $d > 0$, as shown by the dashed blue and red lines of Figure 4A. Figure 4B shows the bisection judgments of Figure 3B that are, now, recomputed relative to the dashed blue and red lines. The green areas in Figure 4A sketch the locations of the movable line for the bisection judgments shown in Figures 3B and 4B. Comparison of the recomputed judgments for vertical lines (Figure 4B) with the bisection judgments for horizontal lines (Figure 3A) shows that, now, the results are very similar for vertical and horizontal lines, wherein both show a small negative slope as a function of disparity.

Image symmetry

We made a distinction between image symmetry and object symmetry. To investigate which of the two types of mirror symmetry describes the bisection judgments, we computed $\alpha - \beta$ as a function of disparity for both types of symmetry (Figure 5). Image symmetry predicts that $\alpha - \beta = 0$ for all disparities, indicated by the blue horizontal line. The predictions for object symmetry depend on the viewing distance, which was 50 cm in the experiments. However, it may be that judgment of object symmetry is related to the perceptual rather than to the physical viewing distance. To find out at what distances our subjects perceived the bisection stimuli, we computed the predictions of object symmetry for viewing distances of 30, 50, and 70 cm (Figure 5, red lines). The curves of $\alpha - \beta$ that predict object symmetry are parabolas with vertices that are offset by a small positive disparity (shifted to the right by about 5 min in Figure 5). The offset is caused by the fact that the 3-D bisection stimuli were viewed in slightly eccentric directions and that zero disparity was defined relative to the image plane (superposition on the screen). Figure 5 shows that image symmetry (blue line) and object symmetry (red lines) make very different predictions for $\alpha - \beta$ as a function of disparity. Object symmetry predicts that, for positive and negative disparities larger than 20 min, $\alpha - \beta$ should be positive and should progressively increase with increasing disparity. Comparison of the bisection judgments shown in Figures 3A (horizontal lines) and 4B (vertical lines) with these predictions suggests that the experimental data are best described by image symmetry. Furthermore, Figure 4 shows that 3-D bisection is best explained by monocular image symmetry. This result implies that monocular rather than cyclopean viewpoints are used for bisection judgments. Which eye's image is symmetrical appeared to be related to the 3-D layout of the bisection stimulus and not to a specific eye or class of disparity.

What remains to be explained is the small negative slopes of $\alpha - \beta$ as a function of disparity (Figures 3A and 4B). We speculate that image symmetry of nonequidistant stimuli may be affected by the well-known phenomenon of size constancy, which involves that the perceived depth of an object influences its perceived size (Howard & Rogers, 2002). Size-constancy effects imply that if depth is well defined, people judge the size of a more distant object as larger than that of an object of equal retinal size located at a nearer distance (Carlson, 1962; Epstein, 1963). We speculate that the size-constancy effects cause the

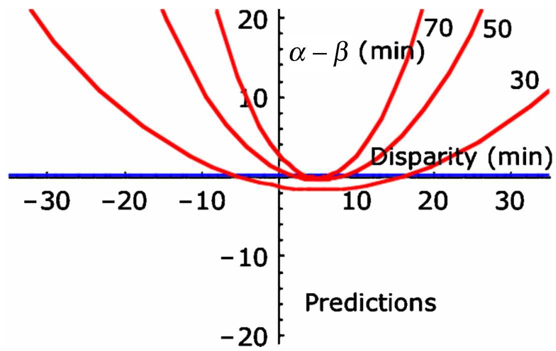

Figure 5. Predictions. Image symmetry predicts bisection judgments along the blue horizontal line. The red lines are object-symmetry predictions for three viewing distances (expressed in centimeters).

phenomenon that separations between two non-equidistant lines are judged differently from separations between two equidistant lines.

Implications for 3-D shape perception

Our bisection results for vertical lines showed that bilateral symmetry in binocular vision is best explained by image symmetry in one of the eyes' images. Figure 4 shows that the left eye dominated for uncrossed disparity located at the left side of the fixation point and for crossed disparity at the right side of the fixation point. The right eye dominated for the other two disparity–side combinations. To demonstrate the implication of this bisection result for stereoscopic vision, we composed a stereogram in which three checkerboards are partly occluded by a checkered bar in the foreground (Figure 6).

The partly occluded checkerboard (Figure 6A) demonstrates that position-dependent eye dominance holds for the perception of the checkerboard. If we fixate the vertical bar, the binocularly perceived pattern of the left background corresponds to that seen by the left eye. Similarly, the right eye dominates for the right part. The local monocular dominances explain an extraordinary property of stereopsis, namely, that all details visible to the left and right eyes are also visible in stereoscopic vision and that perceived direction near occluders is determined monocularly (Erkelens, Muijs, & van Ee, 1996; Erkelens, & van Ee, 1997a, 1997b; van Ee, Banks, & Backus, 1999). A second extraordinary property of stereopsis is that the inclusion of all details does not induce perceptual deformations. Figure 6A demonstrates this phenomenon. In stereoscopic vision, the checkerboard is nine checkers wide and eight checkers high. Yet, it is perceived as a square (van Ee & Erkelens, 2000)! If we place the 9 × 8 checkerboard in the same depth plane as its occluder (Figure 6B), it is perceived as a rectangle. Therefore, the perceived shape of the checkerboard depends on the depth between board and occluder. Depth-dependent differences in shape cannot be attributed to size constancy because size-constancy effects are isotropic. In the literature, it has been suggested that partly occluded details are perceptually compressed in the horizontal direction (Ohtsuka & Ono, 1998). Horizontal compression, however, should affect all scales. If it transforms the rectangular checkerboard into a square, it should transform the square-shaped checkers into upright rectangles. In Figure 6A, however, the individual checkers are perceived as squares. The rectangular checkerboard of Figure 6B has been horizontally compressed to a square to demonstrate the effect of horizontal compression on the perceived shape of the individual checkers. Figure 6C shows the compressed checkerboard. As a result of the horizontal compression, the individual checkers are perceived as upright rectangles. Comparison of the perceived

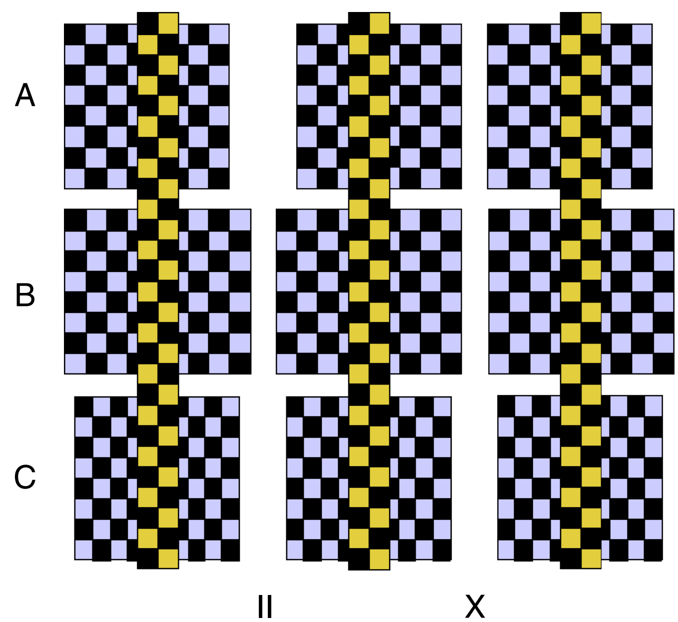

Figure 6. Stereogram of partially occluded checkerboards. Panel A represents a square-shaped (8 × 8) checkerboard that floats at some distance behind the two-checkers-wide frontal bar. Panels B and C represent checkerboards that are attached to the backside of the bar. During stereoscopic viewing, the boards of Panels A and B show identical numbers of checkers (horizontal: 3.5 + 2 + 3.5 = 9; vertical: 8). The perceived aspect ratios are different: The purple–black board of Panel A is perceived as a square and that of Panel B is perceived as a rectangle. The purple–black board of Panel C is identical to that of Panel B, except that, by horizontal compression, the rectangular aspect ratio of the board has been transformed into a square. Due to the compression, the individual checkers have become upright rectangles. The symbol || indicates stereo pairs for uncrossed viewing, and X denotes pairs for crossed viewing. The colors are used just for convenience. The way observers perceive the shape of the individual checkers and the checkerboards demonstrates that they use either of the two monocular 2-D images, but not the cyclopean view, to assess 3-D shape.

checkers of the background boards of Figures 6A and 6C shows that horizontal compression is in conflict with the perceived shape of the checkers. The correct solution to the shape problem is that, consistent with the 3-D bisection judgments, shape is judged from parts visible from either of the monocular viewpoints (see also van Ee & Erkelens, 2000, for a more detailed discussion on the role of binocular eye posture).

Neural mechanisms

Is it possible that there are separate neural mechanisms for the perception of image symmetry and object symmetry? Until now, most experimental studies were not suited to answer this question because conclusions on the perception of symmetry have been mainly drawn from judgments of symmetry in 2-D images in which object symmetry cannot be manipulated independently of image symmetry. Due to the "accidental-viewpoint" property of the human visual system, 2-D images taken from accidental viewpoints are not easily interpreted as 3-D objects (Koning & van Lier, 2006). Therefore, some results from 2-D symmetry studies may refer to image symmetry whereas other results may refer to object symmetry. Separate mechanisms for the perception of image symmetry and object symmetry would clarify a few unexplained reports in the literature. It would explain the not well understood psychophysical finding that symmetry detection is both tolerant and sensitive to small perturbations (Barlow & Reeves, 1979; Wagemans, 1995). Tolerance and high sensitivity are no paradoxical properties if they are associated with different mechanisms. Separate mechanisms would also explain the experimental result of Tjan and Liu (2005) who found that symmetry discrimination was worst near perfect symmetry when asymmetry was introduced by geometric deformations, whereas the opposite result was obtained when asymmetry was introduced by random replacement of dots. In this respect, it is important to note that affine, deformed symmetric images may represent symmetric objects seen from a skewed viewpoint. A mechanism designed to detect object symmetry should be preferably insensitive to such deformations. Therefore, affine deformations may selectively affect the mechanism for image-symmetry detection. On the other hand, random replacement of dots does not mimic changes of viewpoint and, therefore, this type of manipulation may be appropriate for the detection of object symmetry.

Rather little is known about the neural basis of symmetry perception (Beck, Pinsk, & Kastner, 2005). Wilkinson and Halligan (2003) discussed that it would appear to operate at an early level of visual processing. In single-cell recordings of rhesus monkey, Lee, Mumford, Romero, and Lamme (1998) found late enhanced responses of V1 cells when their receptive fields were centered on the symmetry axis of figures defined by texture. They interpreted the late symmetry responses as being generated after feedback from an extrastriate cortical area. Norcia, Candy, Pettet, Vildavski, and Tyler (2002) found late responses to symmetry in visual evoked potentials of humans that were consistent with the feedback hypothesis. Significant contribution of V1 to symmetry perception was denied by two very recent studies (Sasaki, Vanduffel, Knutsen, Tyler, & Tootell, 2005; Tyler et al., 2005) that reported robust activity in higher order regions of the human visual cortex but little activity elsewhere in the brain. Until now, all neural studies on symmetry perception used 2-D stimuli. Those mixed results from the literature necessitate 3-D stimuli to elucidate what brain areas contribute to image symmetry and object symmetry.

Conclusion

Using our novel paradigm, we dissociated perception of object symmetry from perception of image symmetry. We found that bisection settings were different at the horizontal and vertical edges of our 3-D object, which we explained by taking into account the distinct viewpoints of the left and right eyes for either of the visible sides of the 3-D object. Thus, image symmetry from a monocular vantage point, rather than object symmetry, predicted our 3-D bisection results. We discussed that this finding dovetails nicely with findings in the domains of both stereoscopic direction perception and stereoscopic shape perception: In those domains, observers do not use a single cyclopean reconstruction but they use the eye at the visible side of a 3-D object to perform tasks. We conclude that observers use either of the two monocular 2-D images separately, but not a single cyclopean view, to assess 3-D symmetry when occlusion is involved.

Acknowledgments

We wish to thank Pieter Schiphorst for technical assistance. This research is supported by the Netherlands Organization for Scientific Research (NWO/ALW).

Commercial relationships: none.
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Footnote

[1] The mentioned geometric illusions can be viewed at, for instance, http://www.lottolab.org, http://www.michaelbach.de/ot/index.html, and http://viperlib.york.ac.uk.

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