The role of vertical mirror symmetry in visual shape detection

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The goal of our study is a better understanding of the role of vertical mirror symmetry in perceptual grouping. With a simple psychophysical task and a set of controlled stimuli, we investigated whether vertical mirror symmetry acts as a cue in figure-ground segregation. We asked participants to indicate which of two sequentially presented Gabor arrays contained a visual shape. The shape was defined by a subset of Gabor elements positioned along the outline of an unfamiliar shape. By adding orientation noise to these Gabor elements, the shape percept became less salient. Across the different noise levels, symmetric shapes were easier to detect than asymmetric ones. This finding indicates that vertical mirror symmetry is indeed used as a cue in perceptual grouping.

Keywords: bilateral symmetry, perceptual organization, perceptual grouping, figure-ground, shape detection

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Introduction

Despite the complexity and ambiguity of the visual environment, human observers are highly proficient in detecting and recognizing objects. A crucial step in this seemingly effortless process is to determine which parts of the visual input belong to the same object. A vision system aimed at grouping together relevant object parts would benefit from using all relevant information sources.

The Gestaltists in the early twentieth century have postulated a number of information sources and grouping principles that shape our visual perception, such as good continuation, closure, proximity, similarity, and symmetry (Koffka, 1935). Over the last decades, a number of psychophysical and neurophysiological studies have tried to reveal the mechanisms underlying these visual grouping principles. The contribution to perceptual grouping is well established for good continuation, closure, proximity, and similarity. We will first review some studies showing that these Gestalt laws are indeed powerful organizational principles. The role of symmetry in perceptual organization, however, is less clear. We will discuss empirical evidence that detection of symmetry is fast, accurate, and robust, but we will argue that the ease of symmetry detection does not automatically imply an active role for symmetry in perceptual organization.

Grouping cues

The principle of *good continuation* states that spatially aligned neighboring features tend to aggregate to create a stable percept of a continuous contour (Wertheimer, 1923). This grouping tendency depends on a number of factors, such as separation and orientation of local elements, contour length, and curvature properties. Field, Hayes, and Hess (1993) asked participants to detect a winding path in an array of otherwise randomly oriented elements and showed that detection performance increased with the number of path elements, the length of the path, and the collinearity of neighboring elements. From these observations, Field et al. (1993) advocated the existence of an association field between the local elements: The specific relationship between the local elements determines whether the path segregates from the background. Because the grouping of local elements into a global path requires integration beyond the receptive field size of V1 neurons, Field et al. (1993) ascribed a crucial role to lateral connections between V1 neurons. Lateral connections between V1 neurons might indeed provide the neural circuitry for the principle of good continuation. Experimental support for this view comes from Fitzpatrick (1996) who observed anisotropy in the tree shrew's striate cortex: Lateral connections between neurons tuned to the same orientation are more

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numerous and extend further than connections between neurons tuned to different orientations. Similar results were obtained by Schmidt, Goebel, Löwel, and Singer (1997) in area 17 of the cat. Not only are lateral connections more numerous between neurons tuned to the same orientation, the effect is even larger for neurons whose receptive fields are also spatially aligned. Angelucci et al. (2002) did not find a similar anisotropy within macaque striate cortex. They did, however, observe anisotropy in the feedback connections from extrastriate areas to area V1. They argued that contour completion in macaque V1 is a global-to-local process mediated by feedback connections to V1.

The interplay between local and global stimulus properties in contour grouping has been illustrated by a number of studies within the "path" paradigm (reviewed by Hess & Field, 1999; Hess, Hayes, & Field, 2003). Kovács and Julesz (1993) argued that when local stimulus properties are held constant, path detection depends on the global structure of the path. In a series of experiments, they found that the detection of closed contours in a background of randomly oriented Gabor elements allowed for a larger spacing between adjacent elements than detection of open contours, even if both contours had the same length, curvature, and eccentricity. This finding relates to the Gestalt law of *closure*: Our visual system prefers closed over open regions and tries to fill in gaps to perceptually close a region. Closure operates on a more global stimulus level than good continuation: It also requires detection of collinear local elements, but the integration of these elements results in a stability beyond the local association fields. The special status of closed contours has been confirmed by Hess, Beaudot, and Mullen (2001) who compared processing times for closed and open contours. They found that closed contours are detected faster than open contours with the same curvature. To explain the closure enhancement effect, Pettet, McKee, and Grzywacz (1998) compared fully closed contours with open-ended contours. While removing one element from a closed contour seriously affected detectability, the same operation hardly influenced detection performance for open-ended contours. Tversky, Geisler, and Perry (2004) showed that the advantage of closed over open contours could be fully explained by probability summation: If detecting a contour in a background of random elements depends on the detection of a cluster of n aligned elements, closed contours are easier to detect simply because more clusters of n aligned elements are present in closed contours compared to open contours. According to Pettet (1999), it is not the closure but the smoothness of the contour that determines detection performance: High curvature as well as direction changes in curvature impede detectability. This finding is confirmed by Hess et al. (2001) who showed that contour integration is slower for curved than for straight contours.

Some of the above studies already stressed the importance of element spacing in contour detection (Field et al., 1993; Kovács & Julesz, 1993). The process behind this observation relates to the Gestalt law of *proximity,* also introduced by Wertheimer (1923). It states that our visual system groups together closely adjacent elements. The ecological validity of this grouping principle is clear: In everyday perception, elements that are closer together have a higher chance of belonging to the same object (Brunswik & Kamiya, 1953). A recent study by Quinn, Bhatt, and Hayden (2008) illustrates the fundamental role of proximity: Using a novelty preference test, they showed that 3- to 4-month-old infants already employ proximity to group arrays of dots. An earlier demonstration of the dominant role of proximity in perceptual grouping is provided by Uttal, Bunnell, and Corwin (1970). They asked participants to detect a straight line in an array of dots. Dot spacing appeared to be the crucial factor for detectability: A smaller distance between the dots resulted in higher detection performance, even when the dot arrays were presented tachistoscopically. Kubovy and Wagemans (1995) used ambiguous dot lattices in which spontaneous grouping of dots could result in multiple perceived orientations. By systematically manipulating the distance between the dots, Kubovy and Wagemans (1995) showed that proximity determines the odds of organizing the lattice in one or another orientation. From their results, they suggested a pure distance law: The strength of proximity grouping decays exponentially with interdot distance (Kubovy, Holcombe, & Wagemans, 1998). Extending the paradigm to lattices in which curved organizations could be perceived, Strother and Kubovy (2006) found that curvilinear organizations were more salient than rectilinear ones, even when the distance between the dots favored the rectilinear grouping.

Wertheimer's (1923) principle of *similarity* states that elements with similar features tend to be grouped together. In an experiment where grouping by proximity and grouping by similarity gave rise to incongruent orientations, Ben-Av and Sagi (1995) found that grouping by proximity dominated perception at stimulus presentation times below 100 ms. With longer presentation times, other grouping principles (in this case similarity in shape and luminance) took over. This finding was confirmed by a series of ERP studies showing that proximity grouping generates earlier occipital activation than grouping by similarity (Han, 2004; Han, Ding, & Song, 2002; Han, Song, Ding, Yund, & Woods, 2001). Apparently, grouping by proximity and grouping by similarity also involve different cortical areas (Han, Jiang, Mao, Humphreys, & Gu, 2005).

Much psychophysical research has focused on the interaction between proximity and similarity. Zucker, Stevens, and Sander (1983) showed that proximity grouping in dot lattices is modulated by grouping based on the brightness similarity of the dots. In a visual flanker task, Quinlan and Wilton (1998) asked participants to rate how well a central target grouped with adjacent flankers, thereby manipulating proximity, shape similarity, and color similarity between the elements. They demonstrated the dominance of proximity over similarity. However, in some cases grouping by similarity did override grouping by proximity. A comparable interaction between proximity and continuation has been found by Claessens and Wagemans (2005). They used lattices of oriented Gabor elements, much like the dot lattices used by Kubovy and Wagemans (1995). Again, there was evidence of strong grouping by proximity. However, orientation alignment of Gabor elements sometimes did override the proximity grouping.

Symmetry as grouping cue?

According to the Gestalt law of *symmetry,* symmetrical regions of the visual field tend to be perceived as figures. The rationale behind this law is that symmetry is a nonaccidental property (Wagemans, 1992, 1993): A symmetric projection on the retina most likely results from a real (symmetric) object in the outside world (see Discussion section). However, unlike the grouping benefit revealed for the aforementioned cues, no clear benefit of symmetry on perceptual grouping has been demonstrated yet. A study by Feldman (2007) is suggestive for the role of symmetry in perceptual grouping, but this study did not directly compare symmetric and asymmetric stimulus configurations.

The role of symmetry in visual perception was first discussed by Mach (1886/1959) who distinguished three types of symmetry: Translational (repetition) symmetry, reflectional (mirror) symmetry, and centric (rotational) symmetry. He also argued that in case of mirror symmetry similarity judgments are easier when two shapes are symmetrical about a vertical axis than about a horizontal axis. Bahnsen (1928) was the first to illustrate the importance of symmetry as a cue for perceptual grouping. He used stimuli with alternating symmetric and asymmetric black and white fields. His subjects reported to see the fields with symmetric contours as figures against an asymmetric background on 90% of the trials. Bahnsen, however, did not control for convexity of the contours when constructing his stimuli (Kanizsa & Gerbino, 1976). Julesz (1971) showed that mirror symmetry is more readily detected than translational or centric symmetry. Goldmeier (1936/1972) empirically validated Mach's suggestion that vertical mirror symmetry is more salient than horizontal mirror symmetry. In a forced-choice similarity task, his participants chose the figure that preserved the vertical mirror symmetry of a target image over the figure that preserved the horizontal mirror symmetry. The advantage of vertical over horizontal symmetry has since been confirmed by a number of studies (for an overview, see Wagemans, 1995; Wenderoth, 1994).

To verify the putative role of symmetry in perceptual grouping, the ease of symmetry detection is of crucial importance. Over the past decades, many studies have shown that the detection of symmetry is fast, accurate, and robust. Julesz (1971) found that subjects only needed 50 ms to detect symmetry in textured patterns. Carmody, Nodine, and Locher (1977) showed that subjects were able to discriminate between symmetric and asymmetric random shapes that were presented for only 25 ms. Barlow and Reeves (1979) found that subjects only needed 100 ms to detect mirror symmetry in arrays of random dots. They also showed that replacing mirror-paired dots with randomly positioned dots hardly hampered the detection of vertical mirror symmetry. Symmetry detection is also robust against modest affine transformations such as skewing (Sawada & Pizlo, 2008; Wagemans, van Gool, & d'Ydewalle, 1991, 1992) and against translation of the symmetry axis toward peripheral presentation locations (Barlow & Reeves, 1979; Julesz, 1971; Saarinen, 1988, but see also Barrett, Whitaker, McGraw, & Herbert, 1999; Gurnsey, Herbert, & Kenemy, 1998).

The ease of symmetry detection revealed by the above studies confirms the status of symmetry as a candidate cue for perceptual grouping. However, the fact that symmetry is readily detected does not necessarily imply that symmetry aids in the segregation of an object from its background. Neurophysiological research might help answer this question by pinpointing how early in time symmetry responses arise and where in the visual system's hierarchy a symmetry-sensitive region is situated. Norcia, Candy, Pettet, Vildavski, and Tyler (2002) have studied the neural underpinnings of symmetry detection in dot arrays. They found that selectivity for symmetry at occipital locations emerges relatively late (220 ms). This suggests that symmetry detection takes place in extrastriate areas. Tyler and Baseler (1998) and Tyler et al. (2005) have used fMRI to determine the locus of symmetry specificity. They found that early visual areas (V1–V4) were not differentially activated by symmetric versus random dot patterns. However, a difference in BOLD signal was observed in a bilateral region of the lateral occipital cortex (medial and posterior to hMT/V5).

Neurophysiological and psychophysical studies on symmetry perception have mainly focused on the detection of symmetry in simple geometric patterns (e.g., Corballis & Roldan, 1974; Feldman, 2007) or in dot arrays (e.g., Norcia et al., 2002; Tyler et al., 2005). Although symmetric dot arrays usually contain the same local information as their nonsymmetric counterparts, they also reveal salient structures (contours and shapes) that are absent in the nonsymmetric arrays. Therefore, an effect observed with these dot arrays cannot be attributed solely to symmetry. As already pointed out by other researchers (Norcia et al., 2002; Sasaki, Vanduffel, Knutsen, Tyler, & Tootell, 2005), the observed effect might also be due to a differential response to perceptually salient global structures. Locher and Wagemans (1993) have explicitly examined the effect of grouping of spatial structure on symmetry detection and they observed that error rates and response times were significantly reduced when additional structures were available (see also Dry, 2008). The effect of grouping on symmetry detection has also been demonstrated by Labonté, Shapira, Cohen, and Faubert (1995). They showed that the detection of symmetry is preceded and facilitated by grouping based on proximity or similarity information. This illustrates the role of other grouping cues in the detection of symmetry. However, the Gestalt view on symmetry is yet to be tested: Is there an active role of symmetry in perceptual grouping?

Symmetry refers to a global shape characteristic, much in the same way as closure does. The key question is whether this global stimulus property also contributes to the goodness or stability of the perceptual organization. To answer this question, we believe that the spontaneous use of global symmetry information needs to be evaluated. In the experiment we present in the next section, participants had to detect a shape in a noisy background. The shape was either symmetric or asymmetric, but no explicit symmetry judgment was requested. In other words, participants were free to make use of the symmetry information to decide on the presence of a visual shape. We also made sure that no local symmetry information was available in the stimuli. This allowed us to test specifically for the effect of global symmetry on perceptual grouping.

Methods

Our research focused on the role of symmetry in figure-ground organization. More precisely, we asked whether the global symmetry of a shape helps to detect it in a cluttered background. In a two-alternative forced-choice (2AFC) task, participants had to indicate which of two sequentially presented stimuli comprised the outline of an unfamiliar two-dimensional shape. The shapes were embedded in arrays of oriented Gabor elements and were only defined by the continuation of the Gabor elements along the contour of the shape. By adding orientation noise to the contour elements, the good continuation cue was disturbed and the embedded shape became less salient (Figure 1). We directly compared the detectability of symmetric and asymmetric shapes for different levels of orientation noise. If symmetry acts as a cue in figure-ground segregation, we would predict that symmetric shapes can tolerate more orientation noise than asymmetric ones to be equally detectable.

Participants

Three experienced psychophysical observers and 39 untrained participants (mean age: 20 years, age range: 18–45 years) volunteered for this study. All participants had normal or corrected-to-normal vision. The study was performed with the informed consent of the participants and was approved by the K.U.Leuven Ethics Committee.

Stimuli and presentation

The stimuli were arrays of 308 non-overlapping Gabor elements on a gray background. Unfamiliar two-dimensional shapes were embedded in the arrays. The arrays comprised 496 × 496 pixels. Each Gabor element was defined as the product of a sine wave luminance grating (frequency of 2.5 cycles/deg) and a two-dimensional Gaussian envelope (standard deviation of 0.12 deg in both dimensions). Our choice of stimuli was inspired by Kovács and Julesz (1993) who used similar Gabor arrays to investigate the grouping of local elements into global configurations. The advantage of using Gabor elements is that they roughly model the receptive field organization of simple cells in striate cortex (Marčelja, 1980). Moreover, their orientation can easily be manipulated.

The embedded shapes were generated by summing six radial frequency components (radial frequency component k being a sine function with wavelength $2\pi/k$), with amplitudes for each sine wave chosen uniformly between 0 and 1, and plotting the sums as radial coordinates in a polar coordinate system (for an early application of radial frequency components, see Shepard & Cermak, 1973). This method yielded unfamiliar closed contour shapes. The difference between symmetric and asymmetric shapes resulted from phase shifting the individual sine waves: For symmetric shapes, the sine waves were shifted in such a way that they reached a minimum or maximum value at $\pi/2$ radians. Without this constraint, the resulting shapes were asymmetrical.

Next, each shape was scaled to such an extent that its surface area equaled one sixth of the array size. To reduce interstimulus differences in visual complexity (defined as surface area divided by squared contour length), the range of possible contour lengths was restricted. Next, we defined 32 equidistant locations along the contour of each shape and superimposed them with Gabor elements. For the symmetric stimuli, we ascertained that the 32 contour elements were not mirror-paired by shifting the starting location along the contour. In this way, we avoided the introduction of a local symmetry cue. Finally, the center of mass of each shape was colocalized with the geometric center of the array.

Thirty-four Gabor elements were then placed inside the contour of each shape. To add an element, a candidate location within the contour was selected at random. Candidate locations within 18 pixels of a previously selected Gabor element were discarded. This process was repeated until all 34 elements were placed inside the contour. The same procedure was followed for 242 Gabor elements outside the contour. After generating a Gabor array, we checked whether the local density was similar

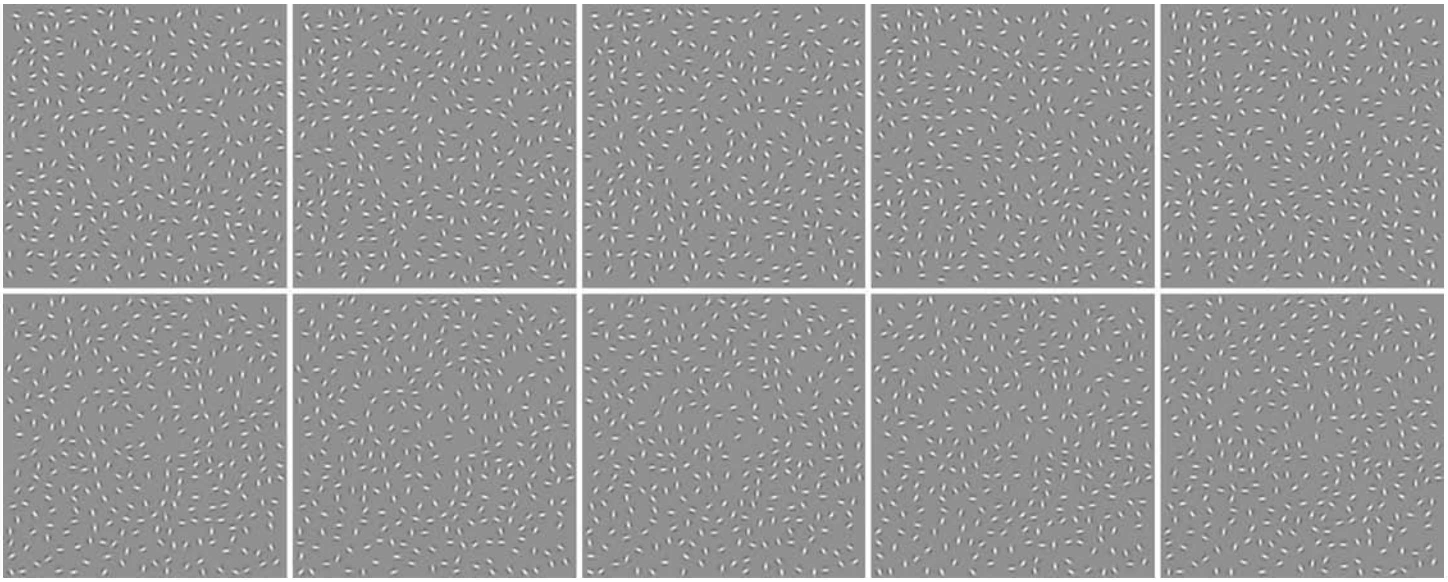

Figure 1. Sample stimuli used in the experiment, with increasing levels of orientation noise added to the elements: 0, 10, 20, 30, and 40 degrees. (Top) Symmetric shape. (Bottom) Asymmetric shape.

for interior, contour, and exterior elements. To accomplish this, we first calculated for each Gabor element the Euclidean distance to its nearest neighbor. Student's *t*-tests were applied to test for differences in Euclidean distance between interior, contour, and exterior elements. Gabor elements located within 24 pixels from the border of the array were not taken into account for the calculation of the average Euclidean distance, since these elements had fewer neighbors and, hence on average, a larger Euclidean distance to the nearest neighbor. Arrays with a significant difference in Euclidean distance between interior, contour, and exterior elements were discarded.

This procedure ensured that for all stimuli the local density is comparable for contour, interior, and exterior elements or, in other words, that contour elements were not detected by proximity grouping. We also made sure that the set of symmetric stimuli and the set of asymmetric stimuli did not differ in the continuation along the contour of the shapes. To this end, we first calculated the total angular difference between the adjacent contour elements with orientations parallel to their local tangent. We then selected subsets of symmetric and asymmetric stimuli for which no systematic difference in summed deviation angles was present.

One thousand symmetric and one thousand asymmetric stimuli were used in the experiment, each with a different 2D shape embedded in the array. Over all stimuli, the average center-to-center distance between the Gabor elements was 0.61 visual degrees. The orientation of interior and exterior Gabor elements was sampled uniformly between 0° and 180°. For a contour element, we always started from the curvilinear orientation, parallel to the local tangent of the contour. For non-target stimuli, we added orientation noise sampled uniformly between plus or minus 45° and 90° to the curvilinear contour orientation. For target stimuli, orientation noise from a Gaussian distribution centered around zero was added to the curvilinear contour orientation. By increasing the standard deviation of the Gaussian noise distribution, more orientation noise was added to the elements, and hence, the grouping of the elements was impeded. For each stimulus, we created 6 different noise levels, with average orientation noise per element 15°, 20°, 25°, 30°, 35°, or 40°.

A set of visual masks was created by scrambling the phase spectra of the original Gabor arrays following a circular normal (vonMises) distribution.

The stimuli were generated in the MATLAB environment and were presented using the Psychophysics Toolbox extensions (Brainard, 1997). To display the stimuli, we used a 21″ Sony GDM-F520 CRT monitor with a screen resolution of 1152 × 864 pixels and a frame rate of 85 Hz. The luminance of the gray background was approximately 40 cd/m^2. A chin rest was used to ensure a fixed viewing distance of 90 cm. At this distance, the stimuli subtended 11.5 degrees of visual angle. The room was darkened for the entire duration of the experiment.

Task and procedure

Detectability of visual shapes was measured using a 2AFC procedure, in which one interval showed a target stimulus depicting a Gabor array with an embedded visual shape whereas the other showed a non-target stimulus with no visible shape. A trial consisted of a fixation cross, a target (nontarget) stimulus, a non-target (target) stimulus, and a uniform gray answer screen, all separated by visual masks (Figure 2). We randomized all trials for stimulus

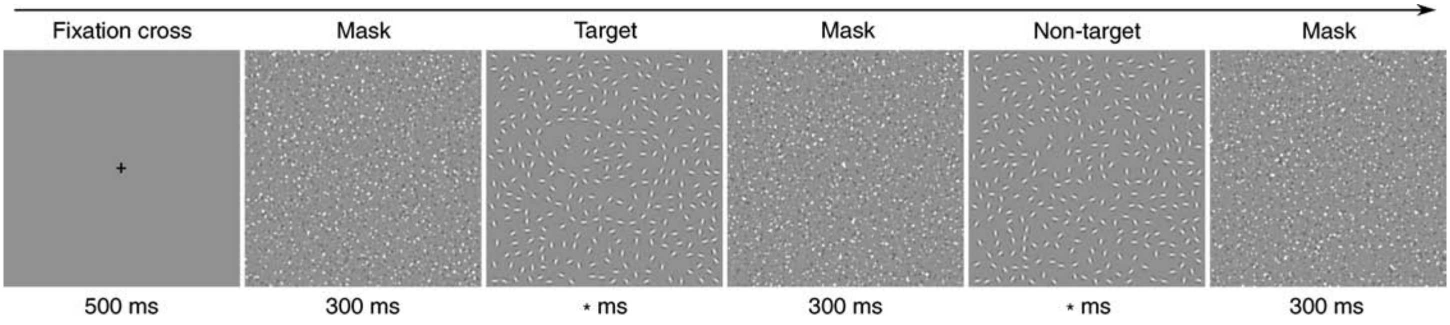

Figure 2. Time course of a trial. *The presentation time for target and non-target was defined on an individual level using an adaptive procedure (see text).

class (symmetry or asymmetry), time window (target in first or second interval), and orientation noise (15°, 20°, 25°, 30°, 35°, or 40°). After each trial, participants indicated with a button press which interval contained the visual shape. No symmetry judgment was required. Auditory feedback was given after each response. Stimuli were presented in blocks of 50 trials.

All subjects first participated in a training phase with 400 trials to get acquainted with the task. During the last 300 trials of the training phase, all stimuli had a medium level of difficulty: 27.5° of orientation noise. Stimulus presentation time started at 200 ms and was subsequently adjusted using an adaptive method (Watson & Pelli, 1983). This procedure enabled us to find the presentation time at which an observer reached a performance level of 75% correct. It follows from the instantaneous nature of visual perception that a possible advantage of vertical symmetry should be obvious at short presentation times. Therefore, we limited the allowed presentation times to a maximum of 350 ms. Participants who needed longer presentation times were discarded. As such, 13 unexperienced and 3 trained psychophysical participants were selected. The shortest required presentation time was 101 ms and the longest required presentation time was 347 ms.

After the training phase, the remaining 16 participants performed another 1500 trials. The task remained the same, but six different noise levels were now presented: 15°, 20°, 25°, 30°, 35°, or 40° of orientation noise. Presentation time for target and non-target stimuli varied between individuals, based on the performance in the adaptive training phase. For each combination of stimulus class and orientation noise level, 125 responses were registered.

Statistical analysis

A random intercepts (modified) logistic regression analysis predicting correct detection with stimulus class and orientation noise as fixed effects and participant as a random intercept was performed on the data. Since we did not sample the extremes of the orientation noise continuum, detection performance at our highest noise condition was still well above chance level. Therefore, we estimated the lower bound (γ) of detection performance (π_D) from the data, i.e., the link function is logit $(\frac{\pi_D-\gamma}{1-\gamma})$. The statistical analysis was performed with SAS procedure NLMIXED (SAS version 9.2).

Results

Figure 3 displays the observed detection performance for both the symmetric and the asymmetric trials, averaged over participants. The interaction term of stimulus class (symmetric/asymmetric) and orientation noise level was not statistically significant ($t(15) = -0.75$, $p = 0.47$). In the model without the interaction term (see Table 1 for parameter estimates and 95%

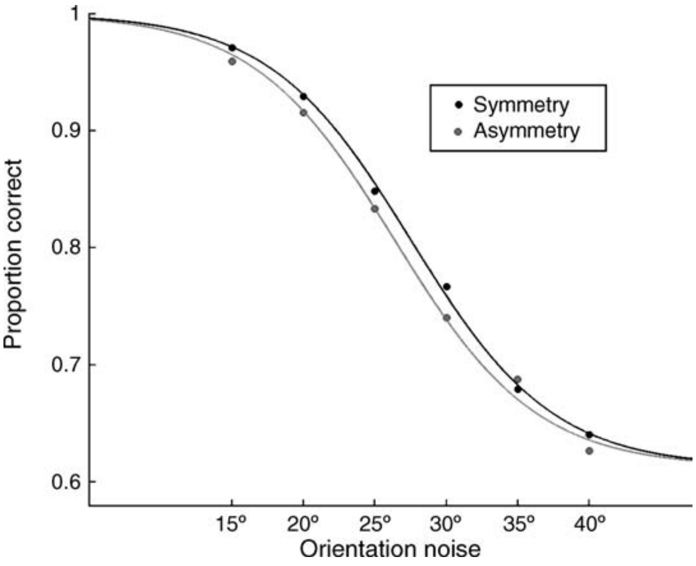

Figure 3. Observed percentage correct for detection of symmetric (black dots) and asymmetric (gray dots) shapes plotted as a function of orientation noise. Each data point corresponds to 2000 trials. A modified logistic regression function (see text) was fitted through the data.

Parameter	Estimate (SE)	*p*-value	95% Confidence interval
Intercept	5.33 (0.21)	<0.0001	[4.88, 5.79]
Orientation noise	−0.20 (0.01)	<0.0001	[−0.22, −0.18]
Stimulus class	0.23 (0.07)	0.0057	[0.08, 0.38]

Table 1. Parameter estimates for the modified logistic random intercept analysis obtained from Proc SAS NLMIXED.

confidence intervals), the effect of orientation noise was significant ($t(15) = -21.19$, $p < 0.0001$): Detecting a visual shape became harder when more orientation noise was added to the Gabor elements. When correcting for the orientation noise level, the stimulus class was significantly related to the response ($t(15) = 3.22$, $p = 0.0057$). The symmetry benefit, reflected by the lateral shift between the two curves in Figure 3, was 1.14°. The analysis further showed the necessity of the random intercept ($p < 0.0001$).

Note that the three authors who participated in the experiment were included in the above analysis. We do not expect this to have a major influence on the results, because the randomization of conditions, the short presentation times, and the amount of orientation noise added to the contour elements made a bias toward a symmetry benefit unlikely. Nevertheless, we repeated the analysis with the 13 naive participants only. Similar effects were observed. Again, a significant main effect for orientation noise ($t(12) = -18.84$, $p < 0.0001$) and for stimulus class ($t(12) = 2.67$, $p = 0.02$) was found, with no interaction between stimulus class and orientation noise level ($t(12) = -0.06$, $p = 0.95$). In summary, we conclude that because of (1) the absence of an interaction between stimulus class and noise level and (2) the significant effect of the stimulus class on the response, the advantage of vertical symmetry in shape detection is irrespective of the noise level.

Amount of symmetry

In the above analyses, we made a strict distinction between symmetric and asymmetric stimuli. However, the asymmetric stimuli varied somewhat in their symmetry along the vertical axis. Some asymmetric shapes showed more vertical mirror symmetry than others. As an index for vertical mirror symmetry, we calculated the proportion of overlap in the area of the figure when it is flipped over the vertical axis. This yielded a value of 1 for all symmetrical shapes and ranged between 0.62 and 0.91 for the asymmetric shapes. An a posteriori analysis on the asymmetric trials with the vertical mirror index as the only regressor showed that vertical symmetry leads to a better detection performance ($p < 0.0001$). The same conclusion was obtained when we performed the analysis (on both symmetric and asymmetric trials) around the horizontal axis, i.e., more horizontal symmetry also yields a better detection performance ($p = 0.0013$).

Discussion

Our results show that vertical mirror symmetry does act as a cue in perceptual organization. We are confident that we applied a very conservative way of testing the null hypothesis. The only difference between our two sets of stimuli pertained to vertical mirror symmetry. Unlike the dot arrays in the aforementioned studies, our Gabor arrays were not contaminated with unwanted grouping cues. We controlled for surface area, contour length, continuation along the contour, local density, and number of Gabor elements. The equidistance of the contour elements could not act as a grouping cue, since it was only defined along the embedded contour (i.e., the exact Euclidean distance varied between contour pairs). Moreover, the use of unfamiliar shapes ensured that no systematic lexical differences between symmetric and asymmetric stimuli could influence the results. In our design, no direct symmetry judgment was required from the participants. Nonetheless, our data show that symmetry information was used to decide on the presence of a shape outline in the Gabor arrays. As such, our findings support the Gestaltists' claim: Symmetry is used as a cue in perceptual organization.

As we argued before, symmetry is a nonaccidental property: An impression of symmetry is most likely induced by a real (symmetric) object. In fact, a perfect bilateral mirror symmetry, which is seen from a non-orthogonal viewpoint, gives rise to a skewed symmetry in the projected retinal images and skewed symmetry can, therefore, be used to infer mirror symmetry in the world. Empirical research also suggests that skewed symmetry is indeed used this way (Saunders & Knill, 2001; Wagemans, 1992, 1993). This nonaccidental property of symmetry even leads viewers to assume 3D bilateral symmetry when interpreting 2D asymmetric shapes (McBeath, Schiano, & Tversky, 1997), a bias toward symmetry, which is also found for other regularities (Feldman, 2000).

The nonaccidental characteristic of symmetry also plays an important role in Biederman's (1987) recognition-by-components theory. In this theory, bilateral symmetry is one of the nonaccidental properties used to quickly identify "geons", the basic building blocks of object recognition. According to Biederman, bilateral symmetry should therefore be processed preattentively. The common finding that symmetry is detected efficiently in brief presentations supports the view that the underlying mechanism works preattentively. More support for the preattentive detection of mirror symmetry comes from

Baylis and Driver (1994). They showed that discriminating between symmetric and asymmetric filled polygons did not depend much on the number of steps along the jagged edge of the polygon. This suggests a parallel preattentive process.

Other studies have shown, however, that visual symmetry does not pop-out but instead requires a serial visual search process (Olivers & van der Helm, 1998). Moreover, another line of studies has investigated how regularity detection interacts with objectness, suggesting that the symmetry of a pair of contours is easier to detect when they belong to the same object, whereas their repetition is easier to detect when two objects are concerned (Baylis & Driver, 1994; Friedenberg & Bertamini, 2000; Koning & Wagemans, 2009). Note that the paradigm that we are using does not fit in a two-stage model of visual attention. This class of models claims that the visual input is segregated into figure and background preattentively, before attention is drawn to the segregated objects. With the artificial stimuli we used, figure-background segregation and object detection are two sides of the same coin. Segregating the figure from the background and detecting the visual shape hidden in the background happen simultaneously.

Driver, Baylis, and Rafal (1992) reported results from a neuropsychological case study that also favor the idea that symmetry can be derived preattentively. They investigated symmetry detection in a patient with object-centered hemineglect: He failed to attend to the left side of objects. Because he could not compare both sides of an object, he was unable to detect vertical symmetry. Interestingly, when asked which of the two sets of shapes were seen as figures against a background, he clearly preferred the symmetrical shapes in much the same way as normal observers do (Bahnsen, 1928). This observation indicates that covert symmetry detection is intact during the preattentive stage of figure-ground segregation. The visual neglect only arises when explicit symmetry judgments are to be made on the segregated figure.

The Gestalt view on symmetry has been downplayed by a number of authors (Jenkins, 1983; Labonté et al., 1995; Pashler, 1990). The common argument is that grouping based on other principles precedes and facilitates symmetry detection. For instance, in random dot arrays coherent structures around the symmetry axis are detected by means of proximity or collinearity grouping. These salient structures are then used as a cue to discriminate between symmetric and nonsymmetric dot patterns. In their eccentricity study, Gurnsey et al. (1998) found that symmetry embedded in an array of Gaussian blobs was only detected accurately at fixation. They argue that since symmetry is not detected accurately across the visual field, it cannot play a significant role in image segmentation. Symmetry only becomes relevant for the visual system after it is fixated. With the central presentation of our stimuli, we observed a small benefit of symmetry on shape detection. Since symmetry detection becomes less accurate with increasing eccentricity, a measurable symmetry benefit becomes less likely when the shapes are presented away from central fixation.

In our stimuli, symmetry was only defined on a global, configural level. There was no local symmetry in the positions of the Gabor elements. Therefore, the detection of global symmetry could only follow the local grouping based on collinearity of the Gabor elements. Preattentive detection of symmetry was therefore not possible in our experiment. However, after (or during) the process of global symmetry detection, symmetry does contribute to the perceptual organization of the visual input. Probably symmetry only comes into play in interaction with other grouping cues that (partly) precede the symmetry grouping. A similar interactive view on the interrelationships between more local or semi-local grouping at the element level and more global or semi-global grouping at the object or object-part level was presented in the context of fragmented outline identification (Panis & Wagemans, 2009). It is also consistent with an incremental but not purely serial symmetry detection mechanism, as proposed in the bootstrap model (Wagemans, van Gool, Swinnen, & Van Horebeek, 1993; see also Dry, 2008). In this view, the symmetry advantage will be most pronounced when grouping based on other cues is too slow or when that grouping leads to ambiguous interpretations of the visual input. More research is needed to test this assumption.

Conclusions

Using a controlled set of stimuli and a simple psychophysical task, we showed that observers take advantage of vertical symmetry information in deciding on the presence of a shape outline in arrays of oriented Gabor elements. This finding indicates that vertical mirror symmetry helps to segregate a figure from a background.

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