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Symmetry and repetition in perspective

Gert van der Vloed [a,*], Árpád Csathó [b], Peter A. van der Helm [a]

[a] *Nijmegen Institute for Cognition and Information, Radboud University Nijmegen, Montessorilaan 3, 6525 HR Nijmegen, The Netherlands*

[b] *Faculty of Medicine, Institute of Behavioral Sciences, University of Pécs, H-7624 Pécs, Szigeti u. 12, Hungary*

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Abstract

Although ecologically relevant, perspective views of symmetries and repetitions have hardly been investigated. Any symmetry or repetition that is not oriented orthogonally to the line of sight yields perspective distortions on the retina. In this study, these distortions are analyzed in terms of first-order structures (i.e., virtual lines between corresponding points) and second-order structures (i.e., correlation quadrangles formed by two virtual lines). In the literature, these structures have been proposed to guide the detection of frontoparallel symmetry and repetition. But what about perspective views? First, the analysis in this study shows that perspective distorts the retinal first-order and second-order structures of symmetry and repetition differently. Second, the results of two experiments on this distortion difference suggest that, in perspective views, symmetry and repetition detection is not preceded by normalization but occurs directly on the basis of the retinal first-order and second-order structures.

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* Corresponding author.
E-mail address: g.vandervloed@nici.ru.nl (G. van der Vloed).

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1. Introduction

In this study, we investigate the effects of perspective distortions on symmetry and repetition detection. Symmetry (also called bilateral or mirror symmetry) and repetition (also called transpositional or translational symmetry) are regularities that the human visual system uses to process and structure the information that enters through the retina (Palmer, 1983; Wagemans, 1995). For instance, many living organisms and many man-made objects possess some form of symmetry. There has been a lot of research into the detection of symmetry (for overviews see Tyler, 1996; van der Helm & Leeuwenberg, 1996; Wagemans, 1995). Repetition has been investigated less extensively (e.g., Baylis & Driver, 1994, 2001; Bertamini, Friedenberg, & Kubovy, 1997). So far, research on these two regularities has focused mainly on their detection when presented two-dimensionally viewed head on. Then, these regularities do not have the perspective distortions that are characteristic of views of real world objects. Symmetrical objects rarely have their symmetry planes exactly aligned with the line of sight of the observer, and repeats rarely are viewed head on at an equal distance of the viewer. Hence, the usefulness of a symmetry and repetition detection mechanism depends crucially on its susceptibility to symmetries and repetitions with perspective distortions. As far as we know, the effects of perspective distortions have not been investigated for repetition and only to a limited extent for symmetry.

Szlyk, Rock, and Fisher (1995), for instance, asked participants to judge the symmetry or asymmetry of surface patterns and multi-element patterns. Patterns were presented either frontoparallel or 65° slanted from the line of sight. Asymmetrical images were construed in a way that would yield a symmetrical image on the retina when viewed at a 65° angle. They found that, with full depth-cues, participants responded primarily to the objective shape of the distal images while, with reduced depth information, participants responded primarily to the proximal projection. They concluded that symmetry perception must take place at a relatively late, post-constancy, stage of processing, that is depth perception must precede an analysis of symmetry. This allows symmetry to be processed by its objective distal shape under appropriate depth cueing.

Furthermore, Locher and Smets (1992) constructed three types of symmetry stimuli: two-dimensional (2-D) stimuli with all symmetry pairs in the same plane, three-dimensional (3-D) stimuli with depth differences between symmetry pairs, and four-dimensional (4-D) stimuli consisting of 3-D stimuli that rotated during stimulus presentation. They found that symmetry detection deteriorated when stimuli were not viewed orthogonally and that increasing stimulus dimensionality did not improve performance. For the 4-D stimuli, performance actually was worse than for the 2-D stimuli. They suggested, without further specification, that this might have something to do with the structural relations described by Jenkins (1983) and Wagemans, van Gool, and d'Ydewalle (1991). These structural relations are the focus of the current study.

We first present a theoretical analysis of these structural relations and how they are affected by perspective. Then, we report two experiments in which we investigated the effect of perspective distortions of these structural relations on symmetry and repetition detection.

1.1. Structural relations in symmetry

In a symmetry pattern, all the virtual lines between symmetry points are parallel and have midpoints that are colinear. In an analysis of component processes of symmetry perception, Jenkins (1983) concluded that, to detect symmetry, the human visual system first detects the orientational uniformity of these virtual lines, and after that their midpoint colinearity.

Wagemans et al. (1991), however, argued that these two factors are not enough to explain symmetry detection. They investigated skewing of symmetry patterns using affine transformations. Then, Jenkins' orientational uniformity and midpoint colinearity are preserved. However, the detection of skewed symmetry is considerably worse than the detection of unskewed symmetry. Therefore, Wagemans et al. (1991) proposed that, in the processing of symmetry, there has to be a role for second-order structures called 'correlation quadrangles' (i.e., symmetrical trapezoids formed by pairs of virtual lines), and Wagemans, van Gool, Swinnen, and van Horebeek (1993) implemented this idea in a plausible process model (see also van der Helm & Leeuwenberg's, 1999, reply to Wagemans, 1999). These second-order structures are undistorted in unskewed symmetries, but are distorted in skewed symmetries. In a skewed symmetry, the virtual lines still show orientational uniformity and midpoint colinearity, but they no longer form symmetrical trapezoids. Due to the preserved first-order structures, skewed symmetries can still be matched to their unskewed originals (Wagemans, 1993) but, according to Wagemans et al. (1991), the loss of second-order structures explains the detectability difference in between skewed and unskewed symmetries.

Skewing by affine transformations seems an appropriate manipulation given the objective of Wagemans et al. (1991) to study the relevance of the second-order structures, but it does not seem appropriate given our objective to study the effects of perspective distortions. Affine transformations yield an approximation of perspective distortions. This approximation is perhaps good if the depth changes in the stimulus are small relative to the viewing distance, but not in general. For instance, under an affine transformation, a perfect repetition remains a perfect repetition (see below), which is generally not true under perspective. Also in symmetry, perspective generally destroys more than affine transformations do. (For a more detailed overview of the relation between affine and perspective transformations, we refer to Wagemans, van Gool, Lamote, & Foster, 2000.)

For instance, Fig. 1A depicts a frontoparallel view of a symmetry, Fig. 1B depicts the same symmetry rotated about its axis, and Fig. 1C depicts this symmetry rotated about an axis orthogonal to the symmetry axis. Fig. 1C still shows a perfect symmetry, but Fig. 1B shows drastic distortions that are illustrated further in Fig. 2. That is, when a symmetry pattern is rotated about its symmetry axis, not just second-order structures are distorted, but orientational uniformity and midpoint colinearity are also lost. Because the virtual lines connecting symmetry points are slanted with

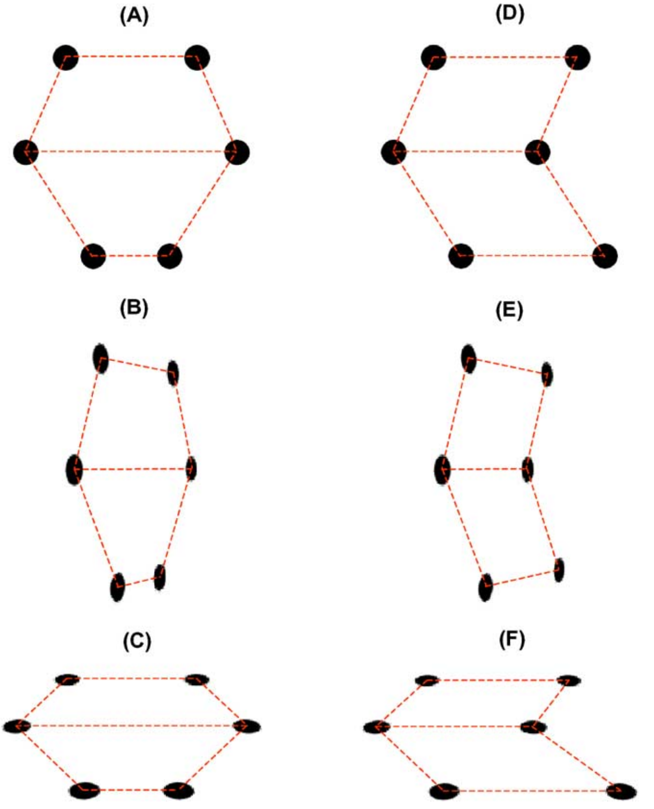

Fig. 1. A symmetry (left column) and a repetition (right column) in three different orientations: (A,D) frontoparallel orientation, (B,E) rotated about the vertical midline and (C,F) rotated about the horizontal midline.

respect to the viewpoint of the observer, they converge towards a vanishing point when projected onto a 2D plane such as the retina. This destroys orientational uniformity (i.e., the lines are no longer parallel). Furthermore, the virtual lines only share midpoints if they have equal lengths, and the symmetry axis no longer coincides with the midpoints of the virtual lines: When the distance between two symmetry points increases, their midpoint moves farther away from the symmetry axis in the direction of the symmetry half that is slanted towards the observer.

1.2. Structural relations in repetition

Just as symmetry, repetition also has first-order and second-order structures. As Jenkins noted, the virtual lines connecting corresponding elements in repeats not only have orientational uniformity but also uniform size. Furthermore, in terms of Wagemans' second-order structures, repetition also has correlation quadrangles, namely, parallelograms. When a repetition is skewed using affine transformations

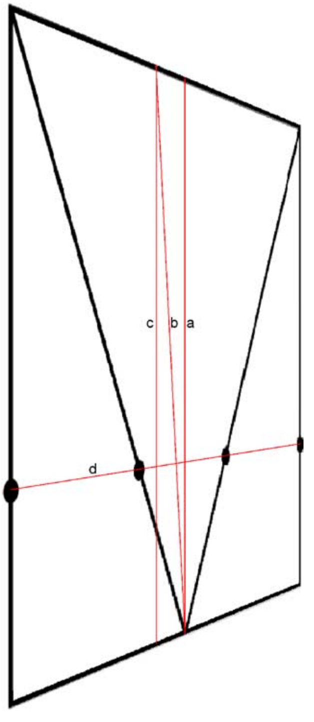

Fig. 2. Loss of midpoint colinearity for symmetries rotated about their symmetry axes. Line 'a' coincides with the symmetry axis, that is, with the midpoints of the lines connecting symmetry points in 3-D space, for the triangle as well as for the rectangle. In the 2-D image, however, line 'b' coincides with the retinal midpoints of the rotated triangle, and line 'c' coincides with the retinal midpoints of the rotated rectangle. Line 'd' illustrates that retinal midpoints of the triangle (where line 'b' intersects with line 'd') are closer to the symmetry axis (line 'a') than retinal midpoints of the rectangle (where line 'c' intersects with line 'd').

this always results in another perfect repetition. Whereas the trapezoids in a symmetry are distorted by skewing, the parallelograms in a repetition transform into new parallelograms, thus producing another perfect repetition. Under perspective, however, the first-order and second-order structures in repetition are distorted. The distortions in repetition are different from the distortions in symmetry.

For instance, Fig. 1D depicts a frontoparallel view of a repetition, Fig. 1E depicts the same repetition rotated about the axis that separates the two repeats, and in Fig. 1F the repetition is rotated about an line orthogonal to that. Just as in the case of symmetry, orientational uniformity is lost when a repetition is rotated about the axis that separates the two repeats. Then, uniform size is also lost, as illustrated in Fig. 3. That is, first, when two corresponding points are closer to the observer, the retinal distance between these points is larger than when the two points are farther away from the observer. Second, when a horizontal line is leveled with the eye of the beholder its retinal projection remains a horizontal line, but when it is presented higher or lower its retinal projection deviates from a horizontal line and becomes, moreover, longer as the deviation becomes larger.

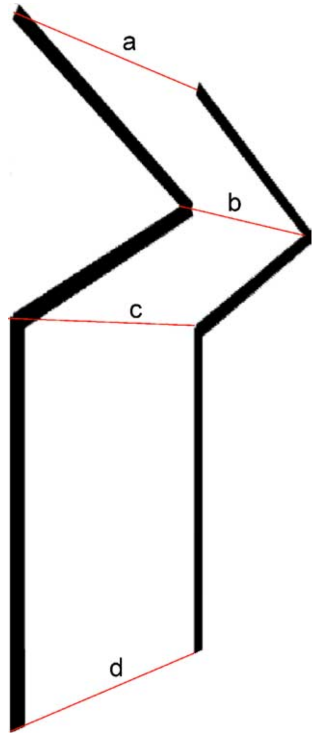

Fig. 3. Corresponding points in a repetition are farther apart when these points are close to the observer (line 'a'), and are closer together when these points are farther away from the observer (line 'b'). When two points of a horizontal repetition are leveled with the eye of the observer, they form a horizontal line (line 'c'), and when they are lower (or higher) they become oblique (line 'd').

When a repetition is rotated about the axis orthogonal to the axis that separates the two repeats, orientational uniformity is preserved but uniform size is lost. Virtual lines between corresponding points are longer in the parts that are slanted towards the observer and shorter in the parts that are slanted away from the observer. Because a parallelogram requires two pairs of lines with equal length, the second-order structures also get distorted.

In the experiments reported here, we used symmetries with a vertical symmetry axis, and repetitions with a horizontal transposition. We looked at the effect of perspective distortions by rotations about a vertical axis (henceforth Y-rotations) and a horizontal axis (henceforth X-rotations). For symmetry, Y-rotations are rotations about the symmetry axis and X-rotations are rotations about an axis orthogonal to the symmetry axis. For repetition, Y-rotations are rotations about the axis separating the two repeats and X-rotations are rotations about an axis orthogonal to that. On the one hand, in both a Y-rotated symmetry and a Y-rotated repetition all structural relations are distorted. On the other hand, in an X-rotated symmetry all structural relations are preserved, but in an X-rotated repetition only orientational uniformity is preserved. We therefore expect a larger difference between the two types of rotation for symmetry than for repetition.

At this point, it is expedient to emphasize that this study does not focus on differences between X-rotations and Y-rotations in general, but that it uses these rotations merely as a means to investigate differences between symmetry and repetition under ecologically valid distortions. Furthermore, to control for effects of other 3-D cues, we used two stimulus types, namely, dot patterns and blob patterns. Dot patterns consisted of black dots on a white background without an explicit outline, and blob patterns consisted of black and white irregular blobs within a fairly explicit outline. Rotated dot patterns provide a relatively strong 3-D cue by the gradients in dot size, dot spacing, and dot shape, whereas rotated blob patterns provide a relatively strong 3-D cue by the explicit outline.

2. Experiment 1: Symmetry

2.1. Method

2.1.1. Participants

Twenty participants (5 males and 15 females) performed the experiment. They were aged between 21 and 29 and had normal or corrected-to-normal visual acuity. All participants were undergraduate or postgraduate students at the Radboud University Nijmegen, and were paid or received course credits.

2.1.2. Stimulus materials

Two stimulus types were used (see Fig. 4). One stimulus type consisted of Gaussian blob patterns, composed of black and white patches. These patterns were created as follows: The image was filled with random Gaussian noise and blurred with a Gaussian filter with an 8-pixel radius. Afterwards, the pattern was thresholded to obtain black and white images. The other stimulus type consisted dot patterns. Black dots with a pixel radius of 23 pixels were placed on a white background. For both stimulus types, random stimuli were produced by creating an entire stimulus in one go, and vertical symmetries were produced by creating first one pattern half which then was mirrored to get the other half. The luminance of the black stimulus parts was 0.31 cd/m^2 and the luminance of the white stimulus parts was 99.8 cd/m^2.

Perspective distortions in these patterns were created using an openGL program with a simulated viewing distance of 10 cm. Each pattern was rotated in 3-D at four different angles (−60°, −30°, 30° and 60°) about the vertical midline and the horizontal midline, respectively. The orthofrontal image subtended 5.1° visual angle for both width and height. For the rotated images the visual angle changed as follows. Parallel to the rotation axis, the side that was tilted towards the observer increased to 5.9° and 6.6° visual angle for the 30° and 60° rotations, respectively; the side that was tilted away from the observer decreased to 4.6° and 4.1° visual angle, respectively. Orthogonal to the rotation axis, the width of the stimulus decreased to 3.9° and 2.7° visual angle, respectively.

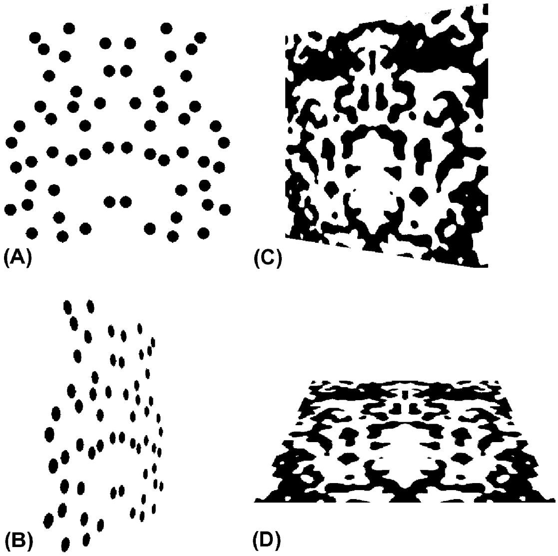

Fig. 4. Examples of symmetry stimuli: (A) a frontoparallel dot pattern, (B) the same dot pattern rotated 60° about the vertical midline, (C) a blob pattern rotated −30° about the vertical midline and (D) the same blob pattern rotated 60° about the horizontal midline.

Ten different stimuli were produced for each subcondition. The total experiment consisted of 360 trials: Stimulus Type $2 \times$ Symmetric or Random $2 \times$ Orientation $9 \times$ Stimuli 10.

2.1.3. Apparatus

A standard PC and a Philips 109B monitor with a 1024×768 pixel resolution were used to present the stimuli. The stimuli were displayed on a white background. The participants viewed the screen from a distance of 185 cm and a button box was used to record their responses.

2.1.4. Procedure

Participants were instructed to discriminate symmetry stimuli in various 3-D orientations from random stimuli in various 3-D orientations by pressing the appropriate button on the button box. It was emphasized that fixation should be maintained throughout each trial and responses should be made as quickly and accurately as possible.

The two stimulus types were presented in separate blocks. Block order was counterbalanced over subjects. The order of the stimuli within each block was randomized. Before each block participants performed 18 practicing trials with feedback about the correctness of their response. During the actual experiment, no feedback was given. Before the test stimulus appeared, a fixation cross was presented centered on the screen for 500 ms, followed by a blank screen for 500 ms, after which the stimulus was presented for 60 ms. Reaction times (RTs) were measured from the onset of the pattern.

2.2. Results

Because the frontoparallel condition should be included in the analysis of the *X*-rotations as well as in the analysis of the *Y*-rotations, these analyses were run separately and the interactions with rotation axis were analyzed excluding the frontoparallel condition. RT analyses were done for all responses (i.e., both correct and incorrect responses). All pairwise comparisons between the same degree of rotation in opposite directions were run, yielding no significant differences for RTs nor for error rates. Therefore, in further investigations of rotation effects, no comparisons were made between negative and positive angles of rotation. The data for the random stimuli were also analyzed. These data show no evidence of trade-offs with the data patterns for symmetry. Therefore, these data are not discussed further. The data for symmetry are depicted in Fig. 5.

2.2.1. X-rotation

The effect of rotation was significant for RTs, $F(4,16) = 5.777$, $p < .01$, but not for error rates. Further investigation of this effect revealed that participants were significantly slower for the 60° conditions than for the 30° conditions and the frontoparallel condition $F(1,19) = 13.750$, $p < .01$, while there were no significant differences between the frontoparallel condition and the 30° conditions.

2.2.2. Y-rotation

The effect of rotation was significant for both error rates, $F(4,16) = 10.884$, $p < .001$, and RTs, $F(4,16) = 28.259$, $p < .001$. Further investigation of these effects revealed that participants were significantly slower, $F(1,19) = 12.738$, $p < .005$, and made more errors, $F(1,19) = 8.598$, $p < .05$, in the 30° conditions than in the frontoparallel condition. Furthermore, participants were slower, $F(1,19) = 127.141$, $p < .001$, and made more errors, $F(1,19) = 21.828$, $p < .001$, in the 60° conditions than in the 30° conditions and the frontoparallel condition.

2.2.3. X-rotation versus Y-rotation

There was a main effect of Rotation Axis for both error rates, $F(1,19) = 52.876$, $p < .001$, and RTs, $F(1,19) = 34.865$, $p < .001$. Participants were faster and made fewer errors for *X*-rotations than for *Y*-rotations. The interaction between axis of rotation and the amount of rotation was significant for both error rates $F(3,17) = 4.615$, $p < .05$ and RTs $F(3,17) = 4.307$, $p < .05$. Further investigation of this interaction revealed that, for *Y*-rotation, participants made more errors in the 60° conditions than in the 30° conditions, $F(1,19) = 16.741$, $p < .001$. For *X*-rotation, this difference was not significant. Furthermore, for both *X*-rotation and *Y*-rotation, participants were slower in the 60° conditions than in the 30° conditions. This effect was significantly stronger for *Y*-rotation than for *X*-rotation, $F(1,19) = 13.079$, $p < .001$.

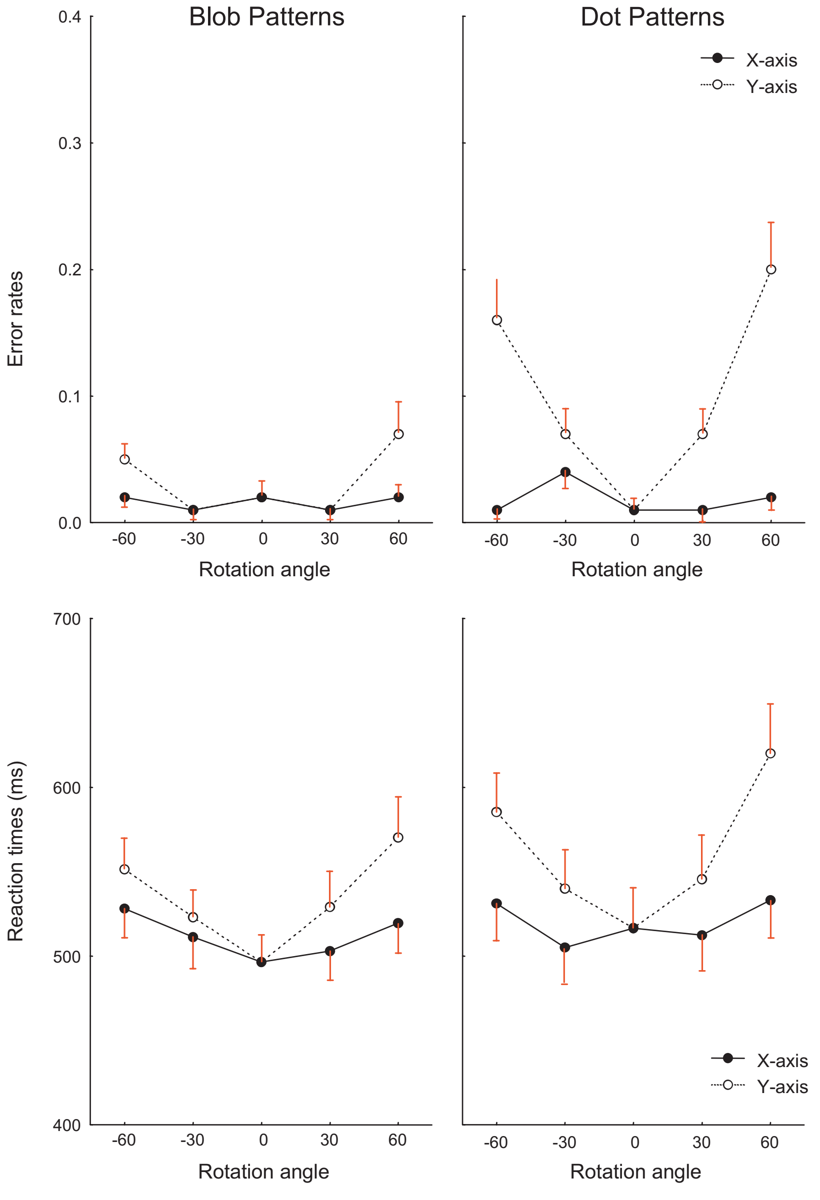

Fig. 5. Error rates and reaction times for symmetry patterns.

There also was a significant interaction between stimulus type and axis of rotation for both error rates, $F(1,19) = 29.155$, $p < .001$, and RTs, $F(1,19) = 7.963$, $p < .05$. Further investigation revealed that, for X-rotations, there was no significant difference in error rates between dot stimuli and blob stimuli. For Y-rotations, however, participants made significantly more errors for dot patterns than for blob patterns, $F(1,19) = 33.501$, $p < .001$, and showed a non-significant tendency to be slower for dot patterns than for blob patterns, $F(1,19) = 3.387$, $p = .081$.

2.3. Discussion

In terms of retinal stimulus properties, the results are in compliance with the hypothesis that symmetry perception weakens when orientational uniformity, midpoint colinearity, and second-order structures are distorted. The effects of *Y*-rotation were stronger than the effects of *X*-rotation. In addition to this effect of rotation axis there was also an interaction between rotation axis and the angle of rotation. The difference between *Y*-rotation and *X*-rotation became larger with larger rotation angles.

The fact that there was still a significant effect of *X*-rotation for reaction times when the stimulus was 60° rotated, could be explained by the fact that the stimulus size was greatly reduced compared to the frontoparallel condition and that the stimulus elements vary more in spatial scale. In a previous research (Csathó, van der Vloed, & van der Helm, 2003) we showed that symmetry perception may be hindered when a symmetry is composed of areas with different spatial scales.

For *Y*-rotation, the proportion of errors was lower for blob patterns than for dot patterns. This can be explained in terms of a matching problem, as follows. The perspective shear by *Y*-rotation produces a size difference between corresponding dots or blobs. This size difference, together with the absence of orientational uniformity, creates a problem of matching corresponding elements, but less so for the blobs because, in contrast to the dots, the blobs can still be distinguished on the basis of their uniqueness in shape. The absence of such an effect for *X*-rotation could be explained by the fact that, in *X*-rotated stimuli, both the size of corresponding elements and the orientational uniformity are preserved, so that matching does not have to rely on the unicity of element shapes.

3. Experiment 2: Repetition

3.1. Method

The participants in Experiment 1 also participated in Experiment 2. The construction of the stimulus materials was the same as in Experiment 1 with two exceptions. First, to create repetition stimuli, the stimulus part on the left-hand side of the vertical midline was made identical to the stimulus part on the right-hand side of the vertical midline. Second, for blob stimuli, the random stimuli were created out of two separate halves, to introduce discontinuities along the vertical midline. In blob patterns, such discontinuities are not present in symmetry but are present in repetition (see Fig. 6). Introducing such discontinuities in the random stimuli as well, avoids that participants can discriminate repetition from random on the basis of the presence or absence of these discontinuities alone.

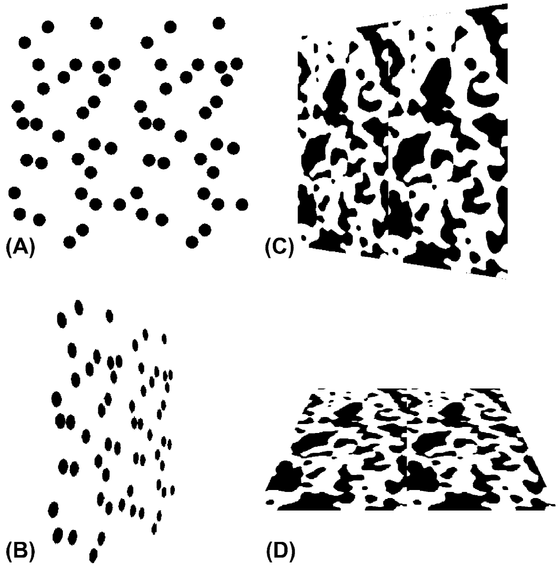

Fig. 6. Examples of repetition stimuli: (A) a frontoparallel dot pattern, (B) the same dot pattern rotated 60° about the vertical midline, (C) a blob pattern rotated −30° about the vertical midline and (D) the same blob pattern rotated 60° about the horizontal midline.

Apparatus and procedure were identical to those of Experiment 1 with one exception. Under equal presentation times, orthofrontal symmetry is known to be far better detectable (i.e., faster and more accurate) than orthofrontal repetition. Therefore, in Experiment 2, the stimuli were presented for 400 ms instead of 60 ms to make the task difficulty better comparable to the task difficulty in Experiment 1.

3.2. Results

Like in Experiment 1, separate analyses were run for X-rotations and Y-rotations including the frontoparallel condition, and the interactions with rotation axis were analyzed excluding the frontoparallel condition. RT analyses were done for all responses (i.e., both correct and incorrect responses). No pairwise comparison between the same degree of rotation in opposite directions yielded a significant difference for RTs or for error rates. Therefore, in further investigations of the effects of rotation angle, no comparisons were made between negative and positive angles of rotation. The data for the random stimuli were also analyzed. These data show no evidence of trade-offs with the data patterns for repetition. Therefore these data are not discussed further. The data for repetition are depicted in Fig. 7.

3.2.1. X-rotation

The main effect of rotation was significant for RTs, $F(4,16) = 3.836$, $p < .05$, and for error rates, $F(4,16) = 4.161$, $p < .05$. The main effect of stimulus type was significant for error rates, $F(1,19) = 9.181$, $p < .01$. Participants made more errors

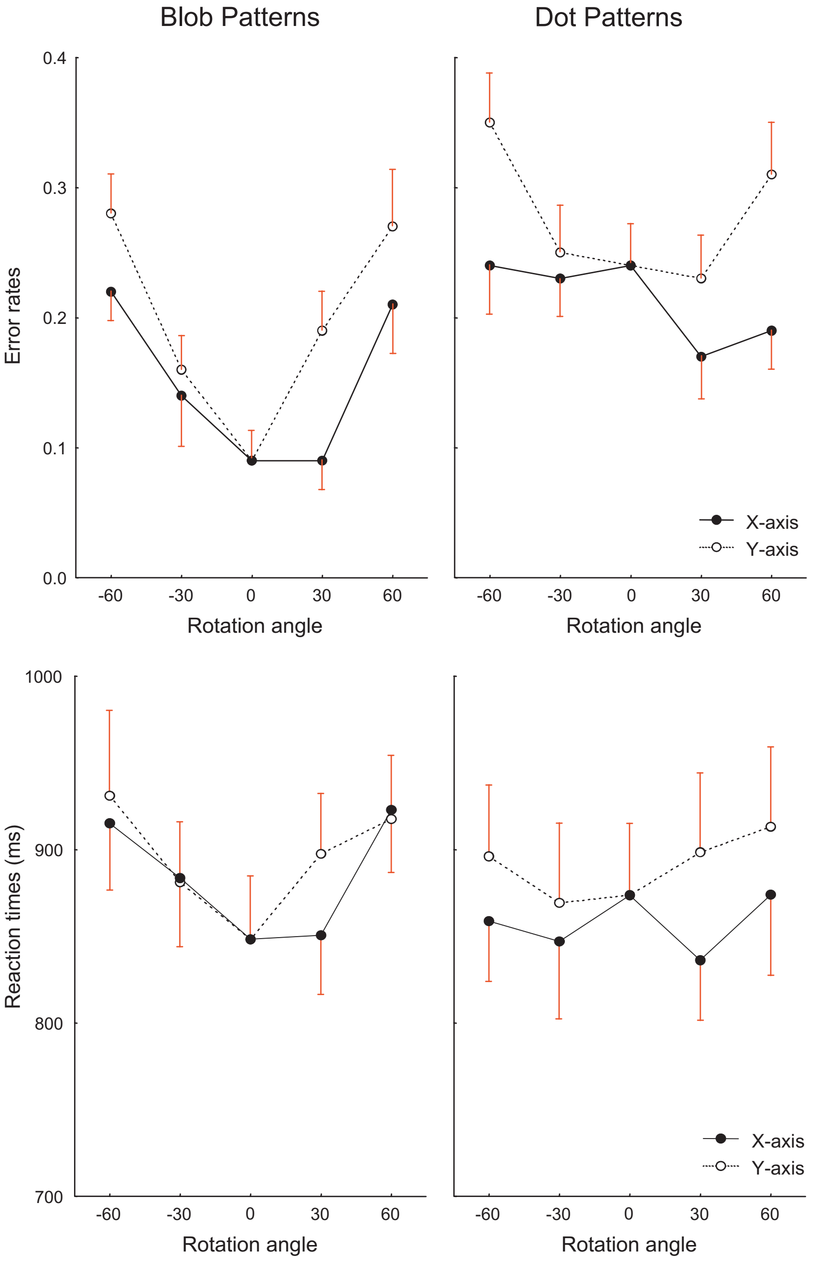

Fig. 7. Error rates and reaction times for repetition patterns.

responding to dot stimuli than to blob stimuli. Furthermore the interaction between rotation angle and stimulus type was significant for error rates, $F(4,16) = 3.441$, $p < .05$.

Further investigation of the rotation effects for RTs revealed that the 60° conditions were significantly slower than the 30° conditions and the frontoparallel condition, $F(1,19) = 7.495$, $p < .05$, while there were no significant differences between the frontoparallel condition and the 30° conditions.

Further investigation of the interaction between rotation angle and stimulus type for error rates revealed that the effect of rotation was significant for blob stimuli, $F(4,16) = 7.121$, $p < .005$, but not for dot stimuli. This rotation effect for blob stimuli showed a pattern consistent with the pattern found for RTs. Participants made more errors in the 60° conditions than in the 30° conditions and the frontoparallel condition, $F(1,19) = 15.124$, $p < .001$, while there were no differences between the frontoparallel condition and the 30° conditions.

3.2.2. *Y-rotation*

The effect of rotation was significant for error rates, $F(4,16) = 4.854$, $p < .01$, but not for RTs. There also was a main effect of stimulus type for error rates, $F(1,19) = 11.831$, $p < .01$. Participants made more errors responding to dot patterns than to blob patterns.

Further investigation of the rotation effect for error rates revealed that participants made more errors responding to the 60° conditions than to the 30° conditions and the frontoparallel condition, $F(1,19) = 14.727$, $p < .005$, while there were no differences between the 30° conditions and the frontoparallel condition.

3.2.3. *X-rotation versus Y-rotation*

There was a main effect of Rotation Axis for both error rates, $F(1,19) = 13.222$, $p < .005$, and RTs, $F(1,19) = 5.331$, $p < .05$. Participants were faster and made fewer errors when responding to *X*-rotations than to *Y*-rotations. The interaction between Rotation Axis and Rotation Angle was not significant.

3.3. *Discussion*

In terms of retinal stimulus properties, the results of Experiment 2 are largely consistent with the hypothesis that the difference between *X*-rotation and *Y*-rotation is smaller for repetition than for symmetry. Just as in Experiment 1, participants performed significantly poorer for *Y*-rotations than for *X*-rotations but, in contrast to Experiment 1, this difference was not incremental: There was no significant interaction between angle of rotation and rotation axis.

The fact that subjects performed worse on *Y*-rotated patterns than on *X*-rotated patterns could be explained by the preserved orientational uniformity in the *X*-rotated patterns. That is, uniform size is destroyed and second-order structures are distorted for both *X*-rotation and *Y*-rotation, while orientational uniformity is destroyed for *Y*-rotation but not for *X*-rotation. As Jenkins (1983) demonstrated, patterns that consist only of uniformly oriented point pairs are still reliably discriminated from random patterns. In the current experiment, participants could have used this preserved orientational uniformity in the X-rotated repetitions to discriminate between rotated repetitions and rotated random patterns.

Furthermore, in this experiment both X-rotation and Y-rotation show a higher proportion of errors for dot stimuli than for blob stimuli. As was found earlier (Csathó et al., 2003), repetitions show a scale effect in that they are detected more easily when the pattern elements are coarser (symmetry does not show such a scale effect). This scale effect can explain the general advantage of blob patterns over dot patterns in the current experiment, because the blob patterns were relatively coarse-scaled and the dot patterns relatively fine-scaled. To assess consistency with these previous findings, we tested whether our frontoparallel conditions showed a difference between stimulus types for repetition and for symmetry. Indeed, for repetition, participants made more errors for dot patterns than for blob patterns ($F(1, 19) = 32.603$, $p < .001$), whereas for symmetry no such difference appeared.

This advantage of blob patterns over dot patterns, however, seems to wane when the patterns are X-rotated. Just as in Experiment 1, this finding can be attributed to a matching problem. In repetition, blob shapes are harder to match as the repetition is more X-rotated. For example, in Fig. 6D, the blobs at the left and the blobs at the right are sheared in opposite directions. This implies larger qualitative shape-deformations for larger X-rotations and, therefore, a bigger matching problem. Because the dots in the dot patterns are much smaller than the blobs in the blob patterns, this qualitative shape-deformation is much less severe in dot patterns. For Y-rotation, the perspective shear produces size differences between corresponding elements, but no qualitative shape-deformations. Therefore, as found, the Y-rotated blob patterns can be expected to keep their coarse scale advantage over the Y-rotated dot patterns.

4. General discussion

The results show, not surprisingly, that perspective views of symmetry and repetition weaken their perceptual salience. The question, however, is whether this weakening is indeed to be attributed to the perspective distortions in the retinal image or rather to the costs of a normalization that precedes regularity detection. For instance, in the latter case, it could be that the visual system picks up 3-D cues, determines the 3-D orientation of the pattern, mentally rotates the images to the frontoparallel plane (i.e., normalizes the image), and only then performs regularity detection (i.e., on the mentally rotated image instead of on the retinal image). This line of thinking would be consistent with Szlyk et al.'s (1995) idea that symmetry perception is a post-constancy operation that depends on the perception of a rotated figure as being slanted in depth. Examples of usable 3-D cues are texture gradients and implicit or explicit contours. Within this line of thinking, it seems reasonable to suppose that larger angles of rotation produce higher reaction times and error rates (Shepard & Metzler, 1971; see, however, also Willems &

Wagemans, 2001). So, let us discuss first to what extent normalization costs alone might account for the observed drops in performance.

4.1. Normalization costs account

The data on symmetry are ambiguous with respect to this account. On the one hand, the fact that *X*-rotated symmetries show rotation effects might be because texture gradients and contours evoke a normalization process even though this process is not required for the task (after all, the retinal image remains symmetrical). The fact that *Y*-rotated symmetries show much larger rotation effects might then be because they do require normalization. On the other hand, Saunders and Knill (2001) showed that symmetry actually helps to retrieve the orientation of 3-D surfaces. This suggests that symmetry detection is part of the normalization process rather than something that merely occurs after normalization. Furthermore, McBeath, Schiano, and Tversky (1997) showed that, in the absence of other 3-D cues, viewers have a bias to interpret asymmetric retinal projections as oblique views of symmetrical objects. This suggests that the symmetry detection process takes place irrespective of (other) depth cues.

Furthermore, for repetition, both types of rotation produce distorted repetitions as retinal projections, but the effects of *Y*-rotation were larger than the effects of *X*-rotation. This is problematic for an account in terms of normalization costs. If the increased error rates and reaction times would be merely an effect of normalization costs, there hardly seems a reason to expect a difference between *Y*-rotation and *X*-rotation because, in both cases, patterns would have to be mentally rotated an equal number of degrees. If anything, one might then actually expect that the effects of *Y*-rotation would be smaller than the effects of *X*-rotation because, unlike in *X*-rotation, the virtual lines in *Y*-rotation converge to a vanishing point, which provides an additional cue for the 3-D orientation. By the way, it is true that axis effects have been shown in mental rotation (e.g., Pani, William, & Shippey, 1995; Parsons, 1995; Willems & Wagemans, 2001); these effects, however, do not apply to differences between rotations about a vertical axis and a horizontal axis, but to differences between these canonical axis orientations and axes that are not canonically oriented.

Finally, in the local discussions, we explained the general advantage of blob stimuli over dot stimuli in terms of 2-D image properties, but can it also be explained within the normalization account? When rotated, the elements in both blob stimuli and dot stimuli show differences in spatial scale that can be used to retrieve the 3-D orientation. In contrast to dot patterns, blob patterns also have explicit contours that provide a further cue for the 3-D orientation. This additional depth cue could, within the normalization analysis, be taken to yield an advantage of blob stimuli over dot stimuli. However, for repetition, we also found that *X*-rotation affects blob stimuli but not dot stimuli and, in the local discussions, we explained also this effect in terms of 2-D image properties. This effect seems to contradict an explanation based on the facilitating effects of additional depth cues in blob stimuli. Furthermore, one could just as well argue that rotated dot stimuli contain additional depth cues in the form of gradients of dot size, dot spacing and dot shape.

In summary, the normalization costs account alone explains hardly anything of our data. Let us therefore return to our line of reasoning in the local discussions, to discuss in more detail to what extent retinal distortions in Jenkins' first-order structures and Wagemans' second-order structures might account for the observed drops in performance.

4.2. Retinal distortions account

For symmetry, an account in terms of retinal distortions in first-order and second-order structures predicts a large difference between Y-rotation and X-rotation. Y-rotation destroys orientational uniformity and midpoint colinearity, and distorts second-order structures, whereas X-rotation preserves all these properties. The data of the first experiment support this prediction. Y-rotation produces more severe drops in performance. Furthermore, with increasing rotation angle the difference between the two rotation types becomes stronger. The fact that X-rotated patterns yet show an effect can be explained by the fact that these patterns show more variation in spatial scale, which by itself is capable of weakening symmetry perception (Csathó et al., 2003).

Hence, retinal distortions in first-order and second-order structures account straightforwardly for the symmetry data. Nevertheless, symmetry alone does not yet compellingly favor this account over the normalization costs account, because both accounts predict the observed difference between Y-rotated and X-rotated symmetry. Repetition, however, yields a stronger differentiation between the two accounts, as follows.

In contrast to the normalization costs account, the account in terms of first-order and second-order structures does predict the observed difference between Y-rotated and X-rotated repetitions. In repetition, Y-rotation distorts all first-order and second-order structures, while X-rotation destroys uniform size and distorts second-order structures but does not destroy orientational uniformity. Jenkins (1983) found that his subjects could reliably discriminate random dot patterns from patterns that consisted merely of uniformly oriented dot pairs. This indicates, according to him, that the detection of orientational uniformity is the basic mechanism that precedes the integration of multiple dot pairs into a global percept. This also suggests that, in our repetition experiment, the preservation of orientational uniformity under X-rotation but not under Y-rotation has indeed been responsible for the observed difference between Y-rotated and X-rotated repetitions.

Furthermore, in this analysis, Wagemans' second-order structures are taken to guide the integration of multiple point pairs into a global percept. In repetition, these second-order structures are parallelograms formed by connecting two virtual lines between corresponding points. Under Y-rotation, such a parallelogram is completely distorted: It no longer has parallel lines. Under X-rotation, however, it is only partly distorted: It still has two parallel lines. This suggests that the observed difference between Y-rotated and X-rotated repetitions can also be attributed to this difference in terms of second-order structures.

Finally, if a parallelogram is distorted such that the two virtual lines between corresponding points have uniform size but not uniform orientation, then it no longer has parallel lines. Inversely, however, if a parallelogram is distorted such that the two virtual lines between corresponding points have uniform orientation but not uniform size, then it still has two parallel lines. This suggests that the relative importance of orientational uniformity, as found empirically by Jenkins, can be understood theoretically in terms of Wagemans' second-order structures.

5. Conclusion

We do not exclude that, preceding regularity detection, perception includes a normalization process to retrieve orthofrontal views of 3-D rotated stimuli. Such a normalization process alone, however, does not explain our current data on 3-D rotated symmetries and repetitions. In fact, our data are in fine accordance with the idea that the visual system analyzes the retinal projections of 3-D rotated symmetries and repetitions in terms of Jenkins' first-order structures and Wagemans' second-order structures. This suggests that the detection of symmetries and repetitions is not a post-normalization process but rather an integral part of 3-D object perception.

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