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The force of symmetry revisited: symmetry-to-noise ratios regulate (a)symmetry effects

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Abstract

Freyd and Tversky's [Am. J. Psychol. 97 (1984) 109] data suggested that human observers tend to overestimate relatively high levels of symmetry (symmetry effect), and tend to underestimate relatively low levels of symmetry (asymmetry effect). However, on the basis of their holographic approach to visual regularity, van der Helm and Leeuwenberg [Psychol. Rev. 103(3) (1996) 429] predicted that, at any level of symmetry, both symmetry and asymmetry effects may occur as a consequence of correct estimates of symmetry-to-noise ratios. This prediction was tested in two experiments, with tasks and stimuli similar to those in Freyd and Tversky's study. First, subjects had to judge whether a noisy symmetry is more similar to a slightly more symmetrical variant or to a slightly less symmetrical variant. Second, for every pair of stimuli in such a triadic comparison, subjects had to judge which stimulus is the more symmetrical one. The results from both experiments show that the occurrence of (a)symmetry effects indeed depends on symmetry-to-noise ratios.

PsycINFO classification: 2323; 2340
Keywords: Visual perception; Symmetry; Signal-to-noise ratio

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1. Introduction

Mirror symmetry (henceforth, symmetry) is a non-accidental property in our physical environment (Binford, 1981). Symmetry is a structural characteristic of most living organisms and many man-made constructions. To observers, therefore, symmetry might have significance by signaling the presence of organisms and other objects. Probably, as an adaptive consequence of this, symmetry is detected rapidly and effortlessly (Julesz, 1971) and it is an important correlate of aesthetic preference (Rhodes, Proffitt, Grady, & Sumich, 1998; Thornhill & Gangestad, 1999).

Studies on symmetry detection have reported the relevance of symmetry in a wide variety of perceptual processes. For example, symmetry was found to be a crucial component in object recognition (Pashler, 1990; Vetter & Poggio, 1994) and in the judgment of object orientation in space (Howard & Templeton, 1966; Szlyck, Rock, & Fisher, 1995; Wagemans, 1993; Wilson, Wilkinson, Lin, & Castillo, 2000). Symmetry is also assumed to be an important aid to the visual system in coping with various perceptual ambiguities. For example, symmetrical images are usually perceived as figures, not grounds (e.g., Driver, Baylis, & Rafal, 1992). For shape perception, Palmer (1985) provided evidence that the preferred description of a shape might be different when it is embedded in a context with horizontal or vertical symmetry. Observers also have a strong tendency to identify the shapes of polygons as silhouettes of symmetrical 3D objects (McBeath, Schiano, & Tversky, 1997). Furthermore, completion of partially occluded objects tends to go towards symmetrical objects (Kanizsa, 1975; van Lier, van der Helm, & Leeuwenberg, 1995; van Lier & Wagemans, 1999).

In addition to this general importance of symmetry in basic perceptual tasks, there are reports that human observers seem to overestimate the amount of symmetry in an image (Carmody, Nodine, & Locher, 1977; Garner, 1970; King, Meyer, Tangey, & Biederman, 1976). To our knowledge, the first systematic study into this phenomenon was conducted by Freyd and Tversky (1984), as follows.

In a series of experiments, Freyd and Tversky investigated the role of symmetry in form similarity. In their main experiment, the stimuli were totem-like outlines consisting of a central vertical pole with horizontally protruding limbs. A trial consisted of a standard noisy symmetry along with a slightly more symmetrical variant and a slightly less symmetrical variant, and the task was to judge which variant is more similar to the standard. Freyd and Tversky distinguished between triads with a relatively high level of symmetry and triads with a relatively low level of symmetry. In the high overall symmetry condition, the limbs were horizontally aligned; in the low overall symmetry condition, the limbs were horizontally misaligned (see Fig. 1). In both cases, a more symmetrical variant and a less symmetrical variant were constructed by lengthening or shortening the limbs in a standard by the same physical amount. Nevertheless, in the high overall symmetry condition, subjects judged the more symmetrical variant as being more similar to the standard (a *symmetry effect*), whereas, in the low overall symmetry condition, they judged the less symmetrical variant as being more similar to the standard (an *asymmetry effect*). Freyd and

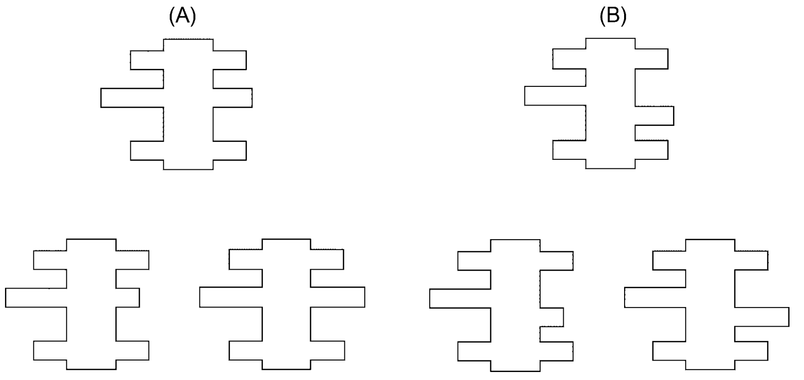


Fig. 1. Schematic presentation of Freyd and Tversky's (1984) experimental trials. In their high overall symmetry condition (A) or in their low overall symmetry condition (B), a standard (top) is presented with a less symmetrical variant (bottom-left) and a more symmetrical variant (bottom-right). (After Freyd & Tversky, 1984.)

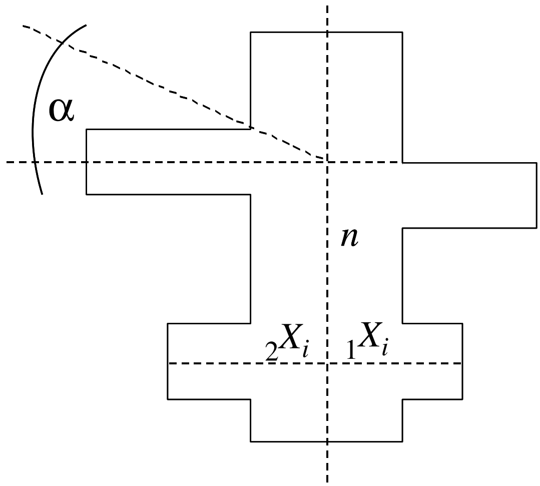
Tversky therefore concluded that the overall level of symmetry is the decisive factor in triggering biases toward either symmetry or asymmetry.

In our view, however, this conclusion is not that obvious. Barlow and Reeves (1979), for instance, found that symmetry judgments are pretty accurate. Furthermore, in our view, it is clear that the (perceived) degree of symmetry in an individual pattern depends on the symmetry-to-noise ratio in the pattern. This, as such, does not yet explain the (a)symmetry effects found by Freyd and Tversky, but our point is that they did not control for symmetry-to-noise ratios. This is next discussed in more detail.

Freyd and Tversky subjected their stimuli to Zimmer's (1984, Eq. 10) symmetry metric which is tailored to patterns like Freyd and Tversky's totem-like stimuli. Starting from grid points on the symmetry axis of a totem-like stimulus, Zimmer's metric takes, at each grid point, the proportion of mismatch in area multiplied by the proportion of mismatch in alignment between parts at each side of the symmetry axis; these proportions are summed and then divided by the number of grid points, to yield a final index of symmetry between 0 and 1 (see Fig. 2). Hence, Zimmer's metric does not incorporate a global symmetry-to-noise ratio but, rather, an average local symmetry-to-noise ratio.

Using Zimmer's metric, Freyd and Tversky reported, for their high overall symmetry condition, mean symmetry indexes of 0.923 for the standards, 0.962 for the more symmetrical variants, and 0.896 for the less symmetrical variants. For their low overall symmetry condition, they reported mean symmetry indexes of 0.857 for the standards, 0.886 for the more symmetrical variants, and 0.831 for the less symmetrical variants.

On the basis of these mean symmetry indexes, we observe that the levels of symmetry in Freyd and Tversky's high and low overall symmetry conditions were actually not that far apart. Furthermore, in both conditions, the mean symmetry index of



$$Z = \frac{\sum_{i=1}^{i=n} \frac{_1X_i}{_2X_i} \cos(\alpha)}{n}$$

Fig. 2. A nearly symmetrical totem-like stimulus with one shifted part, and the metric Zimmer proposed to calculate the degree of symmetry in stimuli like this. In Zimmer's metric, $_1X_i$ and $_2X_i$ refer to the lengths of the limbs measured from the symmetry axis, and n refers to the number of grid points on the symmetry axis. At each grid point, the proportion of mismatch in area ($_1X_i$ divided by $_2X_i$) is multiplied by the proportion of mismatch in alignment between parts at each side of the symmetry axis ($\cos(\alpha)$); these proportions are summed and then divided by the number of grid points (n), to yield a final index of symmetry between 0 and 1. (After Zimmer, 1984.)

the standards was closer to that of the less symmetrical variants than to that of the more symmetrical variants (especially for the high overall symmetry condition). Hence, if Freyd and Tversky would have used these symmetry indexes as predictors, they would have had to predict an asymmetry effect not only in their low overall symmetry condition (as they indeed found) but also in their high overall symmetry condition where, however, they actually found a symmetry effect. Hence, this symmetry effect does not seem explicable on the basis of Zimmer's symmetry index and, as a consequence, Freyd and Tversky could only conclude that it was due to an overestimation of the amount of symmetry.

However, a closer inspection of the stimulus examples in Freyd and Tversky's article (see our Fig. 1) shows that, in their high and low overall symmetry conditions, they actually performed different manipulations of the symmetry-to-noise ratio in the standards to construct the more symmetrical variants. In the high overall symmetry condition, noise was replaced by symmetry, whereas, in the low overall symmetry condition, noise was replaced by symmetry along with new noise (the less symmetrical variants were constructed by the corresponding inverse operations). As van der Helm and Leeuwenberg (1996) argued, these different symmetry-to-noise ratio manipulations form a confounding factor in Freyd and Tversky's experiment.

In fact, starting from their holographic approach to visual regularity, van der Helm and Leeuwenberg (1996) predicted that, at any overall level of symmetry, both symmetry effects and asymmetry effects can be triggered by appropriate symmetry-to-noise ratio manipulations. This prediction is based on the assumption that (a)symmetry effects are not the result of wrong judgments of amounts of symmetry but are the result of correct judgments of symmetry-to-noise ratios. This is discussed next in more detail.

First, the holographic approach quantifies the detectability of a visual regularity by the *weight of evidence* (WoE) for this regularity in a pattern. The WoE of symmetry, in particular, is quantified by $W = S/n$, where S is the number of symmetry pairs, and n the total number of elements in the stimulus. For instance, for a perfect symmetry, $n = 2S$, so that it gets a WoE of $W = 0.5$. Furthermore, for a noisy symmetry, $n = 2S + R$ (where R is the number of noise elements in the pattern), which implies that the formula $W = S/n$ can be rewritten into $W = 1/(2 + R/S)$. Hence, in contrast to Zimmer's metric, WoE is explicitly a function of the global symmetry-to-noise ratio.

Second, keeping physical changes the same, a standard noisy symmetry with $W_{\text{standard}} = S/n$ can be made more symmetrical by each of the following three basic types of symmetry-to-noise ratio manipulation: (1) by adding P symmetry pairs, (2) by removing $2P$ noise elements, or (3) by adding symmetrical counterparts to P noise elements. The standard can be made less symmetrical by corresponding inverse operations. These different manipulations also have different effects on WoE, as follows.

Type 1, comprising the addition or removal of P symmetry pairs, yields $W_{\text{more}} = (S + P)/(n + 2P)$ for the more symmetrical variant, and $W_{\text{less}} = (S - P)/(n - 2P)$ for the less symmetrical variant. Then, as can be verified easily, W_{standard} is closer to W_{more} than to W_{less}. Type 2, comprising the removal or addition of $2P$ noise elements, yields $W_{\text{more}} = S/(n - 2P)$ and $W_{\text{less}} = S/(n + 2P)$, respectively. In this case, W_{standard} is closer to W_{less} than to W_{more}. Type 3, comprising the addition or removal of $2P$ symmetrical counterparts, yields $W_{\text{more}} = (S + 2P)/(n + 2P)$ and $W_{\text{less}} = (S - 2P)/(n - 2P)$, respectively. Then, W_{standard} is again closer to W_{more} than to W_{less}. Hence, if WoE is taken as a predictor in triadic comparisons as used in Freyd and Tversky (1984), then a symmetry effect is predicted under the types 1 and 3 manipulations, whereas an asymmetry effect is predicted under the type 2 manipulation.

To be clear, for very low levels of symmetry (i.e., when there is more noise than symmetry), WoE yields other predictions. Hence, also WoE predicts that the level of symmetry is a relevant factor, but this prediction is not applicable to Freyd and Tversky's study. WoE yields other predictions when WoE is lower than $W = 0.25$ or, in terms of Zimmer's (1984) metric, when the symmetry index is lower than about 0.50. Such low levels of symmetry not only are far below the ones considered by Freyd and Tversky, but also seem too low to be tractable empirically by way of triadic comparisons. Therefore, in this study, we focus on relatively high levels of symmetry.

Furthermore, the central question in this study is whether (a)symmetry effects are due to incorrect judgments of amounts of symmetry (as Freyd & Tversky, 1984, argued) or due to correct judgments of symmetry-to-noise ratios (as van der Helm & Leeuwenberg, 1996, predicted). To this end, it hardly matters which specific symmetry metric is employed. That is, we employed WoE to predict (a)symmetry effects, but the same predictions follow from Zimmer's metric and probably also from any other reasonable metric (like, e.g., Dakin & Watt's, 1994, metric).

In two experiments, we investigated differential effects of symmetry-to-noise ratio manipulations, namely, for triadic similarity judgments and for dyadic symmetry judgments. For both experiments, six conditions were designed such that both WoE and Zimmer's metric predict symmetry effects in three of these conditions and asymmetry effects in the other three conditions.

2. Experiment 1: Similarity judgments

2.1. Method

2.1.1. Participants

The 25 participants were undergraduate or postgraduate students at the University of Nijmegen (18–34 years old), with normal or corrected acuity by self-report. They were either paid or received course credits for their participation and were naive with regard to the purpose of the experiment.

2.1.2. Stimuli

The stimuli were totem-like line drawings similar to those used by Freyd and Tversky (1984). Every stimulus consisted of a central vertical pole with two pairs of horizontally protruding limbs. The limbs were aligned in each pair. All lines subtended 4.2 min of visual arc at 0.81 cd/m^2 luminance. The stimuli were displayed on a white background with 99.8 cd/m^2 luminance. Three types of stimuli were prepared: standards, more symmetrical variants and less symmetrical variants.

First, five standards were produced by varying limb lengths and limb pair positions on the central pole (see Fig. 3). The size of the central pole was 150×42 pixels in every standard and subtended $2.7° \times 0.76°$ visual angle. The upper and the lower limb pairs were positioned at an average distance of 78 pixels (a range of 54–100 pixels; 0.8–1.79°) apart from each other, and every limb had a thickness of 25 pixels (0.45°). The symmetry of the standards deviated from perfect vertical symmetry: every limb pair consisted of a longer limb and a shorter limb. The average length of the longer limbs was 65 pixels (a range of 42–77 pixels; 0.75–1.38°) for the upper pairs, and 84 pixels (a range of 61–100 pixels; 1.09–1.79°) for the lower pairs. The average length of the shorter limbs was 38 pixels (a range of 26–47 pixels; 0.46–0.84°) for the upper pairs, and 48 pixels (a range of 31–61 pixels; 0.55–1.09°) for the lower pairs. The five standards were left–right mirrored to produce 10 standards in total.

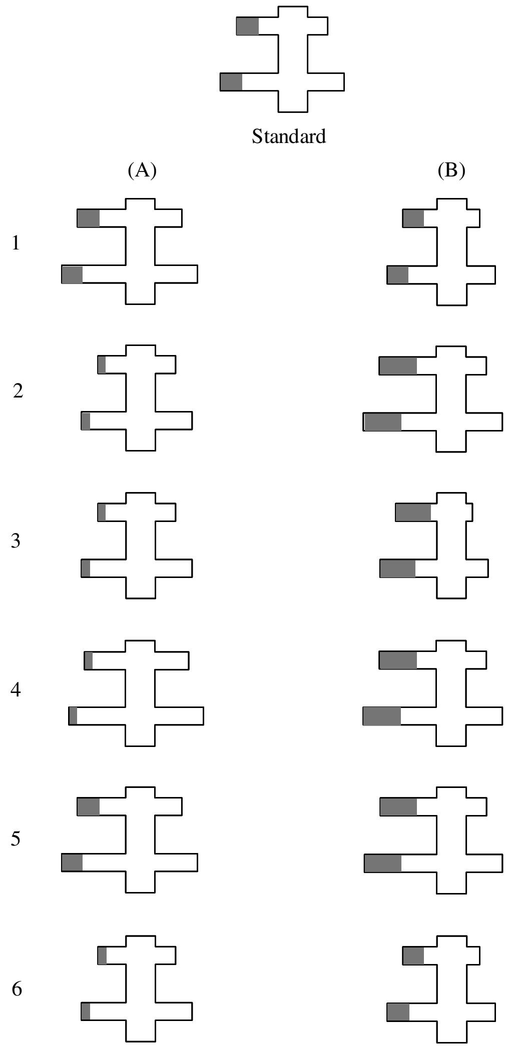


Fig. 3. Example stimuli from the six conditions in Experiment 1. Horizontal bar pairs in the standard (top) were lengthened or shortened to get more (A) and a less (B) symmetrical variants. The light areas indicate the symmetry, and the dark areas indicate the noise (in the actual stimuli, all areas were light). Conditions 1 and 2 involve a pure symmetry manipulation and a pure noise manipulation, respectively. Conditions 3–6 are mixed conditions involving both symmetry and noise manipulations. For further information, see text and Table 1.

To produce more and less symmetrical variants of a standard, both limb pairs were shortened or lengthened by P pixels. P was fixed for each standard separately, and varied over the standards with a range of 28–48 pixels (0.49–0.85°). As described in the introduction, we considered three basic manipulation types.

Under the first manipulation type (i.e., adding or removing symmetry pairs), all four limbs were lengthened by $P/2$ pixels to get a more symmetrical variant, and were shortened by $P/2$ pixels to get a less symmetrical variant. Under the second manipulation type (i.e., removing or adding noise elements), the longer limb in each bar pair was shortened by P pixels to get a more symmetrical variant, and was lengthened by P pixels to get a less symmetrical variant. Under the third manipulation type (i.e., adding or removing symmetrical counterparts), the shorter limb in each limb pair was lengthened by P pixels to get a more symmetrical variant, and was shortened by P pixels to get a less symmetrical variant. The more symmetrical variants never reached perfect symmetry.

Six conditions were prepared for the triadic comparison of a standard stimulus with a more and a less symmetrical variant. First, a so-called "pure symmetry" condition, in which both variants involved a manipulation of the amount of symmetry in the standard. Then, a so-called "pure noise" condition, in which both variants involved a manipulation of the amount of noise in the standard. Finally, four so-called "mixed" conditions, in which a pair of variants involved both symmetry and noise manipulations. In the two pure conditions, the two variants in a triadic comparison differed in the number of pixels along the contour, whereas, in the four mixed conditions, they did not. Table 1 gives an overview of the six conditions and Fig. 3 shows example stimuli for each condition.

The six conditions were chosen such that both WoE and Zimmer's metric would predict symmetry effects in three conditions and asymmetry effects in the other three conditions. To substantiate this, we calculated W values (for WoE) and Z values (for Zimmer's metric) for each stimulus separately. Both WoE and Zimmer's metric can be quantified in a few different ways that, however, do not differ qualitatively regarding whether a symmetry effect or an asymmetry effect is predicted. Because our stimuli are outline patterns, we chose to quantify WoE in terms of pixels in the stimulus outline and, to keep in line with this, we chose a grid in terms of pixels to quantify Zimmer's metric. Fig. 4 shows the W values and Z values for the standards. Tables 2 and 3 show the differences in W values and Z values between a standard and its more symmetrical variant ($\Delta W_{\text{more}} = W_{\text{more}} - W_{\text{standard}}$ and $\Delta Z_{\text{more}} = Z_{\text{more}} - Z_{\text{standard}}$, respectively), and between a standard and its less symmetrical variant ($\Delta W_{\text{less}} = W_{\text{standard}} - W_{\text{less}}$ and $\Delta Z_{\text{less}} = Z_{\text{standard}} - Z_{\text{less}}$, respectively). The negative values of $\Delta^2 W = \Delta W_{\text{more}} - \Delta W_{\text{less}}$ and $\Delta^2 Z = \Delta Z_{\text{more}} - \Delta Z_{\text{less}}$ in conditions 1, 3, and 5, im-

Table 1
The six triadic comparison conditions in Experiment 1 (see also Fig. 3)

Condition	More symmetrical variant	Less symmetrical variant
1	P symmetry pairs added	P symmetry pairs removed
2	$2P$ noise elements removed	$2P$ noise elements added
3	$2P$ noise elements removed	$2P$ symmetrical counterparts removed
4	$2P$ symmetrical counterparts added	$2P$ noise elements added
5	P symmetry pairs added	$2P$ noise elements added
6	$2P$ noise elements removed	P symmetry pairs removed

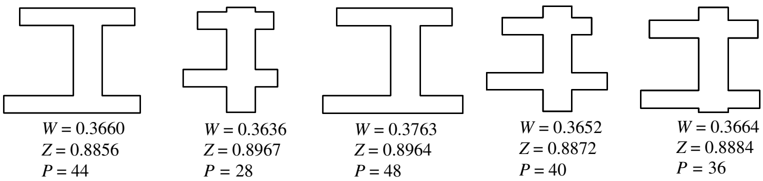


Fig. 4. The five standard stimuli used in the experiments, and the W values (for WoE) and Z values (for Zimmer's metric) for each of the standards. To produce more and less symmetrical variants of a standard, both limb pairs were shortened or lengthened by P pixels.

Table 2
Quantification of van der Helm and Leeuwenberg's (1996) weight of evidence metric (WoE) for the triadic comparisons in Experiment 1

Conditions		Standards					Means	Effects
		1	2	3	4	5		
1	ΔW_{more}	0.0115	0.01	0.0114	0.012	0.0102	0.0109	
	ΔW_{less}	0.0138	0.0118	0.014	0.0147	0.0121	0.0132	
	$\Delta^2 W$	−0.0024	−0.0017	−0.0026	−0.0026	−0.0019	−0.0022	Sym
2	ΔW_{more}	0.0378	0.0314	0.0425	0.0397	0.0331	0.0369	
	ΔW_{less}	0.0313	0.0268	0.0347	0.0326	0.0281	0.0307	
	$\Delta^2 W$	0.0065	0.0046	0.0078	0.0071	0.0051	0.0062	Asym
3	ΔW_{more}	0.078	0.0314	0.0425	0.0397	0.0331	0.0369	
	ΔW_{less}	0.0655	0.055	0.0704	0.069	0.0573	0.0634	
	$\Delta^2 W$	−0.0277	−0.0236	−0.0279	−0.0293	−0.0242	−0.0265	Sym
4	ΔW_{more}	0.0543	0.0469	0.0575	0.0567	0.0485	0.0527	
	ΔW_{less}	0.0313	0.0268	0.0347	0.0326	0.0281	0.0307	
	$\Delta^2 W$	0.0229	0.0201	0.0228	0.0241	0.0205	0.0220	Asym
5	ΔW_{more}	0.0115	0.01	0.0114	0.012	0.0102	0.0109	
	ΔW_{less}	0.0313	0.0268	0.0347	0.0326	0.0281	0.0307	
	$\Delta^2 W$	−0.0199	−0.0167	−0.0233	−0.0206	−0.0178	−0.0197	Sym
6	ΔW_{more}	0.0378	0.0314	0.0425	0.0397	0.0331	0.0369	
	ΔW_{less}	0.0138	0.0118	0.014	0.0147	0.0121	0.0132	
	$\Delta^2 W$	0.0240	0.0196	0.0285	0.025	0.021	0.0237	Asym

Note: $\Delta^2 W = \Delta W_{more} - \Delta W_{less}$, where $\Delta W_{more} = W_{more} - W_{standard}$ and $\Delta W_{less} = W_{standard} - W_{less}$. Hence, a negative value of $\Delta^2 W$ predicts a symmetry effect (Sym), and a positive value of $\Delta^2 W$ predicts an asymmetry effect (Asym).

ply that, in these conditions, the standards are predicted to be closer in symmetry to their more symmetrical variants than to their less symmetrical variants. In other words, in conditions 1, 3, and 5, a symmetry effect is predicted. By the same token, the positive values of $\Delta^2 W$ and $\Delta^2 Z$ in conditions 2, 4, and 6, imply that, in these conditions, an asymmetry effect is predicted.

Table 3
Quantification of Zimmer's (1984) symmetry metric for the triadic comparisons in Experiment 1

Conditions		Standards					Means	Effects
		1	2	3	4	5		
1	ΔZ_{more}	0.0104	0.009	0.0104	0.0116	0.0094	0.0101	
	ΔZ_{less}	0.0128	0.011	0.0131	0.0146	0.0113	0.0125	
	$\Delta^2 Z$	−0.0024	−0.002	−0.0027	−0.003	−0.0019	−0.0024	Sym
2	ΔZ_{more}	0.0564	0.0573	0.0665	0.064	0.0503	0.0589	
	ΔZ_{less}	0.0371	0.038	0.042	0.0402	0.0346	0.0383	
	$\Delta^2 Z$	0.0193	0.0193	0.0245	0.0237	0.0158	0.0205	Asym
3	ΔZ_{more}	0.0564	0.0573	0.0665	0.064	0.0503	0.0589	
	ΔZ_{less}	0.0677	0.0655	0.0747	0.0752	0.0615	0.0689	
	$\Delta^2 Z$	−0.0113	−0.0082	−0.0082	−0.0112	−0.0111	−0.01	Sym
4	ΔZ_{more}	0.0677	0.0655	0.0747	0.0752	0.0615	0.0689	
	ΔZ_{less}	0.0371	0.038	0.042	0.0402	0.0346	0.0383	
	$\Delta^2 Z$	0.0306	0.0275	0.0327	0.0349	0.0269	0.0305	Asym
5	ΔZ_{more}	0.0104	0.009	0.0104	0.0116	0.0094	0.0101	
	ΔZ_{less}	0.0371	0.038	0.042	0.0402	0.0346	0.0383	
	$\Delta^2 Z$	−0.0267	−0.029	−0.0315	−0.0287	−0.0252	−0.0282	Sym
6	ΔZ_{more}	0.0564	0.0573	0.0665	0.064	0.0503	0.0589	
	ΔZ_{less}	0.0128	0.011	0.0131	0.0146	0.0113	0.0125	
	$\Delta^2 Z$	0.0436	0.0463	0.0534	0.0494	0.0391	0.0463	Asym

Note: $\Delta^2 Z = \Delta Z_{more} - \Delta Z_{less}$, where $\Delta Z_{more} = Z_{more} - Z_{standard}$ and $\Delta Z_{less} = Z_{standard} - Z_{less}$. Hence, a negative value of $\Delta^2 Z$ predicts a symmetry effect (Sym), and a positive value of $\Delta^2 Z$ predicts an asymmetry effect (Asym).

2.1.3. Apparatus

A standard PC with Philips 109B monitor using a 1024×768 pixels resolution presented the stimuli. The participants viewed the screen from a distance of 114 cm.

2.1.4. Procedure

On each trial, three stimuli were presented on the screen: a standard stimulus, along with a more and a less symmetrical variant. The standard stimulus was centered at the top, and the variants were positioned bottom-left and bottom-right, respectively. The horizontal distance between the variants was 370 pixels (6.66°) and the vertical distance between the standard and the variants was 320 pixels (5.76°).

On each trial, the standard stimulus appeared first on the screen. Then, after a delay of 2 s, the two variants followed. The participants were instructed to select the variant that seemed more similar to the standard by pressing the appropriate button on a button box. No speed instruction was given. The three stimuli remained on the screen until a response was given. Comparisons for different conditions were randomized across the experiment. The left–right positions of the variants were counterbalanced across trials, so that each participant performed a total of 120 trials: 2 positions × [6 conditions × 10 standards (5 original and 5 mirrored images)]. Responses were recorded. Before the experiment began, participants were given a number of practicing trials.

2.2. Results

One-sample *T* tests were performed to determine whether responses differed from chance. The significance levels were Bonferroni corrected. Fig. 5 depicts the results for each condition.

Overall, participants had significantly higher preference for the less symmetrical variants (58%) than for the more symmetrical variants ($t(1,24) = -4.1$, $p < 0.01$). Analyses for the separate conditions showed significantly higher preference for the more symmetrical variants in condition 5 only (56%; $t(1,24) = 3.36$, $p < 0.05$). The less symmetrical variants were significantly preferred in condition 2 (63%; $t(1,24) = -3.4$, $p < 0.05$), condition 4 (75%; $t(1,24) = -8.37$, $p < 0.001$) and condition 6 (68%; $t(1,24) = -4.86$, $p < 0.01$). No significant preference occurred in conditions 1 and 3.

We also investigated whether WoE and Zimmer's metric correctly predict the strength of the (a)symmetry effects. That is, larger absolute values of $\Delta^2 W$ and $\Delta^2 Z$ can be taken to predict stronger (a)symmetry effects. We tested this by way of simple linear regression analyses for all stimuli, which showed significant positive

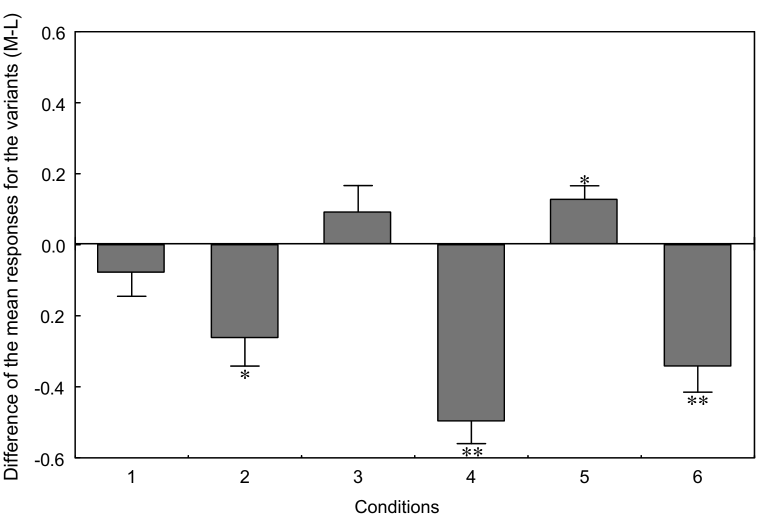


Fig. 5. Subtraction of the mean number of responses for the less symmetrical variants (*L*) from the mean number of responses for the more symmetrical variants (*M*) in each condition of Experiment 1. Error bars represent standard errors of the mean. (*): $p < 0.05$, (**): $p < 0.01$.

relationships between the absolute value of $\Delta^2 W$ and $\Delta^2 Z$, on the one hand, and the number of responses in the predicted direction, on the other hand (WoE: $F(1,119) = 10.69$, $b = 0.29$, $p < 0.01$, $R^2 = 0.08$; Zimmer: $F(1,119) = 33.34$, $b = 0.47$, $p < 0.001$, $R^2 = 0.22$). The R^2 values indicate that a higher proportion of variance is explained by the Zimmer values (22%) than by the WoE values (8%). This is not very surprising because, as mentioned, Zimmer's metric was tailored specifically to totem-like stimuli.

2.3. Discussion

Freyd and Tversky (1984) found a symmetry effect in their high overall symmetry condition, and an asymmetry effect in their low overall symmetry condition. Our stimuli have a symmetry level in between Freyd and Tversky's high and low symmetry levels, and we found an overall asymmetry effect: in the majority of the trials, the less symmetrical variant was judged to be more similar to the standard. More importantly, however, we found that preferences varied strongly with the symmetry-to-noise manipulations. The overall asymmetry effect was mainly due to separate asymmetry effects in conditions 2, 4 and 6. In conditions 1 and 3, however, we found no (a)symmetry effects, and, in condition 5, we even found a symmetry effect. Furthermore, the linear regression analyses showed that both WoE and Zimmer's metric correctly predict the strength of the (a)symmetry effects. The differences between conditions as well as the strength analyses suggest that, as van der Helm and Leeuwenberg (1996) predicted, the occurrence of (a)symmetry effects indeed depends on symmetry-to-noise ratios.

To find further evidence, we performed a second experiment involving dyadic symmetry judgments for all stimuli used in Experiment 1. Experiment 2 serves two purposes. First, the data can be used to check whether, perceptually, our symmetry-to-noise manipulations indeed yielded more and less symmetrical variants as intended. Second, the data can be used to further investigate how the occurrence of (a)symmetry effects is related to symmetry-to-noise ratios.

3. Experiment 2: Symmetry judgments

3.1. Method

3.1.1. Participants

Participants were 18 students (aged between 18 and 26) from the University of Nijmegen who had not participated in Experiment 1. They were either paid or received course credits and had normal or corrected-to-normal acuity. All were naive with regard to the hypotheses.

3.1.2. Stimuli and apparatus

The stimuli and the apparatus were identical to those in Experiment 1.

3.1.3. Procedure

In this experiment, three dyadic comparisons were tested for each triadic comparison from Experiment 1: standard vs. more symmetrical variant (SvM), standard vs. less symmetrical variant (SvL) and more vs. less symmetrical variant (MvL).

On each trial, the two stimuli were presented at the center of the screen, a horizontal distance of 370 pixels (6.66°) apart. The left–right position of the stimuli was counterbalanced across trials. Both stimuli appeared simultaneously and remained on the screen until a response was given. The participants were instructed to determine which stimulus seemed more symmetrical by pressing the appropriate button on a button box. They were also instructed to respond as quickly as possible. Responses and reaction times (RTs) were recorded. Every participant performed 360 trials: 2 positions × [6 conditions × 30 comparisons (10 SvM, 10 SvL, 10 MvL)].

3.2. Results

Both responses and RTs were analyzed. Responses were called "correct" if they agreed with the direction we intended to implement with our symmetry-to-noise manipulations.

Repeated measures ANOVAs were performed to reveal differences between the three dyadic comparison types (see Fig. 6). The correct responses showed a significant main effect of comparison type ($F(2,16) = 97.62$, $p < 0.001$). Further analysis showed that the percentages correct for SvL and SvM did not differ significantly, but that both percentages were significantly lower than the percentage correct for MvL (MvL vs. SvM: $F(1,17) = 130.56$, $p < 0.001$; MvL vs. SvL: $F(1,17) = 168.41$, $p < 0.001$). Also the RTs (for all responses) showed a significant main effect of comparison type ($F(2,16) = 15.21$, $p < 0.001$). Further analysis of all possible contrasts

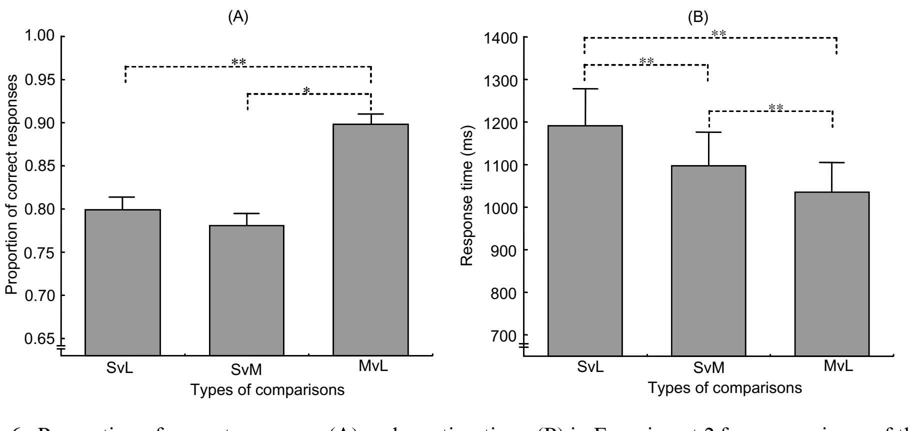


Fig. 6. Proportion of correct responses (A) and reaction times (B) in Experiment 2 for comparisons of the standard and the less symmetrical variant (SvL), for comparisons of the standard and the more symmetrical variant (SvM), and for comparisons of the more and the less symmetrical variants (MvL). Error bars represent standard errors of the mean. (*): $p < 0.05$, (**): $p < 0.01$.

showed that all differences were significant, with slowest responses for SvL and fastest responses for MvL (MvL vs. SvM: $F(1,17) = 10.62$, $p < 0.01$; MvL vs. SvL: $F(1,17) = 30.92$, $p < 0.001$; SvM vs. SvL: $F(1,17) = 24.04$, $p < 0.001$).

Regarding the occurrence of (a)symmetry effects, a comparison between MvL and SvM or SvL is not informative, but the comparison between SvM and SvL is. Therefore, SvM and SvL were compared with Paired-sample t-tests in terms of the six symmetry-to-noise manipulation conditions in Experiment 1. The significance levels were Bonferroni corrected. Results are depicted in Fig. 7.

Compared to the percentage correct for SvL, the percentage correct for SvM was significantly higher in condition 2 ($t(1,17) = 6.84$, $p < 0.001$) and in condition 6 ($t(1,17) = 12.01$, $p < 0.001$), and significantly lower in condition 1 ($t(1,17) = -3.76$, $p < 0.05$) and in condition 5 ($t(1,17) = -11.47$, $p < 0.001$). No significant differences were found for conditions 3 and 4.

Furthermore, compared to the RTs for SvL, the RTs for SvM were significantly faster in condition 2 ($t(1,17) = -5.47$, $p < 0.001$), in condition 4 ($t(1,17) = -3.83$, $p < 0.05$), and in condition 6 ($t\ (1,17) = -6.75$, $p < 0.001$). No significant differences were found for conditions 1, 3 and 5.

Finally, we investigated whether WoE and Zimmer's metric correctly predict participants' certainty in symmetry judgment. That is, a smaller difference in W value or Z value between the two stimuli in a dyadic comparison can be taken to predict that it is more difficult to choose the more symmetrical one. We tested this again by way of a simple linear regression analysis for all stimuli, which showed a significant positive relationship between the number of correct responses and the difference in symmetry values between the two stimuli (WoE: $F(1,359) = 213.46$, $b = 0.61$, $p < 0.001$, $R^2 = 0.37$; Zimmer: $F(1,359) = 283.99$, $b = 0.66$, $p < 0.001$, $R^2 = 0.44$). The relation-

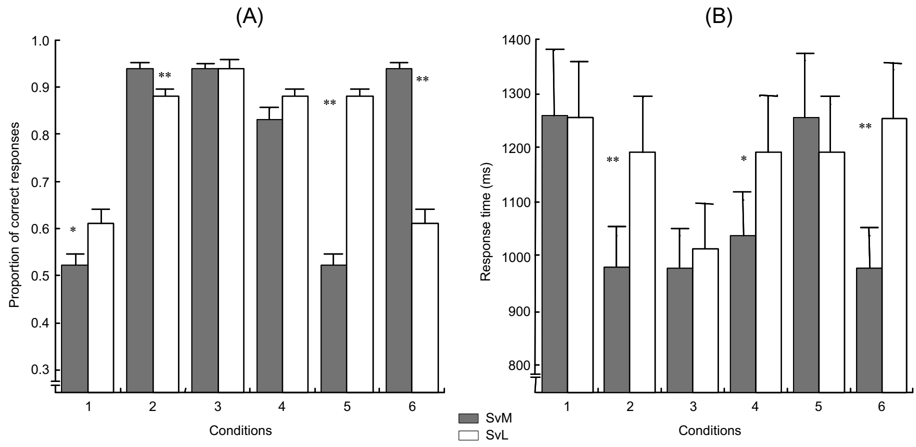


Fig. 7. Proportion of correct responses (A) and reaction times (B) in Experiment 2, in terms of the six symmetry-to-noise ratio manipulation conditions from Experiment 1, for comparisons of the standard with the more symmetrical variant (SvM) and with the less symmetrical variant (SvL). Error bars represent standard errors of the mean. (*): $p < 0.05$, (**): $p < 0.01$.

ship between RTs and the difference in symmetry values was significantly negative (WoE: $F(1,359) = 195.35$, $b = -0.59$, $p < 0.001$, $R^2 = 0.35$; Zimmer: $F(1,359) = 244.85$, $b = -0.64$, $p < 0.001$, $R^2 = 0.41$). Both for correct responses and RTs, the R^2 values indicate that a higher proportion of variance is explained by the Zimmer values (correct responses: 44%, RTs: 41%) than by the WoE values (correct responses: 37%, RTs: 35%). Again, this is not very surprising because, as mentioned, Zimmer's metric was tailored specifically to totem-like stimuli.

3.3. Discussion

Every dyadic comparison type showed a very high proportion of correct responses (see Fig. 6). The highest proportion of correct responses occurred for the MvL comparisons. These findings support not only the perceptual relevance of our symmetry-to-noise manipulations, but also their adequacy in the search for (a)symmetry effects.

Furthermore, responses were slower for SvL comparisons than for SvM comparisons. This indicates that, overall, it was more difficult to distinguish standards from less symmetrical variants than from more symmetrical variants. In other words, this indicates an overall asymmetry effect, just as found in Experiment 1. In general, such a more difficult distinguishability may express itself not only in the form of slower responses but also in the form of fewer correct responses. In this sense, the SvL vs. SvM analysis in terms of the six triadic comparison conditions from Experiment 1 revealed that the occurrence of (a)symmetry effects varies with the conditions. That is, asymmetry effects were found in condition 2 (both for RTs and percentage correct), in condition 4 (for RTs) and in condition 6 (both for RTs and percentage correct). Furthermore, symmetry effects were found in condition 1 (for percentage correct) and in condition 5 (for percentage correct). Furthermore, like in Experiment 1, the strength analyses provided more detailed quantitative evidence for the perceptual relevance of the WoE and Zimmer calculations in dyadic symmetry judgments.

Hence, the findings of Experiment 2 agree well with the findings of Experiment 1, and reconfirm van der Helm and Leeuwenberg's (1996) prediction that the occurrence of (a)symmetry effects depends on symmetry-to-noise ratios.

4. General discussion

The fact that perfect symmetries are rare in nature directs attention to the importance of studying of symmetry under varying amounts of noise. In one of the first empirical studies devoted to noisy symmetry, Barlow and Reeves (1979) measured the discriminability of symmetry as a function of the ratio of paired to unpaired dots. They found that the discriminability of symmetry deteriorates as the proportion of unpaired dots increases. They concluded therefore that symmetry is not an all-or-nothing property but a graded property that degrades gracefully with increasing noise. This conclusion found consistent support in later studies on both low-level and high-level aspects of symmetry perception (e.g., Dakin & Herbert, 1998; Dakin

& Hess, 1997; Dakin & Watt, 1994; Gurnsey, Herbert, & Kenemy, 1998; Jenkins, 1982; McBeath et al., 1997; Rainville & Kingdom, 2000).

For example, in a study on low-level vision, Dakin and Hess (1997) reported that the impairing effect of noise on symmetry detection is invariantly present at a wide range of spatial frequency scales. More particular, their participants showed a reduced level of performance for symmetric images embedded in higher levels of noise, and this effect was irrespective of whether the symmetric images were displayed at low or high spatial frequency scales. Using orientation-specific filters, the same authors also investigated how noise-resistance interacts with different element orientations (i.e., elements oriented parallel or perpendicular to the axis of symmetry). Apart from an advantage (i.e., a higher noise resistance) for orientations perpendicular to the axis, their data for both orientations again consistently show worse performance for higher amounts of noise. This tendency is supported further by Rainville and Kingdom's (2000) results for a wider range of element orientations.

Furthermore, in a study on high-level vision, McBeath et al. (1997) reported a strong linear relationship between the amount of symmetry in 2-D polygons and observers' interpretations about the spatial orientation of these polygons. Asking observers to describe a polygon ("What does the figure look like?") and to decide on its orientation, they found that the observers tended to interpret more symmetrical polygons as 3-D objects aligned with the observer and the less symmetrical polygons as 3-D objects oriented obliquely to the side. Finally, the aesthetical value of symmetry also seems to decrease gradually with increasing amounts of noise (e.g., Rhodes et al., 1998).

The results from the foregoing studies support the relevance of symmetry-to-noise ratios in symmetry perception. They do not, however, exclude that Freyd and Tversky's (1984) (a)symmetry effects might be attributable to an over- or underestimation of the amount of symmetry in an image. After all, for their high overall symmetry condition, probably every reasonable quantification of symmetry-to-noise ratios would have given average symmetry values that predicted an asymmetry effect, whereas they found a symmetry effect. Hence, this symmetry effect indeed seemed to be a consequence of overestimating amounts of symmetry.

In the current study, however, we performed a more detailed investigation into the occurrence of (a)symmetry effects. We tested the prediction van der Helm and Leeuwenberg (1996) derived from their holographic approach to visual regularity, namely, that (a)symmetry effects are not the result of wrong judgments of amounts of symmetry but, rather, the result of correct judgments of symmetry-to-noise ratios. We tested this by way of six symmetry-to-noise ratio manipulation conditions under a constant overall level of symmetry. Symmetry effects were predicted in three of these conditions and asymmetry effects were predicted in the other three conditions. The pattern of results in both experiments largely agrees with these predictions, suggesting that (a)symmetry effects are indeed triggered by correct judgments of symmetry-to-noise ratios.

Furthermore, the strength analyses showed that both WoE and Zimmer's metric correctly predict the strength of the (a)symmetry effects. These analyses not only add support to van der Helm and Leeuwenberg's prediction, but also provide cues as to why conditions 1 and 3 may not have behaved fully as predicted.

First, condition 1 has the smallest absolute values of $\Delta^2 W$ and $\Delta^2 Z$ (see Tables 2 and 3). This suggests that, perceptually, the more and the less symmetrical variants may have seemed equally similar to the standard, so that the similarity judgments in Experiment 1 could not evoke a symmetry effect. Furthermore, conditions 1 and 5 have the smallest differences in W values and Z values between the standard and its variants. This suggests, for the symmetry judgments in Experiment 2, that the perceptual differences between the standard and its variants may have been too small to evoke a fully convincing effect (i.e., the predicted symmetry effect was found for percentage correct, but not for RTs).

Second, condition 3 has the largest differences in W values and Z values between the standard and its variants. In line with this, the symmetry judgments in this condition were faster and more accurate than in the other conditions. It also suggests, however, that these symmetry judgments may have been too easy to evoke a symmetry effect. The large differences between the standard and its variants suggest further that, perceptually, the two variants in this condition may have seemed almost equally unsimilar to the standard, so that the similarity judgments in Experiment 1 could not evoke a symmetry effect.

In sum, the following two conclusions can be drawn on the basis of the results of the two experiments reported here. First, the results provide evidence that, unlike Freyd and Tversky's (1984) suggestion, both symmetry and asymmetry effects can be triggered at the same level of overall symmetry. Second, the results support van der Helm and Leeuwenberg's (1996) prediction that (a)symmetry effects are not the result of wrong judgments of amounts of symmetry but, rather, the result of correct judgments of symmetry-to-noise ratios.

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