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Mapping the perceptual structure of rectangles through goodness-of-fit ratings

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Abstract. Three experiments were carried out to investigate the internal structure of a rectangular frame to test Arnheim's (1974 *Art and Visual Perception*, 1988 *The Power of the Center*) proposals about its 'structural skeleton'. Observers made subjective ratings of how well a small probe circle fit within a rectangle at different interior positions. In experiment 1, ratings of 77 locations were highest in the center, decreased with distance from the center, greatly elevated along vertical and horizontal symmetry axes, and somewhat elevated along the local symmetry axes. A linear regression model with six symmetry-related factors accounted for 95% of the variance. In experiment 2 we measured perceived fit along local symmetry axes versus global diagonals near the corners to determine which factor was relevant. 2AFC probabilities were elevated only along the local symmetry axes and were higher when the probe was closer to the vertex. In experiment 3 we examined the effect of dividing a rectangular frame into two rectangular 'subframes' using an additional line. The results show that the primary determinant of good fit is the position of the target circle within the local subframes. In general, the results are consistent with Arnheim's proposals about the internal structure of a rectangular frame, but an alternative interpretation is offered in terms of the Gestalt concept of figural goodness.

1 Introduction

The present research was motivated by issues concerning the aesthetics of spatial composition in painting and photography. Because painters and photographers compose nearly all of their images within the confines of a rectangular frame, it is reasonable to suppose that people's aesthetic response to an image's composition would be closely linked to the placement of pictorial elements within the surrounding rectangle (eg Arnheim 1974, 1988). Indeed, empirical research has shown this to be the case. Numerous studies have shown that balance around the center of a rectangular frame plays a crucial role in spatial composition, as measured in a variety of different tasks, including participant-controlled adjustments of pictorial elements (eg Locher et al 1998; Pierce 1894; Puffer 1903), explicit judgments of balance (eg McManus et al 1985; Locher et al 2005), and explicit judgments of aesthetic preference (Bertamini et al 2011; Palmer et al 2008). For example, when Palmer et al varied the horizontal position of the object in single-object, rectangular pictures and had viewers rate their aesthetic reactions on a 1 – 7 scale, they found that people generally preferred symmetrical objects to be located at the center of the frame (the center bias), consistent with Arnheim's ideas. Asymmetrical objects with a 'facing' direction, however, were preferred somewhat off-center and facing into the frame (the inward bias) though generally still being located toward the center. Bertamini et al (2011) corroborated the latter effects of facing direction in paintings and drawings of animals in bestiaries. Subsequent research has shown both center and inward biases to influence preferences in the vertical dimension as well (Sammartino and Palmer, in press), although other factors are clearly at work when meaningful objects are portrayed.

Such findings have amply demonstrated that there are robust and systematic influences of the frame on the perception and aesthetic response to the images it contains, but how are such findings to be understood theoretically? The most obvious possibility is that they arise from interactions between the perceived structure of the object in the picture and the perceived structure of its surrounding rectangular frame. This hypothesis was central to the ideas of Rudolph Arnheim, a Gestalt psychologist whose theoretical discussions of spatial composition are among the most sophisticated and widely known analyses of perceptual organization in art (eg Arnheim 1966, 1974, 1988).

At the heart of Arnheim's theory is his concept of the 'structural skeleton' of a frame, which he viewed as the scaffolding on which images were composed. In keeping with his Gestalt training, he saw this implicit structure as arising from the interaction of 'force fields' generated in the brain by perception of the edges enclosing the framed space, directed both inwardly and outwardly from the edges themselves. Figure 1 shows a diagram representing his ideas about the structural skeleton of a square (Arnheim 1974, page 13). He arrived at this diagram by placing a relatively large black disk at various positions within the square and analyzing his perceptual experience in terms of whether the disk tended to 'feel stable' or as if it 'wanted to move' in a particular direction or along a particular axis. The lines shown in figure 1 were Arnheim's attempt to capture these intuitions about the structural stability and 'balance of forces' (ie best positions) for the disk. In presenting figure 1 he explained:

> "Informal explorations show that the disk is influenced not only by the boundaries and the center of the square, but also by the cross-shaped framework of the central vertical and horizontal axes and by the diagonals. The center, the principal locus of attraction and repulsion, established itself through the crossing of these four main structural lines. Other points on the lines are less powerful than the center, but the effects of attraction can be established for them as well. [...] Wherever the disk is located, it will be affected by the forces of all the hidden structural factors. The relative strength and distance of these factors will determine their effect in the total configuration. At the center, all forces balance one another, and therefore the center position makes for rest." (Arnheim 1974, pages 13 – 14)

Perhaps not surprisingly, Arnheim concluded that the single most structurally salient position is the center, which lies at the intersection of all four of the square's global symmetry axes: one vertical, one horizontal, and two diagonal. For this reason, Arnheim claimed the center to be the most balanced and stable point in the framed space, a fact that justified the crucial role he assigned it in analyzing the position of paintings.

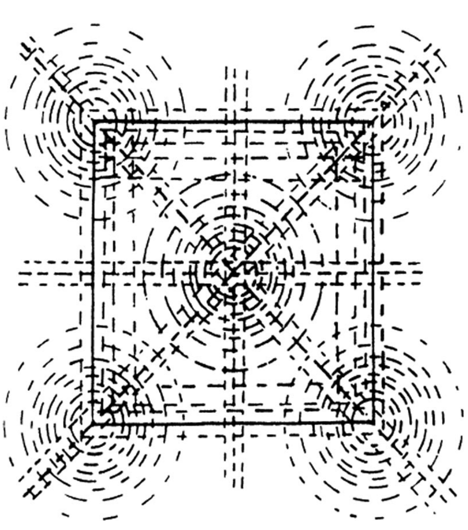


Figure 1. Arnheim's representation of the structural skeleton of a square (from Arnheim 1974). Solid lines are the boundaries of the square, and dashed lines represent positions of stability or near-stability along global symmetry axes and at singular points at the center and vertices. (See text for further details.)

Indeed, the center was so critical to his thinking that he entitled one of his books on spatial composition *The Power of the Center* (Arnheim 1988). Similar importance has been assigned to the notion of center by Christopher Alexander (2002) in his four-volume analysis of architectural structure and function, *The Nature of Order*. Arnheim originally presented his ideas about the structural skeleton of a square in the initial edition of *Art and Visual Perception* based solely on his own intuitions. In later editions of the same book, however, he presented supporting experimental evidence from unpublished research by Goude and Hjortzberg (1967). Their observers saw a 4-cm-wide black circle at various positions within a larger (46 cm $\times$ 46 cm) white square and were asked to report whether the disk exhibited "a tendency to strive in any direction" (Arnheim 1974, pages 14–15). If it did, they were asked to report the strength of this tendency in each of the eight principal directions of space. As Arnheim claimed, the center proved to be the most stable position (ie the one with the least tendency to move). Also consistent with Arnheim's analysis, the reported feelings toward movement were strongest along the global axes of symmetry, which form the principal axes of Arnheim's structural skeleton. Note that global symmetries would be preserved if the circle were to move along these axes, but broken if they moved in any other directions.

In this article, we report the results of additional research mapping the internal structure of a frame, although in this case it is the more common shape of a rectangle rather than square. It is somewhat unfortunate that Arnheim and Goude and Hjortzberg used a square, because the global diagonals of a square (ie the lines connecting opposite vertices with each other) are identical with the diagonal global symmetry axes that bisect the angles in this frame shape. When a square is elongated into a rectangle, its global diagonal symmetry axis is broken and its diagonals[(1)] diverge from its local symmetry axes along the bisectors of its angles.[(2)] It is therefore impossible to say whether Arnheim believed that the structural stabilities of a rectangular frame lie along its global diagonals, along the local symmetry axes of its angle bisectors, or both. (We investigate this question explicitly in experiment 2.)

The method we use here to study the structural properties of a rectangular frame was first devised by Palmer (1991) as a way to examine the perceptual effects of different sorts of symmetries. On each trial observers were shown a single target circle in one of 35 positions from a 5×7 grid within a rectangle and were asked to rate 'how well it fits within the frame' at the presented position using a seven-point scale, where $1 =$ worst fit and $7 =$ best fit. The results showed that ratings were clearly highest when the circle was located at the center, with the next-highest ratings along the vertical and horizontal axes of global symmetry. Elevated ratings were also evident along the diagonal axes of local asymmetry that bisect the angles at the corners. Palmer (1991) used this sampled 'goodness-of-fit' task within square, trapezoidal, and circular frames as well as rectangular ones with comparable results: higher fit ratings when the target circle was positioned along contextually salient symmetry axes. It is worth noting that the experimental task Palmer gave his observers was not unlike the informal task Arnheim reported using on himself to construct the skeleton in figure 1 and that the results, as we shall see, are also consistent with his phenomenological analysis.

In experiment 1, we replicate and extend Palmer's (1991) results within a rectangular frame using a denser sampling of positions: 77 locations from an 11×7 grid. We show that a linear regression model based on six symmetry-related factors accounted for 95% of the variance. This model is far superior to alternative structures, such as the

(1) The diagonals of a rectangle are the two lines that connect its opposite vertices. In a square, they coincide exactly with the global axis of reflectional symmetry about the angle bisectors.

(2) By a 'local symmetry axis' we mean a line about which a geometrical figure is symmetric within a diameter-limited region. The angle bisector of a rectangle is therefore an axis of local symmetry from its vertex to its intersection with the midline along its long dimension.

well-known 'grassfire' or 'medial axis transformation' skeleton (Blum 1967) and the 'maximal a posteriori' skeleton (Feldman and Singh 2006) that have been proposed to represent skeletal axes of two-dimensional shapes. Experiment 2 probes the detailed nature of perceived goodness-of-fit along axes of local symmetry and global diagonals near the corners using a two-alternative forced-choice (2AFC) technique. The results show that fit ratings are elevated along locally symmetric positions on the angle bisectors, rather than along the rectangle's global diagonals, and that fit ratings are higher when the target circle is closer to the vertex of the rectangle's corner. Experiment 3 examines the effect of dividing a rectangular frame into two rectangular 'subframes', as is sometime done in paintings. The results show that the primary determinant of goodness-of-fit within such divided frames is the position of the target circle within the local subframes, with position in the global frame accounting for little, if any, of the variance.

2 Experiment 1: Goodness-of-fit for a circle within a rectangle

In the first experiment we decided to extend the fit measurements previously reported by Palmer (1991) by using a denser sampling of positions (7×11 rather than 5×7) and a rectangle of different aspect ratio (3:2 rather than 4:3). We expected the same trends to be evident, with ratings elevated to the extent that the circle's center coincides with axes of symmetry according to their perceptual salience. Ratings should thus be highest at the center because a circle at that point preserves both the global vertical and horizontal symmetries of the rectangle. Ratings should be next highest along the vertical midline where the circular probe preserves the more salient perceptual symmetry along the vertical axis and somewhat lower along the horizontal midline where it preserves the less salient perceptual symmetry along the horizontal axis. We also expected somewhat elevated ratings along the angle bisectors of the vertices because these are local axes of symmetry up to the intersection of the angle bisector with the horizontal midline (ie reflectional symmetries of a finite diameter along the angle bisector; see footnote 2) in agreement with Palmer's (1991) previous findings.

2.1 *Method*

2.1.1 *Observers.* All twelve observers were students at the University of California, Berkeley, who received partial course credit in their undergraduate psychology course. Their mean age was 20.7 years. All were naive to the purpose and nature of the experiment and gave informed consent in accord with the policies of the University of California, Berkeley.

2.1.2 *Design.* The experiment included 4 blocks of trials, each consisting of 77 rating trials, one for each of the positions of the probe circle at the intersections of an 11×7 grid, for a total of 308 trials. The order of trials was randomized within each block by the presentation software that controlled the experiment.

2.1.3 *Displays.* The white rectangular frame within which the target circle appeared had an aspect ratio of 3:2 and measured 480×320 pixels. It was always presented at the center of the screen on a uniform gray background. The probe dot was black, had a diameter of 34 pixels, and was presented at the intersections of an equally spaced 11×7 grid. The space between the points of the grid was 40 pixels.

The displays were presented on an LCD laptop monitor, whose screen measured 15.4 inches diagonally. Participants viewed them from approximately 60 cm, at which distance the rectangle measured 12.4 deg $\times$ 8.2 deg of visual angle, and the probe circle was 0.85 deg in diameter.

2.1.4 *Procedure.* Participants were initially instructed about the nature of the task. They were told that on each trial they would see a rectangle with a single small circle at a particular position inside it and that their task was to rate "how well the circle fits within the frame at that position" on a seven-point-scale, where good fit corresponded to high numbers and bad fit to low numbers. After being instructed about the task, they were presented with 12 sample displays on a single screen, to acquaint them with the range of variability they would see during the trials. Once the experiment began, they saw an additional 15 practice trials before their ratings were recorded.

At the beginning of each trial, the fixation cross was presented on a gray background for 500 ms. When the cross disappeared, the screen remained gray for another 500 ms, and then the rectangle was presented with the probe circle inside it at one of the 77 possible positions. The display remained on the screen for 10 s, and participants were instructed to look at it and to rate the goodness-of-fit of the probe within the rectangle, pressing a key from 1 to 7 on the laptop keyboard. If they did not make their rating within 10 s, the computer beeped to remind them to make their rating. At the end of each block of trials, participants were given the opportunity to take a short break before proceeding to the next block.

2.2 *Results and discussion*

The ratings, averaged over replications and observers, are plotted in figure 2, where the mean fit ratings are represented by the diameter of the circle (higher ratings → bigger circles) and the darkness of the shading (higher ratings → darker circles). An overall analysis of variance confirmed strong main effects of vertical position ($F_{6,66} = 8.57$, $p < 0.001$), horizontal position ($F_{10,110} = 4.18$, $p < 0.001$), and their interaction ($F_{60,610} = 3.66$, $p < 0.001$).

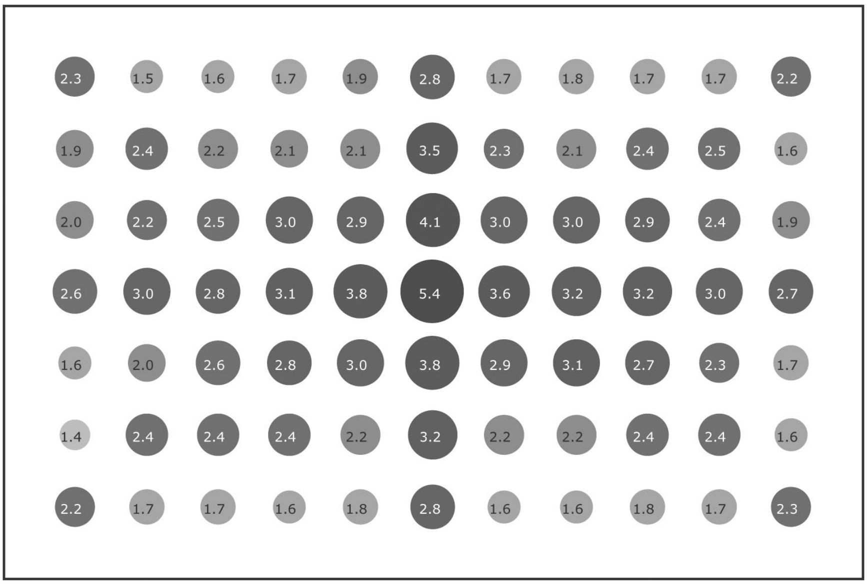


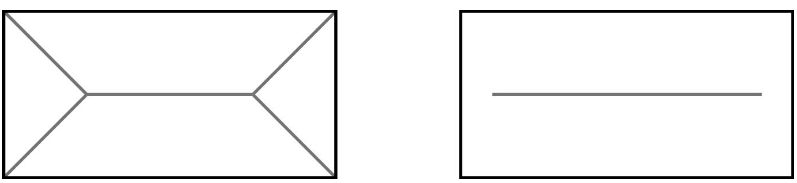
Figure 2. Average 'fit' ratings for the 77 positions in experiment 1. Larger, darker circles represent higher ratings.

There are several obvious patterns evident in the average fit ratings. First, they are highest at the center and fall off monotonically with distance from it. This gradual reduction with distance from the center, presumably reflecting 'the power of the center' discussed by Arnheim (1988), was not evident in Palmer's (1991) previous data, probably because of the smaller number of probed positions in the earlier study. Second, ratings are elevated along both the vertical and horizontal axes of global symmetry. Third, ratings are also somewhat elevated along the angle bisectors, especially near the vertices, where these axes are locally symmetrical.

We analyzed the pattern of the ratings using a multiple linear regression model based on the rectangle's symmetry axes and global diagonals (see footnote 2). We coded several different binary and continuous variables, reflecting properties of the circle's position with respect to the key geometric elements of the rectangle: (i) the probe circle's distance from the horizontal symmetry axis of the rectangle, (ii) the distance from the vertical symmetry axis of the rectangle, (iii) the distance from the nearest global diagonal of the rectangle, (iv) its location on/off the vertical axis of symmetry, (v) its location on/off the horizontal axis of symmetry, and (vi) its location on/off a local axis of symmetry along an angle bisector. A linear model including all of these six variables accounted for a remarkable 95% of the variance in the average fit ratings for the 77 positions,(3) producing a multiple r of 0.97. The distances from the vertical and horizontal symmetry axes together accounted for 66% of the variance, with additional variance being explained by position of the dot on/off the vertical axis (12%), position of the dot on/off the local corner symmetry axis (6%), distance from the nearest global diagonal (6%), and position on/off the horizontal symmetry axis (5%). Moreover, the beta weights (see footnote 4) are as expected, with the distances from the vertical, horizontal, and diagonal axes having negative weights, and the position being on (coded as 1) versus off (coded as 0) the symmetry axes having positive weights.

Overall, these results are impressively consistent with Arnheim's ideas about the structural skeleton of a framed space. All the positions at which the fit ratings of the probe were elevated occurred either along the global symmetry axes (vertical or horizontal) or along the local corner symmetry axis. These axes precisely define the structural skeleton of a rectangle as extrapolated from Arnheim's analysis of a square.

Nevertheless, other theories of skeletal structure must also be examined to determine their compatibility with the present data. One candidate is Blum's (1967) medial axis transformation (or MAT), also known as the 'grassfire transformation'. Intuitively, the MAT is the set of 'quench points' that would result if one started a fire simultaneously along the exterior boundary of a shape that burns at a perfectly constant rate. Figure 3a shows the MAT of a rectangle, which is similar in many ways to the pattern we find in the data, particularly in the prominent representation of the local symmetry axes along the angle bisectors. The MAT differs from our data in several crucial respects, however. First, the MAT does not include the short vertical axis of global symmetry at all, yet these are the positions at which the fit ratings are highest, except for the center. Second, the center of the rectangle has no structural significance in the MAT because the center is indistinguishable from all the other points along the MAT's central axis, which quench simultaneously. Third, the MAT does not include the parts of the long axis of global symmetry beyond its intersection with the angle bisectors. This is also contrary to the present data. Additionally, Palmer (1991) measured the goodness-of-fit for positions of a probe dot within a circle and found elevated ratings along the global vertical and horizontal axes of symmetry rather than



(a) (b)

Figure 3. (a) Medial axis transformation (MAT) and (b) maximum a posteriori (MAP) skeleton of a rectangle (adapted from Feldman and Singh 2006).

(3) The equation of the best fitting model was:
$Y = -0.004$ * DistFromHorAxis $-$ 0.002 * DistFromVertAxis $-$ 0.004 * DistFromNearDiag + 0.614 * OnVertSymAxis + $0.315 \times$ OnHorSymAxis + $0.210 \times$ OnLocSymAxis

just at the single point at the center, which constitutes its grassfire transformation. We therefore conclude that the MAT is qualitatively incompatible with the fit ratings described above and in previous measurements reported by Palmer (1991).

Another theory of skeletal structure that has been proposed to represent shape is the maximum a posteriori (or MAP) skeleton, formulated by Feldman and Singh (2006). Without going into the mathematical details, it is based on Bayesian probabilistic approach, in which a shape is assumed to have 'grown' by a stochastic generative process from the skeleton that is most likely to have produced it. The MAP skeleton for a rectangle is essentially just the longer axis of global symmetry (see figure 3b). Although fit ratings are indeed elevated along this axis, its weaknesses in fitting the present data are quite obvious: it does not contain the shorter axis of global symmetry, gives no special status to the center, and does not contain the axes of local symmetry along the axes of local symmetry. The MAP is thus also qualitatively incompatible with the present goodness-of-fit ratings.

3 Experiment 2. Local symmetries versus global diagonals

The second experiment examined fit judgments for a circular probe located near the rectangle's corners to determine whether the elevated ratings evident there in experiment 1 arose from being located on the locally symmetric portion of the angle bisector or whether they might have arisen from their proximity to the global diagonal of the rectangle. For squares (ie rectangles whose aspect ratio is 1 : 1, as in figure 1), these local corner symmetry axes and global diagonals exactly coincide, but for rectangles of any other aspect ratio they diverge to a degree that depends on the aspect ratio of the rectangle. The best-fitting regression model of the results of experiment 1 included factors reflecting both geometrical features—distance from the closest diagonal and position on/off the local corner symmetry axis—so it is particularly important to clarify whether one, the other, or both of these factors govern people's goodness-of-fit judgments. In this experiment, we used the more sensitive method of two-alternative forced choice (2AFC), rather than ratings of single displays.

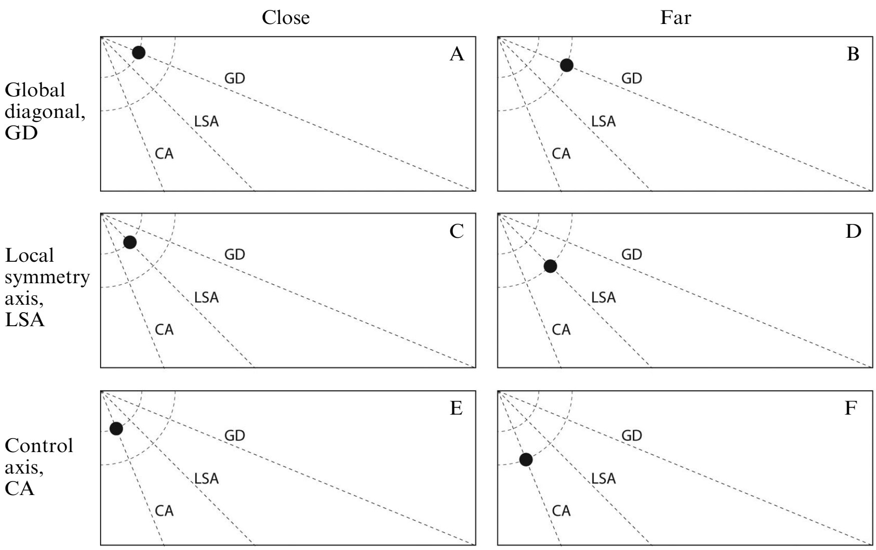


Figure 4. Examples of the possible dot positions around the upper left corner of a 12×5 rectangular frame at close and far positions. In A and B the dots are placed along the global diagonal (GD) axis of the frame; and C and D the dots are placed along the local symmetry axis (LSA).; and in E and F they are placed along the control axis (CA).

Observers were shown two identical rectangles, each containing a single circular probe, and were asked to decide in which of the two cases the probe's 'fit' within the rectangle was better. In the crucial conditions, the probe positions were equidistant from the vertex, but located along either the global diagonal (GD), the local symmetry axis along the angle bisector (LSA), or a control axis (CA) symmetric to the global diagonal reflected about the angle bisector (see figure 4). The aspect ratio of the rectangle was 12 : 5 to optimally differentiate among these three axes, forming equal angles of 22.5°, 45°, and 67.5°, respectively, relative to the long axis of the rectangle. Two distances from the corner were probed (42 and 76 pixels), and all four corners of the rectangles were tested. The 2AFC pairs on a given trial differed only in the position of the probes relative to the same corner of rectangles in the same orientation.

3.1 *Method*

3.1.1 *Observers.* Ten undergraduate students of the University of California, Berkeley, received partial course credit for participating. Their mean age was 19.3 years. All were naive to the purpose and nature of the experiment and gave informed consent in accord with the policies of the University of California, Berkeley.

3.1.2 *Design.* The experiment included a total of 288 trials, consisting of two repetitions of 18 pairwise comparisons at each of the four corners of the two different frames (horizontal and vertical rectangle). The 18 pairwise comparisons consisted of 6 comparisons of the dots placed along different axes at the close distance from the corner (A/C, A/E, and C/E in figure 4 in both spatial arrangements), 6 comparisons along different axes at the far distance from the corner (B/D, B/F, and D/F in figure 4 in both spatial arrangements), and 6 comparisons of dots placed along the same axes but at different distances from the corner (A/B, C/D, and E/F in figure 4 in both spatial arrangements).

3.1.3 *Displays.* Two frames were always presented on a gray background, one in the upper left, the other one in the lower right of the screen so that they were not aligned either horizontally or vertically. Their size was 480×200 pixels, and their orientation on a given trial was always the same. The black dots always had a diameter of 34 pixels and were placed at either 42 (close) or 76 (far) pixels from the vertex.

Displays were presented on an LCD computer monitor measuring 15.4 inches diagonally, with 1280×800 pixel resolution. Participants viewed it from approximately 60 cm. At this distance the dimensions of the rectangles were 12.4 deg $\times$ 5.2 deg, and the circular probe subtended 0.8 deg.

3.1.4 *Procedure.* At the beginning of each trial, a fixation cross was presented in the center of the screen on a gray background for 500 ms. When the cross disappeared, the screen remained gray for another 500 ms, and then two frames were presented, each with a single dot inside it. The displays remained on the screen for 10 s, and participants were instructed to make a button response (left or right) indicating within which frame the dot seemed to fit better. If they did not make their response within 10 s the stimulus disappeared and the computer beeped to remind them to make a choice. At the end of each block of trials, participants were given the opportunity to take a short break.

3.2 *Results and discussion*

The main purpose of the study was to determine whether participants considered the probe dot to fit better along the local symmetry axis of the angle bisector than along the global diagonal or the control axis. We used the data from the 2AFC trials to compute, for each subject, the following: the probability of choosing as better fitting the dot along the local symmetry axis (LSA) versus the dot along the global diagonal axis (GD), the probability of choosing the dot along the GD versus the dot on the control axis (CA), and the probability of choosing the dot along the LSA versus the dot on the CA.

Figure 5a plots the proportion of trials on which participants chose each position of the dot as fitting better for each type of comparison within the rectangular frames, averaged over horizontal and vertical frame orientations and all four corners. Participants judged the dot along the LSA to fit better than along both the GD ($t_9 = 6.02, p < 0.0001$) and the CA ($t_9 = 4.98$, $p < 0.001$), whereas the fit of the positions along the GD and the CA did not differ ($t < 1$). These results show quite clearly that it is the local symmetry axis along the angle bisector rather than the global diagonal that matters in the perception of how well a dot fits within a rectangle near a corner. Indeed, ratings of fit for the global diagonals were not different from those of a structurally unimportant control axis that was in an analogous geometrical relation to the angle bisector.

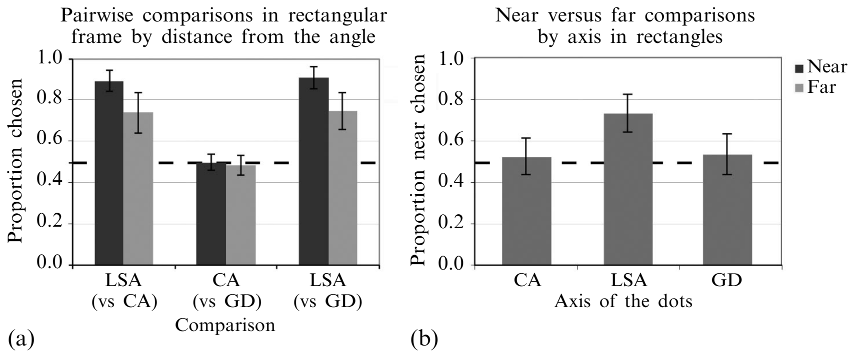


Figure 5. Results of experiment 2. Histograms show the proportion of trials on which the probe was chosen as fitting better at the indicated position—local symmetry axis (LSA), global diagonal (GD), or control axis (CA)—than in the comparison position (in parentheses) [panel (a)] and for probes near the vertex fitting better than those far from the vertex along the same axis [panel (b)].

To examine the effects of distance from the vertex, we analyzed the data from the comparisons between positions along the same axes, but at different distances from the vertices, to determine whether positions closer to the corner were judged to fit better than positions farther from it. For each participant, frame aspect ratio, and axis, we computed the average probabilities of choosing the dot closer to the corner as fitting better than the dot farther from the corner. As shown in figure 5b, the fit of the dot varied reliably with distance only along the LSA, where the positions closer to the corner were chosen as fitting better than the positions farther from the corner ($t_9 = 2.55$, $p < 0.05$). The corresponding probabilities computed from the comparisons along the other two axes (GD and CA) were not significantly different from chance (0.5) or from each other ($t < 1$).

The results of experiment 2 thus clearly show that participants judged the local symmetry axis along the angle bisectors to be the best location for the dot in the vicinity of the corner, preferring it to both the global diagonal and to the control axis, which did not differ from each other. This is consistent with Arnheim's view that the structural skeleton arises from perceptual forces that are generated from the boundaries of the frame in every direction, which implies that locally symmetrical positions should be the ones in which 'forces' originating from different borders would balance each other. The fact that participants considered the dot to fit better closer to the corner than farther from it along the angle bisectors of the rectangular frames is also consistent with Arnheim's view that the vertices are 'attractors'. The fact that the preference for the closer positions was not found along the other two axes, however, means that the attraction of the corner was specific to its angle bisector, where the forces near the corner are balanced.

If the local symmetry axis is, in fact, the critical geometric feature near the corners why, then, did the multiple regression analysis of the results of experiment 1 include the distance to the nearest global diagonal? There are several possibilities. One is that the global diagonal is more important toward the center of the frame than it is near the corners. We note, however, that as the global diagonal gets closer to the center, it becomes relatively more similar to the vertical and horizontal axes of the frame. Another is that distance from the global diagonal may actually be accounting for some of the variance due to the effects of distance from the center of the frame. We note that the best fitting model did not include distance from the center, but that the distances from the horizontal, vertical, and diagonal axes together serve as a surrogate for it. Why, then, does distance from the center not emerge as the better fitting variable? It seems likely that it is because distances from the center along different directions can be weighted differently when the three different distance measures are included. Regardless, the present results with an optimally sensitive 2AFC method make it abundantly clear that near the corners, it is the local symmetry axis rather than the global diagonal that matters. We will therefore ignore the global diagonal in the remainder of this article, with the caveat that future research may identify that it indeed makes some unique contribution to goodness-of-fit.

4 Experiment 3. Goodness-of-fit within subspaces of a partitioned rectangle

Arnheim conceived the structural skeleton as a dynamic configuration of forces in the perceptual space that was created by the elements present there, particularly by the borders that bound it. This conception implies that the structure should change if other borders divide the space into inner subspaces, because they should create their own local structural skeleton. In the first two experiments we found that the positions along on the structural skeleton of a rectangular frame (the center plus the global and local symmetry axes) were the ones where fit ratings of a single probe dot were elevated above surrounding positions. In the present experiment, we examine whether the same structural skeleton can also be found within subspaces of the frame, using the same fit-rating paradigm as in experiment 1. We therefore designed an experiment in which the rectangular frame was partitioned into two subspaces by a single dividing line.

In this experiment, we modified the rating paradigm by switching from a 7-point Likert scale to an approximately continuous 100-pixel line-mark rating scale. We decided to adopt this rating procedure to reduce the possibility that participants would be able to remember their ratings for different stimulus conditions and thus be influenced by these memories in their successive judgments. We did not want them to try to be consistent, but merely to express their subjective assessment about the goodness-of-fit of the dot within the frame.

4.1 *Method*

4.1.1 *Observers.* All thirteen observers were students at the University of California, Berkeley, who received partial course credit in their undergraduate psychology course. Their mean age was 19.3 years. All were naive to the purpose and nature of the experiment and gave informed consent in accord with the policies of the University of California, Berkeley.

4.1.2 *Design.* The experiment consisted of 300 rating trials, grouped in 5 blocks of 60 trials each. The 300 trials resulted from 2 repetitions of 150 different conditions, resulting from four divided frames (two horizontal and two vertical) in which 24 positions were probed and two undivided frames (one horizontal and one vertical) in which all 27 positions were probed. The order of trials was randomized within each block of repetitions by the presentation software that controlled the experiment.

4.1.3 *Displays.* The white rectangular 'outer' frame in which the dot appeared measured 500 pixels × 300 pixels (subtending 12.9 deg × 7.8 deg of visual angle from the viewing distance) and was always presented at the center of the screen on a uniform gray background. This outer frame was either horizontally or vertically oriented and, in 2/3 of the conditions, the space it enclosed was partitioned into two subspaces by a dividing line that was connected to the outer frame along its longer sides (see figure 6). The line was always parallel to the short side of the frame, and so its length was 300 pixels, while its width was 4 pixels (0.1 deg). To give the displays a more uniform and unified appearance, the frame also had a black border, whose thickness was the same as that of the dividing line. The line was always displaced by 50 pixels from the center of the long axis of the frame, either leftward or rightward if the frame was horizontal and either higher or lower if the frame was vertical. In all cases, the line divided the long side of the outer frame into two segments, measuring 200 and 300 pixels respectively (5.2 deg and 7.8 deg), thus producing an inner square (300 pixels × 300 pixels) and a smaller inner rectangle (200 pixels × 300 pixels). The probe dot was black, had a diameter of 34 pixels (0.9 deg) and was presented at the vertices of the 9 × 3 grid illustrated in figure 6a. The space between the points of the grid was 50 pixels along the long frame axis and 100 pixels along the short one. This configuration was chosen so that, when the dividing line was present, we could place the probe at the center positions of both the subframes. Notice that three of the positions of the grid were not used when a dividing line was present, because it would have intersected it. The displays were presented on a 15.4 inch LCD laptop monitor, which participants viewed from approximately 60 cm.

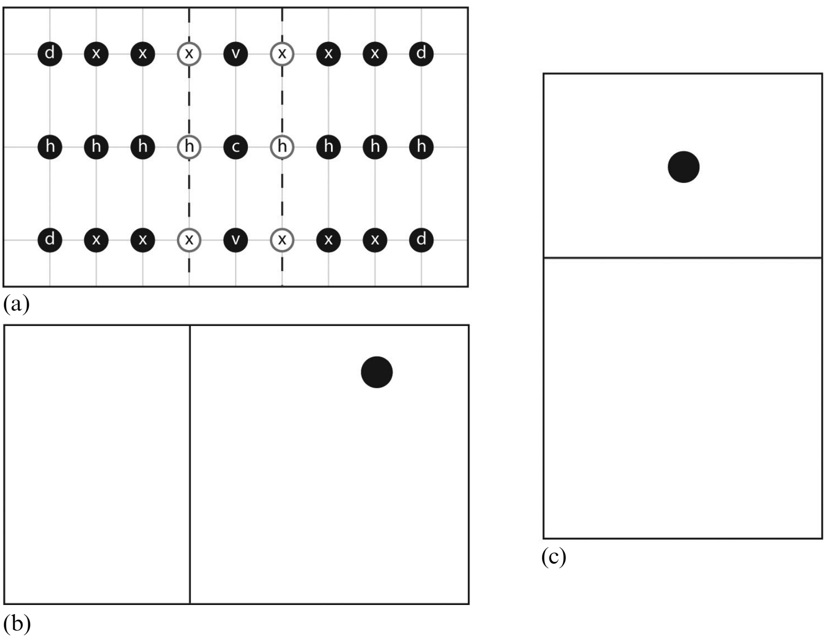


Figure 6. (a) The grid of the 27 possible probe positions (black dots, not to scale) and possible dividing line positions (dashed lines) within the horizontal outer frame. The 24 filled dots were presented in all conditions and the 6 unfilled dots were only presented in the undivided frame conditions. (b) and (c) show example displays in experiment 3 for the horizontal (b) and vertical (c) frame conditions. (Lower case letters inside the gray dots designate symmetry conditions of each position; see text for details.)

4.1.4 *Procedure.* After being instructed about the task, participants were presented with an 'anchoring display', consisting of several stimulus images, to acquaint them with the range of variability they would see during the trials so that they would have some basis for using the response scale effectively.

At the beginning of each trial, a fixation cross was presented on the gray background for 500 ms. When the cross disappeared, the screen remained gray for 500 ms, and then the rectangle was presented with the dot positioned at one of the 27 positions within the undivided frame or one of the 24 positions within the divided frame (figure 6). The displays remained on the screen until a response was made or 10 s had elapsed without a response. Participants were instructed to look at each display and to rate the goodness-of-fit of the probe at that location within the rectangle on a continuous line-mark rating scale, adjusting the position of the marker by using the mouse, and clicking to save their rating. At the left and right ends of the line, labels indicated the lower and upper values of the scale as 'very bad' fit and 'very good' fit, respectively. If they did not make a rating during the first 10 s, the screen was grayed and the computer beeped, to remind them to make their rating. At the end of each block, participants were given the opportunity to take a short break before proceeding to the next block.

4.2 *Results and discussion*
The ratings, averaged over replications and observers, are presented in figure 7 for the undivided frames and in figure 8 for the divided frames. The area and darkness of the circles reflect the mean ratings of goodness-of-fit for a probe circle in the corresponding position within the frame. The results for the undivided frame conditions show a pattern that is similar to that in experiment 1, but not identical. The statistical significances of the following results were assessed by comparing the average rating for the set of positions with a given specification (eg those on the horizontal axis of symmetry, labeled 'h' in figure 6a) with the average rating for the set of 12 control positions that do not lie on any axis of symmetry (labeled 'x' in figure 6a). In both the vertical and the horizontal orientations of the frame, the center ('c' in figure 6a) received higher ratings than its immediate neighbors on the vertical axis of symmetry ('v' in 6a) (mean difference = 51.3, $F_{1,12} = 47.19$, $p < 0.0001$). Fit ratings were also elevated at positions along the vertical symmetry axis ('v' in 6a) (mean

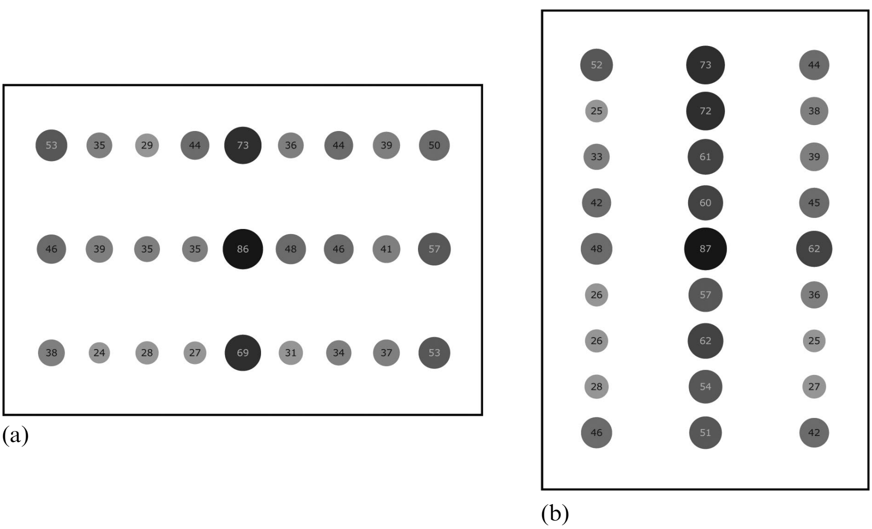


Figure 7. Average fit ratings for the horizontal (a) and vertical (b) orientations of the frame, in the undivided frame condition.

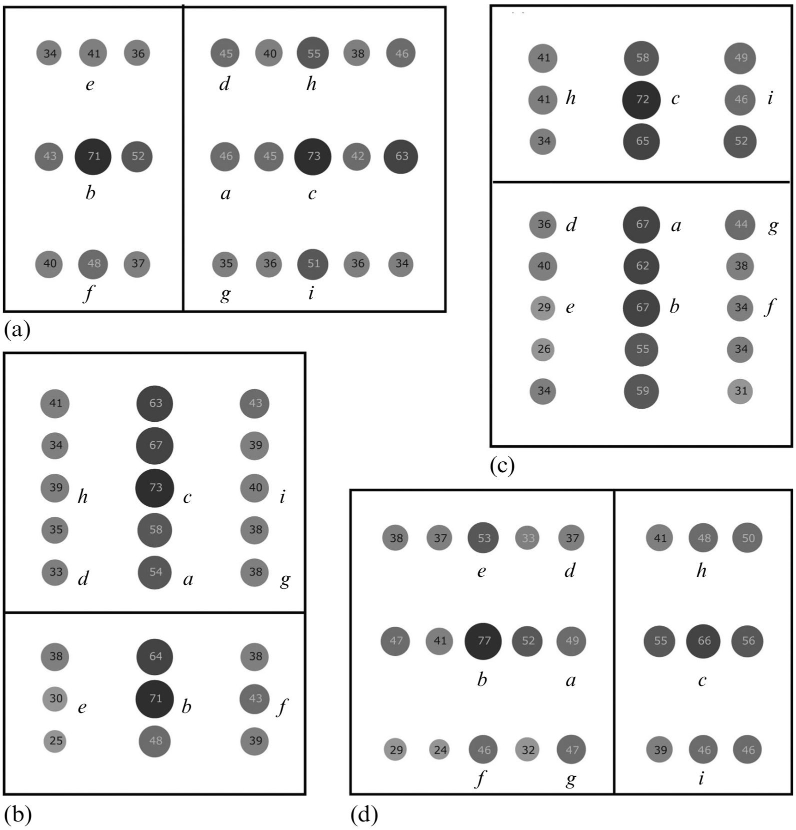


Figure 8. Average fit ratings in the divided frame conditions of experiment 3.

difference = 33.3, $F_{1,12} = 31.67$, $p < 0.001$) and horizontal symmetry axis ('h' in 6a) (mean difference = 15.6, $F_{1,12} = 10.27$, $p < 0.01$), with a trend toward higher ratings at the corners ('d' in 6a) (mean difference = 12.3, $F_{1,12} = 3.43$, $p = 0.09$), all relative to the nonsymmetrical positions ('x' in 6a). Positions along the vertical symmetry axis received higher ratings than those along the horizontal one (mean difference = 17.7, $F_{1,12} = 10.97$, $p < 0.01$). Further tests showed that this was true only in the horizontal frame: $t_{12} = 3.86$, $p < 0.01$, although the effect of frame orientation on the value of this contrast was not statistically significant. The corner positions ('d' in 6a) also were rated as fitting better within the rectangle than the positions closest to them that were not on an axis of symmetry (the closest 'x' positions in 6a) (mean difference = 14.1, $F_{1,12} = 5.03$, $p < 0.05$). Finally, the pattern seems to show generally higher ratings for positions in the upper half of the frame than the lower half (mean difference = 8.1, $F_{1,12} = 9.46$, $p < 0.01$), and in the right half of the frame than in the left half (mean difference = 6.0, $F_{1,12} = 8.70$). These above/below and right/left biases were not evident in the data from experiment 1 and will be discussed in detail below.

The fit ratings for the divided frame condition are clearly different from those for the undivided frame condition, as implied by a significant interaction between the divided/undivided frame conditions and the fit ratings for the 24 exactly corresponding probe positions ($F_{23,276} = 5.63$, 5.78, $p < 0.0001$ when the line was placed on the left and right side of the horizontal frame, respectively; $F_{23,276} = 3.05$, 2.31, $p < 0.001$ when the line was placed on the bottom and top of the vertical frame). Because the center is consistently rated as the best fitting position in a single, undivided frame, a primary question of interest is whether the center of the global outer frame (locations labeled *a* in figure 8) or those of the local inner frames (locations *b* and *c* in figure 8) will produce the higher fit ratings. Fit ratings for probes in these local subframe centers are indeed higher than for those in the global frame center, but only when the frame was horizontally oriented (mean difference = 22.6, $t_{12} = 2.35$, 2.12; $p < 0.05$ when the line was placed on the left and right side, respectively). In the vertical frame, fit ratings for probes in the local subframe centers trended toward higher values than for those in the global frame center only when the line was placed toward the bottom (mean difference = 12.9, $t_{12} = 1.90$, $p = 0.081$). The likely reason for this difference between the horizontal and vertical frame conditions depends on two factors. One is that vertical symmetries are robustly more salient than horizontal ones (eg Corballis and Roldan 1974; Palmer and Hemenway 1978; Palmer 1991). The other is that the positional difference between the global and local centers in the horizontal frame condition constitutes a change in the position of the more salient vertical symmetry axis, whereas that in the vertical frame condition constitutes a change in the less salient horizontal symmetry axis.

To get an overall indication of whether the fit ratings in the divided frames were primarily driven by the symmetry structure of the outer frame or the inner frame that contained the dot, we analyzed the data (averaged across repetitions and observers) using multiple regression models. We coded the position of each probe dot in terms of 12 predictor variables that were specified relative to either the outer, global frame, or the inner, local subframe: (1 – 2) whether or not the probe circle was at the center of the global frame or local subframe, (3 – 4) whether or not it was on the vertical symmetry axis of the global frame or local subframe, (5 – 6) whether or not it was on the horizontal symmetry axis of the global frame or local subframe, (7 – 8) whether or not it was on any of the local corner symmetry axes of the global frame or local subframe, (9 – 10) its vertical (y) coordinate within the global frame or local subframe, and (11 – 12) its horizontal (x) coordinate within the global frame or local subframe. The primary question of interest is which of these two sets of variables accounts for the greater percentage of the variance in the corresponding regression models.

The regression analyses for the horizontal frames confirmed what is evident by inspection of figures 8a and 8d: the structure of the inner frame is the primary determinant of the fit ratings. The best fitting model, explaining 81% of the variance, contained the following five variables: (1) the center of the local subframe (51%), (2) the horizontal symmetry axis, which is the same for local and global frames (+11%), (3) the vertical symmetry axis of the local subframe (+11%), (4) the global x-position (+5%), and (5) the local corner symmetry of the local subframe (+3%). Thus, the only effective variable of the global frame was x-position, which correlated with the overall (and unexpected) rightward bias. The corresponding analysis of the vertical frames produced less lopsided results. The best fitting model, explaining 92% of the variance, contained the following five variables: (1) the vertical symmetry axis, which is the same for local and global frames (78%), (2) the global y-position (6%), (3) the center of the local subframe (+4%), (4) the global x-position (+3%), and (5) the y-position within the local subframe (+1%). Although there are some complexities introduced by the presence of the biases for positions toward the top and right (which may be at least partly an artifact of the response scale; see below), the majority of these results indicate that the local subframe dominates the perceptual structure of a divided rectangle. This finding is consistent with Arnheim's claim that the structural skeleton is created by forces emanating from the borders that enclose a space (see previous quotation from Arnheim 1974, pages 13 – 14) and thereby create the local subframe, the parameters of which are more important than those of the outer global frame in accounting for the variance in fit ratings within divided frames.

The present data show significant positional biases in the pattern of ratings which were not evident in the results of experiment 1: namely, probes closer to the top and right of the surrounding frame were rated as fitting better. Why? One possible explanation for the rightward bias is in terms of response compatibility effects arising from line-mark rating scale in experiment 3. That is, if participants had a tendency to rate probes on the left side of the frame more to the left side of the response scale and probes on the right side of the frame more to the right side of the response scale, the ratings would be higher for probes on the right side of the frame. A similar claim can be made for the upward bias if participants conceived of the ratings made on the right side of the scale as 'higher' ratings and those of the left side as 'lower' ratings, which would produce a similar pattern of biases consistent with the more compatible mapping of locations to responses. Alternatively, these could be 'real' perceptual effects caused by anisotropies of visual space. The higher ratings for probes toward the right is consistent with a small rightward bias in aesthetic preference (eg Palmer et al 2008), which has often been interpreted in terms of asymmetries in visual processing by the left versus right cerebral hemispheres (Levy 1976), and/or to cultural differences related to reading direction (Nachson et al 1999). The corresponding bias in the vertical dimension, however, appears to be a preference toward lower positions, at least for the vast majority of objects, which are typically located below the viewer's eye level (Sammartino and Palmer, submitted). Further research will be required to determine the cause of these positional biases, which are relatively small in any case.

5 General discussion

We have studied goodness-of-fit ratings for a simple circular probe placed at different positions within rectangular frames. The results show robust and systematic positional effects, in that probes were judged to fit better at positions along global and local symmetry axes of the frame with the center—the single point on both the vertical and horizontal symmetry axes—always being the position in which the circle was perceived to fit best. Regression models based on these geometrically based symmetry factors produced good-to-excellent fits to the data.

The present results are consistent with Arnheim's (1974, 1988) view that there are particular locations at which objects fit best within a rectangular frame. The center, the global asymmetry axes, and the local symmetry axes at the corners of the frame define what Arnheim called the "structural skeleton" of a shape. He interpreted it as resulting from the dynamic interaction of forces propagating inward from the borders. He further believed that these forces are phenomenally felt in a viewer's visual experience and that they act perceptually on the elements present within the frame. Along the symmetry axes, these forces achieve a heightened sense of balance, so that any element positioned on them should be seen as more stable than at positions not on them. In this sense one could say that, for Arnheim, elements at those positions fit better within the space of the composition (or "the format" as he called it in *The Power of the Center*).

The present stimuli were certainly not examples of the kinds of artistic displays that Arnheim analyzed, but our findings seem to provide good experimental evidence supporting his ideas about the structural skeleton. Indeed, they confirm that the structural skeleton is not merely a geometrical structure within a rectangular frame, but one that is perceptually relevant to observers, at least in this goodness-of-fit rating task. Our results do not necessarily support either of Arnheim's further claims, however, that this skeleton arises from the interactions of inward forces from the borders of the shaped space or that the higher fit ratings of probes on the structural skeleton are actually due to greater perceptual 'stability'.

In many ways a simpler explanation is that the better fit of probes along axes of symmetry is due to the fact that resulting configurations have higher overall 'figural goodness' or 'simplicity' than conditions in which the probe was located elsewhere. Figural goodness (or 'good Gestalt') is already well established as an important concept in theories of perceptual organization. It originated in Gestalt psychology, where it formed the basis of their principle of Prägnanz: the hypothesis that the visual system tends to perceive the 'best' possible organization given the stimulus conditions. (See Palmer 2009 for a discussion on the central role of Prägnanz in Gestalt theory.) Virtually all later attempts to measure and formalize this notion include assessment of the structural/informational redundancies that arise from various forms of symmetry (eg Attneave 1954; Garner 1974; Hochberg and McAlister 1953; Leeuwenberg 1971; Palmer 1991; van der Helm and Leeuwenberg 1996). The present data further demonstrate the close relation between fit ratings and the local and global symmetries of the entire configuration. It is therefore reasonable to suppose that overall figural goodness could be responsible for most of the effects reported above, including the higher fit ratings along the vertical than the horizontal axes (cf Chipman 1977; Palmer and Hemenway 1978; Royer 1981). Moreover, the pattern of fit ratings is consistent with the differential goodness value of the various symmetry kinds, as specified by Palmer (1991).[(4)]

Explaining goodness-of-fit in terms of figural goodness might be regarded as circular. However, we must notice that these two properties/qualities are not, at least in principle, the same thing, as one is a relation between two individual perceptual units (or, more precisely, the relation between the target element and the surrounding context in which it appears), whereas the other is a global property of a single configuration that is viewed as an undifferentiated whole. Moreover, our data show effects that are not explicitly due to symmetries of the global configuration, including the effects of local symmetries and those of the probe circle's distance from the center and/or axes of symmetry.

To link the current results to questions of aesthetic science, one needs to ask whether the goodness-of-fit ratings correlate with ratings of aesthetic preference. Our experiments were not designed to address this question, but there are several reasons to think that they are indeed correlated. First, there is a strong theoretical rationale that fit ratings should be positively related to aesthetic ratings. One of the most successful theories of aesthetic response is 'fluency theory', which suggests people prefer stimulus displays to the extent that they can be perceived more quickly and easily (Reber et al 2004; Winkielman et al 2006). Previous work by Garner (1974) and others has shown that configurations with greater symmetry are processed more fluently in the sense that they are more easily encoded, more quickly and accurately matched for physical identity, and more accurately remembered than configurations with less symmetry. Given the close relation of symmetry to the present goodness-of-fit ratings, it is highly likely that displays with higher fit ratings will be processed more fluently and thus also be seen as more aesthetically pleasing.

Second, recent experimental studies of aesthetic response to single-object pictures have found a strong and systematic 'center bias' in both the horizontal position (Palmer et al 2008) and vertical position (Sammartino and Palmer, in press) of a meaningful object within a rectangular frame. This center bias appears to be a factor in virtually all cases, but it is particularly pronounced when the object itself is symmetrical about the relevant axis of the frame, suggesting that global symmetry of the entire configuration is a particularly salient feature. Morinaga (1935) reported a similar center bias in aesthetic judgments. He found that the center of a frame was the position at which

[(4)] The differential salience of different forms of symmetry is one of the main advantages of Palmer's (1991) formulation in terms of symmetry over Garner's (1974) theory in terms of rotational and reflection subsets in explaining figural goodness.

viewers considered a single disk to be most beautiful. He also reported that figures in aesthetically pleasing arrangements tend to be placed along the horizontal, vertical, or diagonal line passing through the center of the background. This 'center-passing rule' has been confirmed by more recent investigations by his disciples, who used several different paradigms and related their results to Arnheim's ideas about the structural skeleton of a frame (Mitsui and Noguchi 2002).

Third, and perhaps most convincingly, Griscom and Palmer (submitted) recently reported results explicitly measuring the correlation between goodness-of-fit ratings and aesthetic-reference ratings when the same set of 90 observers viewed the same set of displays. Each participant first made ratings of aesthetic preference and later made ratings of goodness-of-fit for the same visual displays, consisting of a single circle at one of 35 positions in a 5×7 grid within a rectangular frame (as in Palmer 1991). When each set of ratings was averaged over participants, the correlation between the average ratings of aesthetic preference and average ratings of goodness-of-fit was a remarkable 0.95, accounting for 90% of the variance. Clearly, people generally prefer images in which a circle is placed at good-fitting positions within a frame.[5] Clearly, there is a strong relation between the present goodness-of-fit data and aesthetic response, at least when averaged over many viewers.

Finally, it is worth commenting on the relation between the present results and the well-known compositional principle called the 'rule of thirds'. According to this rule, an artist or photographer should divide the frame into equal thirds horizontally and vertically and place the focal object at one of the four points of intersection (eg Field 1845; Smith 1797). The rule of thirds clearly implies that the focal object should not be placed at or even near the center of the frame either horizontally or vertically to produce the most pleasing aesthetic effect, but at or near the third-points, which are distinctly off-center and removed from global symmetry axes. Clearly, this prescription for spatial composition does not conform to any of the good-fitting positions within the frame according to the present results. Indeed, the four 'sweet spots' identified by this rule are positions that our participants systematically rated as fitting poorly within the frame. This seeming discrepancy does not actually surprise us, because we believe that the true purpose of the rule of thirds is to help novice photographers and artists consider more unusual compositions by overcoming their strong natural tendency to place the focal object at the center of the frame or along one of its symmetry axes. The rule of thirds specifically advises against these structurally strong positions within the frame, we believe, because a viewer is much more likely to get 'stuck' on the focal object when it is placed there, to the exclusion of other objects and/or aspects of the scene. Another way of saying the same thing is that following the rule of thirds is likely to make the viewer spread his/her attention more evenly over the picture, which is generally good for enhancing its appreciation. We are currently testing the rule of thirds more explicitly with judgments of aesthetic preference (rather than goodness-of-fit), but some of our previous results already indicate that people's compositional preferences do not conform well to it when compositional preferences are studied in detail (eg Leyssen et al 2012; Palmer et al 2008; Sammartino and Palmer, in press).

The present experiments were aimed primarily at discovering the positional structure of the interior of a rectangular frame, but there are additional aspects of goodness-of-fit that can be studied by using other sorts of probes. The circular probe we used has all possible central symmetries. To study the orientational structure within a frame

(5) Interestingly, individuals varied widely in terms of the extent to which they preferred images in which the circle fit well within the frame, however. The correlations between preference ratings and goodness-of-fit ratings for individuals ranged from about -0.50 to $+0.90$, with an average of $+0.36$.

at different positions, an oriented probe must be used (eg a small rectangle with two-fold symmetry), and to study the directional structure within a frame, a directed probe must be used (eg an isosceles triangle with one-fold symmetry). Further issues concern the effects of multiple probes within the same frame. We are collecting such data and will report the results in subsequent articles.

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