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Effects of element type and spatial grouping on symmetry detection

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Abstract. The influence of local and global attributes of symmetric patterns on the perceptual salience of symmetry was investigated. After tachistoscopic viewing, subjects discriminated between symmetric and either random patterns (experiment 1) or their perturbed counterparts (experiment 2) created by replacing one third of the mirror element-pairs of symmetric stimuli with 'random' elements. In general, it was found that perceptibility of symmetry, measured by response time and detection accuracy, was not influenced in a consistent way by type of pattern element (dots or line segments oriented vertically, horizontally, obliquely, or in all three orientations about the symmetry axis). Nor did axis orientation (vertical, horizontal, oblique), advance knowledge of axis orientation, practice effects, or subject sophistication differentially affect detection. A highly salient global percept of symmetry emerged, on the other hand, when elements were clustered together within a pattern, or grouped in symmetric pairs along a single symmetry axis or two orthogonal axes. Results suggest that mirror symmetry is detected preattentively, presumably by some kind of integral code which emerges from the interaction between display elements and the way they are organized spatially. It is proposed that symmetry is coded and signalled by the same spatial grouping processes as those responsible for construction of the full primal sketch.

1 Introduction

Tachistoscopic investigations of the detection of mirror symmetry show that the percept of symmetry emerges seemingly effortlessly over a wide range of stimuli and viewing conditions. One can rapidly perceive symmetry in simple random shapes (Carmody et al 1977); in dot patterns (Barlow and Reeves 1979) and textures (Julesz 1971); as well as in complex multiple-element abstract art displays (Locher and Nodine 1989). It can be detected at vertical, horizontal, and oblique axes, and when patterns are viewed eccentrically (eg Barlow and Reeves 1979; Locher and Nodine 1989). Furthermore, the mechanism responsible for symmetry detection shows a tolerance for 'smeared' (Barlow and Reeves 1979) and 'skewed' (Wagemans et al 1991) symmetry resulting from fluctuations of correlated element-pairs about a symmetry axis, and for 'imperfect' symmetry patterns where symmetry is degraded by the presence of random elements (eg Barlow and Reeves 1979; Carmody et al 1977; Saarinen 1988).

Although these studies demonstrate convincingly that symmetry in simple and complex visual displays is perceptually very salient, these authors have not explored which characteristics of display elements make symmetry easy to detect. The contribution of specific elements of symmetric patterns to the perceptual salience of symmetry has been investigated by Royer (1981) in a set of nontachistoscopic detection studies. He observed that unpracticed subjects required approximately the same time to detect symmetry in square-field patterns composed of dots as when the patterns were composed of diagonal lines (experiments 1a and 1b). In a second

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experiment, well-practiced subjects displayed similar processing times for symmetric patterns composed of either dots, diagonal lines, or rectilinear lines. Because Royer found that the time required to detect symmetry was largely independent of configurational elements and was, in general, a function of type of symmetry, he concluded that local feature information and symmetry are encoded as integral dimensions in the internal representation of a stimulus.

The present research addressed the clear need for additional exploration of the effects of the characteristics of display elements on symmetry detection. Selection of the stimulus properties investigated was guided by the conjecture that symmetry detection is accomplished by comparisons of grouped pattern information (eg dot densities) symmetrically positioned about the symmetry axis (see, eg Barlow and Reeves 1979; Pashler 1990; Wagemans et al 1990, 1991), rather than by an extensive point-by-point matching of individual elements on either side of the axis (see eg Bruce and Morgan 1975; Julesz 1971; Palmer and Hemenway 1978).

The fact that the mechanism responsible for symmetry detection can identify and match symmetric regions in patterns containing smeared or imperfect symmetries as rapidly as it can detect perfect symmetry supports this assertion. It also fits with views that early visual processes 'package together' neighboring items into groups (Marr 1982; Watt and Morgan 1985), and that symmetry perception occurs after spatial frequency decomposition of an image (Julesz and Chang 1979; Palmer 1985; Royer 1981). Finally, the importance of grouped pattern information is also demonstrated by the finding that in dense random-dot textures only information in the vicinity of the symmetry axis yields symmetry perception; the percept occurs even if elements farther from the axis are random or uncorrelated (Barlow and Reeves 1979; Jenkins 1983; Julesz 1971).

If one accepts that responding "symmetric" to a stimulus results primarily from grouped pattern information, then the question arises as to which visual primitives or descriptors of the spatial organization of a pattern contribute to the functional unit of symmetry detection. Does each of the perceptual primitives responsible for the derivation of the primal sketch as described by Marr (1982) in his visual processing model (namely place tokens, virtual lines, boundaries) contribute to the global percept of symmetry? To what extent, for example, does detection of symmetry depend on the perceptual salience of the symmetry axis—a large-scale boundary feature? Or does symmetry detection require nothing more than a rapid simultaneous comparison of large-scale spatial 'tokens' on either side of the symmetry axis, as suggested by Barlow and Reeves (1979)?

We addressed these questions in the two experiments reported in this paper by examining the contribution of local pattern information in various types of symmetrically organized patterns to the perceptual salience of symmetry as measured by detection time and accuracy. Stimulus characteristics manipulated included element type, type of symmetry, and orientation and spatial organization of elements within the pattern and about the symmetry axis. Examples of these manipulations are presented in figures 1 and 2.

Each of the basis patterns used to generate the set of stimuli was prepared with the use of one of five different elements. Stimuli consisted of lines parallel (0°), or perpendicular (90°), or oblique (either +45° or −45°) with respect to the axis of the pattern, or they contained an equal number of lines oriented in each direction. A fifth version of each basis pattern was composed of dots. In addition, elements were either evenly spaced throughout the patterns (henceforth referred to as 'ungrouped') or grouped in clusters.

How might these differences in local feature properties affect detectability of symmetry? First, consider the influence of element type on the salience of the global percept. In figure 1 the cooperative activity of the aligned perpendicular line segments in the vertically oriented symmetric pattern (figure 1b) produces horizontal perceptual grouping which contributes to the overall horizontal organization of the pattern. Furthermore, the emergent horizontal grouping extends through the entire pattern traversing the vertical axis of symmetry. Appropriate spatial scale size is necessary for these emergent effects to occur (see eg Kinchla and Wolfe 1979).

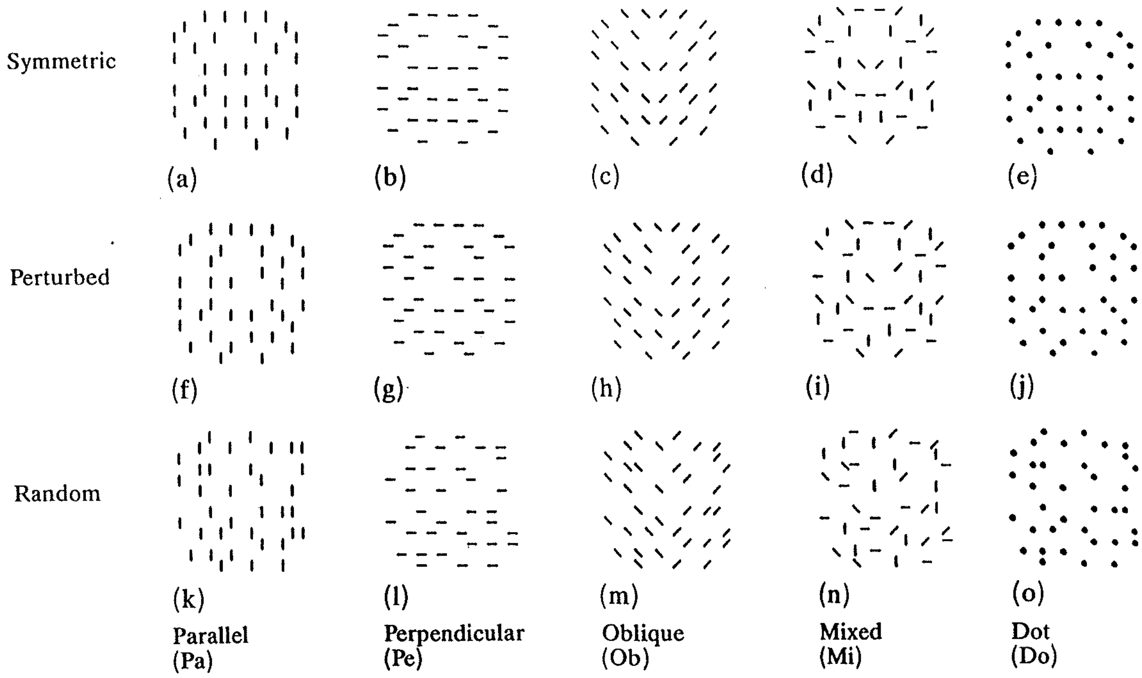

Figure 1. Examples of the pattern types used as targets in the experiments. The top row (a–e) contains five element-type versions of the same symmetric basis pattern. The second row (f–j) contains the corresponding perturbed versions of each symmetric pattern in the top row. Five element-type versions of the same random pattern are presented in the third row (k–o). Axis orientation of each symmetric and perturbed pattern is vertical. The patterns in the first four columns consist of line-elements arranged parallel, perpendicular, oblique, or in all three orientations, to the vertical axis. The stimuli in the last column are dot versions of each pattern type.

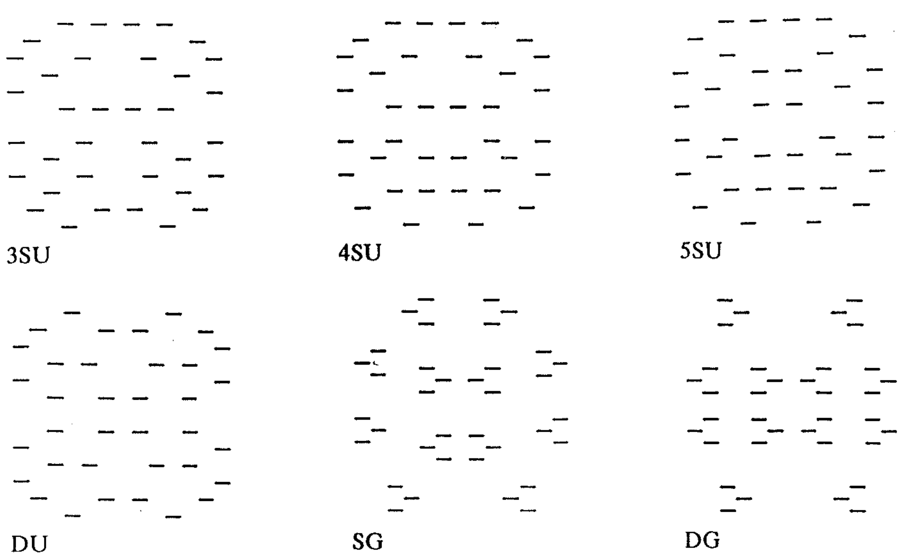

Figure 2. The basis patterns of the six types of symmetry investigated. 3SU: single axis, ungrouped, 3 axis pairs; 4SU: single axis, ungrouped, 4 axis pairs; 5SU: single axis, ungrouped, 5 axis pairs; DU: double axis, ungrouped; SG: single axis, grouped; DG: double axis, grouped.

The many studies of textural segmentation conducted by Beck [see Beck (1982) for a summary] would suggest that the *horizontal* organization produced by the actual and emergent virtual lines in this pattern might interfere with processes responsible for its segmentation about the *vertical* axis and thereby reduce the perceptual salience of both the symmetry axis and vertical symmetry. As Beck has shown, textural segmentation is not generally produced when the slopes of the component lines of a pattern are the same. On the other hand, differences in the distribution of line slopes within a pattern are effective in producing strong segmentation effects, as can be seen in the symmetric pattern composed of oblique lines shown in figure 1c. Phenomenally, the symmetry of this pattern appears more salient than that of the patterns composed of lines oriented either 0° or 90° to the symmetry axis.

If, however, cooperative factors contributing to the global percept override local orientation descriptors, and symmetry detection is dependent primarily upon recognition of collinearity and midpoint correlation of spatial tokens embedded in an emergent whole (eg Jenkins 1983), then the perceptual salience of symmetry should be approximately the same for all line versions of a basis pattern regardless of local orientational structure.

Dot patterns were included in the stimulus set to provide additional insights into the nature of the representation of the global percept. Virtual lines exist between all neighboring dots in a dot pattern (Stevens 1978). Thus, orientation of virtual lines in such patterns is 'random', especially as compared with emergent directional grouping effects which occur in line patterns. As Royer (1981) has noted, dot patterns are more fluid in structure and more subject to alternate paths of closure than are displays composed of other element types.

If local orientation descriptors of symmetric patterns make an important contribution to the segmentation process responsible for the global percept, then the randomness of virtual lines in dot patterns should interfere with segmentation processes responsible for the salience of symmetry. This should result in longer processing times and more errors for dot versus line versions of the same basis pattern. For reasons already mentioned, this would especially be the case for dot patterns versus oblique line patterns. However, if symmetry detection involves comparisons of grouped pattern information (ie large-scale spatial tokens), no significant differences in detection performance measures should occur between dot patterns and line patterns.

We also investigated the salience of symmetry as a function of the elements located about the axis of a pattern. The axis of symmetry, or the symmetric information contained in a narrow strip about the axis, is assumed to play a central functional role in models of symmetry detection which have appeared in the literature (eg Corballis and Roldan 1975; Jenkins 1982, 1983; Palmer and Hemenway 1978). According to these models, the axis of symmetry serves as the 'feature' about which pattern information is evaluated for collinearity. As mentioned above, salience of the symmetry axis appears to be influenced by the grouping processes responsible for the simultaneous generation of virtual lines and boundaries.

Marr (1982) suggested that one way in which boundaries are constructed within an image is by the lining up of terminations of tokens which differ with respect to surface orientation. According to this view, and consistent with Beck's (1982) research, it is the alignment of the terminations of the diagonally oriented virtual and real lines along the central axis of a diagonal-element pattern which is responsible for the perceptual salience of its axis. It follows that the greater the number of such element-pairs about the axis, the stronger or more vivid the emergent boundary feature. Furthermore, if detection of symmetry is dependent upon orientation of line components, then the perceptibility of symmetry should be influenced differentially by the interaction of the number and type of element-pairs about the symmetry axis.

Detection performance for patterns with five diagonal-line element-pairs about the axis should, for example, be superior to that for the other line versions of the same basis pattern, as well as those with fewer numbers of axis-pairs.

This prediction was tested by including in the stimulus set three single-axis basis patterns consisting of three, four, or five correlated element-pairs positioned within the region adjacent to the axis (see figure 2, top row). In addition, because it is frequently reported that more than one axis of symmetry has a facilitating effect upon symmetry detection as compared with single-axis stimuli (eg Palmer and Hemenway 1978; Royer 1981; Wagemans et al 1991), we included one basis pattern in the stimulus set to examine the combined effect of element type and double axes upon detection performance (figure 2, DU).

The influence of type and spatial organization of pattern elements on symmetry detection was also examined by comparing performance measures for stimuli consisting of the same number and type of elements positioned either uniformly or in clusters throughout a pattern (see figure 2). Single-axis and double-axis grouped patterns were included in the stimulus set. If image items are combined and treated by the symmetry detection mechanism as qualitatively similar large-scale units whose collinearity in symmetric patterns is detected independently of their configuration and constituents, no differences in detection performance should occur among grouped patterns as a function of element type. Furthermore, if the functional unit of symmetry detection is grouped pattern information, proximity of display elements in grouped patterns should enable the detection mechanism to aggregate individual elements more efficiently, thereby enhancing detection performance for grouped versus ungrouped stimuli.

Finally, it is reasonable to assume that salience of symmetry may be influenced by an interplay of local and global orientational properties of a pattern. For this reason, the combined influence on detection of local element and global pattern orientation was also examined. Research shows that symmetry can be detected at all orientations ranging from 0° to 90° with tachistoscopic presentation. Although one frequently reads that symmetry about the vertical axis is more salient than symmetry about other axes, in fact, the results of research on this are equivocal. Every possible ordering of detectability of symmetry about different axes can be found in the literature [for a detailed discussion of this research see Wagemans et al (1992)].

For example, Barlow and Reeves (1979) report that vertical asymmetries are the easiest to detect, followed by symmetry about the horizontal and then oblique axes. Carmody et al (1977) and Locher and Nodine (1989) found horizontal symmetry to be as salient as vertical; and Pashler (1990) observed that symmetry about the vertical axis was the most salient, followed by that about both diagonal axes. In contrast to the above findings, however, Pashler observed the least accurate performance with the horizontal case (his experiments 1, 2, and 3). Because display elements differed in these experiments, the global percept may have been influenced differentially by the contribution of local feature groupings. To explore this issue, axis orientation was included as another factor in the present study.

In sum, theoretical considerations of the influence of local and global organizational aspects of a display on symmetry detection and the empirical findings described above make it clear that an understanding of the nature of symmetry detection necessitates investigations of the interplay of stimulus characteristics and viewing condition. Each of the factors described above was included in the two experiments reported here. In the first study, subjects discriminated between symmetric and random stimuli presented tachistoscopically. In the second experiment, subjects were asked to discriminate between the symmetric stimuli used in experiment 1 and their perturbed counterparts created by replacing one third of the symmetric element pairs with asymmetric pairs.

2 Experiment 1

2.1 *Method*

2.1.1 *Subjects.* Four members of the Leuven Department of Psychology, none of whom was involved in this or any related research projects, participated as subjects. To assess the potential influence of extensive practice with symmetry perception tasks upon detection performance, data were also collected from both authors. Each of us has considerable experience as a subject in similar investigations.

2.1.2 *Stimuli and apparatus.* Each stimulus consisted of thirty-six elements, either lines or dots, arranged in an imaginary 13×13 grid. Two constraints were placed on the location of elements in each pattern. First, no element was permitted in the three outer grid locations of any corner of a pattern (eg grid locations 1, 1; 1, 2, and 2, 1 in the upper left corner). This both reduced the square appearance of the patterns and the perceptual reference-frame effects when stimuli were presented in diagonal orientations (see eg Palmer 1985). In addition, column 7 and row 7 of each pattern were left free of elements so that two adjacent line segments did not span the central axes of a pattern.

The set of symmetric stimuli was generated from six basis patterns (see figure 2). Three single-axis ungrouped basis patterns were constructed by reflecting eighteen elements in grid columns 1 through 6 about the vertical axis. These patterns contained three, four, or five element-pairs in the region surrounding the symmetry axis (ie grid columns 6 and 8). None of the remaining elements occupied adjacent grid locations and they were, therefore, spaced as evenly as possible throughout the pattern. Henceforth, these patterns are referred to as 3SU, 4SU, and 5SU, with the number indicating the number of element-pairs about the axis of each type of single-axis symmetry (S) ungrouped (U) pattern.

A double-axis ungrouped pattern (DU), the fourth symmetric basis pattern, was constructed by mirroring nine elements located in the upper left quadrant of the grid about the horizontal and vertical axes. Constraints on location of elements previously mentioned resulted in one double-axis pattern which contained four element-pairs about each axis.

Two additional symmetric basis patterns were constructed of groups or clusters of three elements spaced throughout the pattern such that elements of different clusters did not occupy adjacent grid locations. A single-axis grouped pattern (SG) resulted from mirroring six clusters in grid columns 1 through 6 about the vertical axis of the pattern; and a double-axis grouped pattern (DG) was generated by mirroring three element-clusters in the upper left grid quadrant about both axes.

Two 'random' basis patterns were constructed of elements located throughout the grid (excluding the corner and axis areas mentioned previously) such that elements did not occupy mirror grid locations about the axes of the patterns.

Each of the eight basis patterns was reproduced with the use of each of five types of elements, which resulted in the full set of forty patterns. Patterns consisted of lines one grid-length long parallel (Pa), perpendicular (Pe), or oblique at 45° (Ob) with respect to the axis in the middle of the 36 grid cells. A mixed-orientation (Mi) version of each basis pattern consisted of 12 lines in each of the three orientations; lines of a given orientation were spaced evenly throughout the pattern. The fifth version (Do) was composed of dots located in the center of the 36 grid cells. Examples of each element-type pattern are presented in figure 1.

Two masks were constructed of nine each of the four elements positioned throughout the entire pattern, including row 7 and column 7.

White-on-black slides of all stimuli and masks were rear-projected by Kodak random-access projectors (model S-RA 2500) fitted with electronic shutters (Compur Electronic model No 3) onto a screen masked to present a circular field 11.5 cm in diameter. Displays measured 7.5 cm in diameter on the screen which was positioned 114 cm from the subjects. At this distance, the projected pattern subtended an angle of 3.75 deg; each line one of 0.29 deg; and each dot approximately 0.36 min arc. The masking field appeared in the same visual-spatial position as the stimuli on the screen.

Subjects sat facing the screen in a chair with head restraints which held the head comfortably but firmly in an upright position. They held a panel carrying two response buttons. The only source of illumination in the room during the experimental sessions was that supplied by the computer screen, which was shielded from the subject and the projection screen.

2.1.3 *Overview of the design.* A within-subjects design was employed in which subjects completed two sets of five blocks of trials during each of three 1 h experimental sessions. Within each block, a different random order of the 30 symmetric and 30 random stimuli was presented. Symmetric stimuli consisted of the five line and dot versions of each of the six types of symmetric patterns. The 30 random stimuli were drawn randomly from among the eight possible 90° rotations and reversals of the ten random patterns.

The set of stimuli was responded to in each of four axis orientations: namely, vertical (0°), horizontal (90°), left-right oblique (+45°), and right-left oblique (−45°). These axis orientations are referred to as V, H, L, and R, respectively, throughout this paper. Prior to the start of each of these four blocks of trials, subjects were told the orientation of the axes of the patterns and instructed to respond "symmetric" when they perceived symmetry about that axis. In the fifth block of trials, symmetric patterns appeared equally often in all four orientations—the 'all orientations' condition (A)—and subjects responded "symmetric" to the presence of symmetry about any of the four axes. Inclusion of this condition made it possible to examine the extent to which cueing subjects in advance about the orientation of the symmetry axis in the other four conditions influenced symmetry detection performance.

The five blocks of trials were repeated six times per subject resulting in a total of 1800 individual trials (ie 60 stimuli per block × 5 viewing conditions × 6 repetitions). Presentation order was counterbalanced across repetition of blocks and subjects.

In sum, to examine the factors which contribute to symmetry detection, we use a repeated-measures design with four variables completely crossed: element type (Pa, Pe, Ob, Mi, or Do); symmetry type (3SU, 4SU, 5SU, DU, SG, or DG); axis orientation (V, H, L, R, or A), and repetition of blocks of trials.

2.1.4 *Procedure.* To familiarize the four naive subjects with the stimuli and task, each of them participated in a practice session during which two sets of five blocks of trials were completed. In preparation for each stimulus presentation, subjects were instructed to fixate the center of the display field so that the pattern would be projected to central vision, and to keep his/her head in an upright position. Stimulus presentation time was 250 ms for the first few blocks of practice trials, and was then gradually decreased until, by the ninth and tenth block, presentation time was 125 ms. This was the exposure duration determined by pilot research which gave an overall 'hit' rate of approximately 75% correct responses for each block of trials, the performance criterion chosen to minimize both ceiling effects and chance performance levels. To maintain the same performance criterion for experimental sessions completed by the two authors, one of us responded to stimuli presented for 75 ms, and the other to patterns presented for 10 ms, times also determined by pilot trials.

The experiment was programmed on an IBM personal computer to present a different random order of stimuli and masks for every block of trials. Each trial began with the presentation of a stimulus followed immediately by a masking field which remained on the screen for 1000 ms. Subjects indicated whether a pattern was symmetric (according to the orientation condition) by pressing the button on the response panel which corresponded to their preferred hand; pressing the second button on the panel signalled perception of a random pattern. Instructions to subjects emphasized the importance both of the speed and of the accuracy of their responses. When a response was correct, a tone of 1000 Hz was sounded for 250 ms; if an error was made the subject heard a 450 Hz tone for 400 ms. The next trial began 3800 ms after termination of the mask (the maximal time needed for slide position search). At the end of each block, subjects were told the percentage of correct responses for that block, and the next block of trials began when the subject felt ready to resume. No practice trials were given on any of the experimental days.

For each block of trials, the computer recorded the presentation order of the set of stimuli, and for each stimulus trial the response and the time in milliseconds from stimulus onset to the button being pressed.

2.2 *Results and discussion*

For the symmetric patterns, errors and response times (RTs) (in ms) for all trials were entered into 5 (element type) × 6 (symmetry type) × 5 (axis orientation) × 6 (repetition of trials) × 6 (subjects) mixed-model ANOVAs. Data for the same two measures for the random patterns were subjected to 5 (element type) × 5 (axis orientation) × 6 (repetition of trials) × 6 (subjects) mixed-model ANOVAs. The between-subject factor subjects was included with the within-subject experimental variables in each analysis to determine the impact of individual subject differences on the findings.(1)

Table 1. Results of ANOVAs conducted on data from experiment 1.

Source of data	Degrees of freedom	Error rates		Response times	
		F	p	F	p
Symmetric patterns					
Element type (E)	4	40.28	0.0001	29.82	0.0001
Symmetry type (ST)	5	99.23	0.0001	93.48	0.0001
Axis orientation (O)	4	3.04	0.015	10.48	0.0001
Repetition of trials (R)	5	0.96	0.44	1.31	0.26
Subjects (S)	5	27.01	0.0001	425.06	0.0001
E × ST	20	7.81	0.0001	6.88	0.0001
E × O	16	1.25	0.23	1.14	0.32
ST × O	20	3.42	0.0001	6.39	0.0001
E × ST × O	80	1.06	0.34	0.74	0.96
Asymmetric patterns					
Element type (E)	4	37.44	0.0001	8.25	0.0001
Axis orientation (O)	4	15.32	0.0001	22.93	0.0001
Repetition of trials (R)	5	0.91	0.47	0.86	0.51
Subjects (S)	5	24.69	0.0001	478.90	0.0001
E × O	16	2.24	0.003	3.17	0.0001

(1) Additional ANOVAs were performed on RTs for trials in which there was accurate detection of symmetric and asymmetric patterns. These analyses produced results parallel to those reported in table 1 for the total set of RTs for each type of pattern.

Results of the four ANOVAs are presented in table 1. As seen in this table, for each analysis, the main effect of subjects was highly significant, and the main effect of repetition of trials was not significant. Although the six subjects differed with respect to their overall performance on each dependent variable, as detailed later in this paper, it was found that the factor subjects did not interact in any systematic way with the experimental variables studied. Similarly, no important differences in the pattern of results for either symmetric or asymmetric patterns obtained as a function of repetition of trials. Thus, for the sake of parsimony, table 1 does not include any interaction effects which incorporate these two factors. Tests of simple main effects (Kirk 1968) were used to examine the nature of all significant interactions presented in the table, and differences between means found to be significant at $p < 0.01$ are reported below.

2.2.1 *Symmetric patterns.* The average RT to all symmetric patterns was 889 ms (SD = 348 ms). The average percentage of detection errors for symmetric patterns across all levels of the design and subjects was 23.5% (SD = 4.1%). Thus, the desired overall level of performance between chance and errorless responding was achieved.

Analyses of the RT and error data (see table 1) produced significant main effects of element type, symmetry type, and axis orientation. Also significant for both dependent measures were the element type × symmetry type and symmetry type × axis orientation interactions. Average RTs and error rates for these interactions are contained in tables 2 and 3, respectively. Neither the interaction between element type and axis orientation, nor the three-way interaction was significant for either measure.

Table 2. Mean values of response times (in milliseconds) and percentage error rates (shown in parentheses) for the interaction (element type × symmetry type) found with symmetric patterns in experiment 1. See text for details of abbreviations.

Symmetry type	Element type					
	Pa	Pe	Ob	Mi	Do	mean
3SU	968 (31)	942 (41)	875 (31)	929 (61)	966 (35)	935 (40)
4SU	843 (31)	893 (36)	832 (22)	851 (54)	902 (29)	863 (34)
5SU	889 (23)	887 (23)	820 (19)	923 (55)	851 (23)	874 (29)
DU	849 (22)	885 (28)	620 (3)	818 (24)	887 (29)	811 (21)
SG	785 (6)	729 (6)	735 (17)	767 (9)	755 (11)	755 (10)
DG	769 (6)	748 (8)	649 (4)	705 (12)	741 (9)	722 (8)
Mean	851 (20)	847 (24)	755 (16)	832 (36)	850 (23)	

Table 3. Mean values of response times (in milliseconds) and percentage error rates (shown in parentheses) for the interaction (symmetry type × axis orientation) found with symmetric patterns in experiment 1. See text for details of abbreviations.

Symmetry type	Axis orientation					
	V	H	L	R	A	mean
3SU	925 (37)	1059 (41)	877 (42)	881 (31)	964 (48)	941 (40)
4SU	751 (28)	863 (37)	923 (39)	929 (37)	883 (29)	870 (34)
5SU	769 (22)	881 (30)	910 (27)	931 (29)	867 (35)	871 (29)
DU	711 (14)	763 (12)	853 (32)	873 (26)	796 (22)	799 (21)
SG	729 (9)	774 (12)	746 (9)	757 (8)	766 (11)	754 (10)
DG	745 (14)	807 (8)	670 (6)	692 (4)	703 (7)	723 (8)
Mean	773 (20)	858 (23)	830 (26)	844 (23)	830 (25)	

Data for the two dependent measures, therefore, present the same general picture of the contribution of the factors studied to the salience of symmetry.

(i) *Element type*. The significant element type × symmetry type interaction shows that detection performance was influenced by element type for only two specific kinds of display arrangements (see table 2). First, it was found that symmetry was significantly more salient as measured both by speed and by accuracy of detection in ungrouped double-axis patterns composed of oblique lines than in all other DU patterns, as well as in all single-axis patterns including those composed of diagonal lines. Thus, differences in the line slopes about both axes of an ungrouped pattern produced a percept of symmetry which was uniquely salient as indicated by its almost perfect detectability (mean = 3% errors). As explained in the introduction, this result is most probably caused by segmentation effects based on the oblique orientation of the individual line elements, which suggest or confirm the location and orientation of the symmetry axes.

Second, when single-axis patterns were composed of lines of mixed orientations, detection was no better than chance regardless of the number of elements about the axis. Apparently, the random orientation of local features in such patterns interfered with detection of their symmetrical organization. The significantly higher error rates for all such patterns as compared with all other single-axis ungrouped stimuli was accompanied by RTs comparable to those for all other element types (see table 2). This suggests that a speed/accuracy trade-off occurred for Mi patterns, and that additional processing time may be needed to verify by scrutiny the presence of symmetry in such patterns. It appears, therefore, that local feature information contained in certain types of visual displays differentially influences the way elements are linked together, and correspondingly the salience of the emergent holistic structure which signals the presence of symmetry.

The more general finding of the present experiment is that detection performance was, for the most part, not influenced by type of local display elements, but rather by their relative spatial positions. For, with the exception of the two conditions described above, RTs and error rates were similar for all pattern components within each level of symmetry type. These results were replicated for the same set of symmetric stimuli and their perturbations in experiment 2. And they are consistent with Royer's (1981) finding that time required to detect symmetry was largely independent of configurational elements and was, in general, a function of symmetry type. Taken together, these results suggest that cooperative factors contributing to the global percept of symmetry override local display descriptors, and that detection of symmetry involves a comparison of grouped pattern information. This conclusion is consistent with Royer's assertion that local feature information and symmetry are both encoded as integral dimensions in the internal representation of a stimulus.

(ii) *Axis information*. With respect to the contribution of axis information to detection performance, it was found that the salience of symmetry tended to be enhanced by the number of element-pairs located in the region surrounding the axis for all but Mi elements. On average, detection errors were fewer for 5SU than 4SU patterns, which were in turn fewer than those for 3SU stimuli; RTs were faster for 5SU and 4SU stimuli compared with 3SU patterns (see table 2). Performance differences for the same stimulus conditions achieved significance in experiment 2.

As previously mentioned, presence of a second axis of symmetry in patterns composed of oblique lines significantly improved detection performance above that for DU stimuli composed of all other display elements. In addition, interference created by random local orientation in single-axis ungrouped Mi patterns was significantly and substantially attenuated by the presence of a second symmetry axis in

patterns composed of lines with mixed orientations. Detection performance for Mi - DU stimuli was comparable to that for other DU stimuli (see table 2).
(iii) *Grouping effects*. Symmetry was a more salient feature in grouped versus ungrouped stimuli. With but one exception described shortly, average error rates for all ungrouped patterns were significantly higher than those for grouped patterns (mean = 32% versus 9%, respectively) and response times significantly longer (mean = 865 ms versus 738 ms, respectively). As seen in table 2, when elements were grouped within single-axis or double-axis symmetric patterns, symmetry was perceptually very salient regardless of the orientation of the lines within the clusters, or whether patterns were constructed of lines or dots. Differences between means for all grouped pattern conditions are not reliable for either dependent measure. This suggests that the clusters of individual elements were processed as large-scale 'tokens' whose symmetric positions were very salient, regardless of their configuration and constituents.

The significant element type × symmetry type interaction effects reflect the fact that RTs and error rates were significantly higher for SG patterns composed of oblique lines than for DU or DG patterns composed of the same elements. We have no explanation for this unexpected finding, which was replicated in experiment 2.
(iv) *Axis orientation*. Table 3 presents RTs for symmetric patterns as a function of symmetry type interacting with axis orientation. The significant interaction of these variables is due to the processing advantage (revealed by faster RTs) associated with detection of symmetry about the vertical axis for certain types of symmetry. When subjects were tested for the detection of symmetry about specific axes, RTs for 4SU, 5SU, and DU patterns were fastest for symmetry about the vertical axis, followed by the horizontal and the two oblique axes. In each case, subjects responded to symmetry about the vertical axis significantly more quickly than to symmetry about the oblique orientations but not that much more quickly about the horizontal. No reliable advantage was found, however, when subjects attended to the vertical axis of 3SU, SG, or DG patterns. For SG patterns, no significant RT differences occurred between orientations. And for 3SU and DG stimuli, trials involving the horizontal orientation yielded significantly slower RTs than those for both obliques.

Table 3 also presents detection errors for the same interaction. Significance is due to the reliable difference in performance when subjects tested 3SU patterns for symmetry under the R versus A axis conditions, and for DU stimuli viewed about the V or H axes versus the L axis. Despite these few differences, the important finding is that no single viewing orientation produced an average error rate which was significantly lower than that for *all* other orientations across levels of symmetry type. As seen in table 3, this was the case when subjects attended to the V, H, L, and R axes, as well as when they had to be prepared to detect symmetry about any axis orientation. Thus, the processing advantage associated with the vertical orientation for the conditions described above was not accompanied by more accurate detection of symmetry.

Furthermore, no one orientation produced a processing advantage for the same set of symmetric stimuli in experiment 2. This suggests that the nature of the task performed is an additional factor which must be considered in any explanation of the contribution of axis orientation to symmetry detection; we address this issue in experiment 2. At this point, however, it seems reasonable to conclude that the reason every possible ordering of detection of symmetry about different axes found between the studies, mentioned in the introduction, is due to differences in stimulus characteristics and other factors unique to a particular study.

The literature also fails to provide a definitive conclusion concerning the influence of advance knowledge of axis orientation on detection performance. In the present study, RTs and error rates for patterns oriented about the V, H, L, and R axes in the all-axis condition were approximately the same as when patterns were tested for symmetry about one of these axes within a block of trials (mean RTs = 790 ms, 861 ms, 837 ms, and 862 ms versus 772 ms, 858 ms, 830 ms, and 844 ms; and mean error rates = 22%, 22%, 27%, and 29% versus 20%, 23%, 26%, and 23%, respectively). These findings, which were replicated in experiment 2, demonstrate that advance knowledge of the orientation of the symmetry axis did not facilitate symmetry detection. Thus, it appears that, as Corballis and Roldan (1975) have concluded, subjects were unable to prepare mentally for particular orientations of the symmetry axis.

Wagemans et al (1992) also reported that having a cue about the orientation of the symmetry axis (by means of blocking the trials according to orientation) did not produce a processing advantage for bilaterally symmetric dot patterns; cueing did, however, facilitate detection of skewed symmetry in these patterns. These researchers interpreted their results as showing that no additional information about the axis orientation is needed when global symmetry is sufficiently salient on the basis of the spatial properties only. On the other hand, when the higher-order spatial relations of a pattern are disturbed (eg by skewing), the symmetry detection mechanism is forced to operate more slowly and more locally (eg by a point-by-point comparison). In this situation, advance information about axis orientation can facilitate detection. The results obtained in experiment 1 support the views of Wagemans et al (1992), as there was no effect of blocking in cases where symmetry detection seemed to operate globally.

2.2.2 *Random patterns.* The average percentage of detection errors for random patterns across all conditions and subjects was 25.2% (SD = 5.34%), which is very similar to the average percentage of errors for symmetric patterns (23.5%). Mean RTs for the trials involving random patterns was 1028 ms (SD = 373).

As previously described, ANOVAs were performed on the RT and error data for the random patterns. The results of each analysis appear in table 1.

The main effects of element type and axis orientation and the interaction of these factors were significant for both dependent variables (see table 1). Table 4 contains average RTs and errors for the conditions studied. In general, subjects responded significantly more quickly and more accurately to random patterns composed of lines of mixed orientations than to stimuli composed of any other element type. These findings suggest that the presence of 'local randomness', in the form of variation in line orientation, enhanced detection of randomness at the global level and it did so under all conditions of axis orientation except for vertical, as noted below. Thus, the presence of randomly oriented lines enhanced detection of asymmetry whereas the same display elements interfered with detection of symmetry.

Table 4. Mean values of response times (in milliseconds) and percentage error rates (shown in parentheses) for the interaction (element type × axis orientation) found with random patterns in experiment 1. See text for details of abbreviations.

Element type	Axis orientation					
	V	H	L	R	A	mean
Pa	986 (22)	1161 (35)	1047 (20)	1091 (34)	1014 (29)	1060 (28)
Pe	853 (12)	1030 (32)	1072 (26)	1135 (30)	1074 (30)	1033 (26)
Ob	938 (19)	1030 (24)	964 (31)	1059 (27)	1026 (30)	1003 (26)
Mi	861 (9)	953 (13)	975 (15)	1035 (15)	948 (14)	954 (13)
Do	923 (24)	1091 (39)	1084 (35)	1119 (37)	1059 (29)	1055 (33)
Mean	912 (17)	1053 (29)	1028 (25)	1088 (29)	1024 (26)	

RT was reliably faster and significantly fewer errors occurred when subjects were tested for symmetry-randomness about the V axis versus the H, L, R, and A axis orientations. As was the case for symmetric patterns, a processing advantage was observed for the vertical axis orientation, but, as was also found for symmetric patterns, this processing advantage obtained only under certain conditions.

Main effects for both analyses are qualified by the significant interactions between element type and axis orientation for the RT and error data. As seen in table 4, the interactions were due largely to the differential effect upon both dependent variables associated with the vertical axis conditions. Specifically, responses were significantly faster to Pe and Do patterns tested about the V axis than all other orientations, and to Mi patterns viewed about the V axis versus the R axis. The significant interaction also reflects the fact that, although Mi patterns were responded to more quickly than stimuli composed of other elements within a given orientation condition, not all of these differences were reliable. For the error data, the interaction was due to the fact that significantly fewer errors occurred when Pe stimuli were viewed about the V axis than about the H, L, or R axes.

3 Experiment 2

At this point it seems clear that when the elements of perfect or complete mirror-image patterns are grouped in clusters, the percept of symmetry is very salient regardless of the element type or the number and orientation of symmetry axes. When elements are distributed throughout a perfectly symmetric pattern, however, symmetry detection as measured both by RT and by performance accuracy was influenced by an interaction of these factors. It was not, however, influenced by practice or advance knowledge of the orientation of the symmetry axis.

The second experiment was undertaken to examine further the nature of the interaction effects observed in the first experiment. At the same time, an attempt was made to investigate whether the symmetry detection mechanism is capable of signalling the presence of elements not fitting in the global percept of symmetry. To accomplish these objectives, subjects in the present study discriminated between symmetric stimuli used in the first experiment and perturbations of these stimuli, which were composed of two thirds symmetric and one third asymmetric element-pairs. The proportion of asymmetry introduced into the perturbations was determined by constraints placed on the construction of the symmetric originals and upon findings reported by the studies mentioned above.

3.1 *Method*

3.1.1 *Subjects.* Subjects were both authors and four members of the Leuven Department of Psychology who had not participated in experiment 1.

3.1.2 *Stimuli.* The 30 symmetric stimuli used in the first experiment and a perturbed version of each of these stimuli constituted the stimulus set for this study. The perturbation of each of the four ungrouped basis patterns was generated by repositioning 6 elements in each pattern in grid locations above, below, to the left, to the right, and diagonal to their location in the symmetric pattern. Perturbed elements were located throughout all regions of the ungrouped stimuli, and the constraints on locations of elements imposed on the originals were imposed on their perturbations. For each of the two grouped basis patterns, one cluster of elements near the center of the pattern and one cluster near its perimeter were repositioned so that none of the elements in either cluster-pair occupied mirror grid locations. Each perturbed pattern, therefore, contained 24 elements that were in symmetric pairs, and 12 elements in asymmetric 'pairs'. Examples of perturbed patterns are shown in figure 1.

3.1.3 *Apparatus and procedure.* The apparatus and procedure for experiments 1 and 2 were identical except that stimulus presentation time for unsophisticated subjects was 150 ms in the second experiment, compared with 125 ms in experiment 1. Pilot work indicated that subjects required this increased exposure duration to achieve an overall error rate approximately the same as that for the first experiment. Both authors achieved the same average performance levels in both experiments for the same exposure durations (10 ms and 75 ms).

Each subject in experiment 2 completed five blocks of 60 stimuli six times resulting in a total of 1800 trials per subject, the same number as in the first experiment.

3.2 *Results and discussion*

Table 5 presents results of the 2 (pattern type) × 5 (element type) × 6 (symmetry type) × 5 (axis orientation) × 6 (repetition of trials) × 6 (subjects) mixed-model ANOVAs performed on errors and RTs for all trials. The between-subject variable was subjects. For both dependent measures, the main effect of subjects was significant and the main effect of repetition of trials was not significant. Neither variable interacted in any systematic way with the experimental variables; therefore table 5 does not contain interaction effects which incorporate these two factors.(2)

Analyses indicate that perturbed symmetry was, overall, significantly more difficult to detect than perfect symmetry (mean error rate = 27.8% versus 37.2%), and that identification of symmetric patterns was made significantly more quickly than identification of perturbed stimuli (mean = 755 ms versus 824 ms). In addition to pattern type, main effects due to element type, symmetry type, and axis orientation obtained for both dependent variables. These effects, however, can only be interpreted in terms of the significant two-way and three-way interactions for both dependent measures. The nature of each reliable interaction was examined by tests of simple main effects and differences at $p < 0.01$ between means resulting from these analyses are discussed below.

Table 5. Results of ANOVAs conducted on data from experiment 2.

Source of data	Degrees of freedom	Error rates		Response times	
		F	*p*	*F*	*p*
Pattern type (P)	1	102.23	0.0001	126.62	0.0001
Element type (E)	4	7.10	0.0001	3.44	0.008
Symmetry type (ST)	5	4.91	0.0001	7.45	0.0001
Axis orientation (O)	4	8.33	0.0001	8.96	0.0001
Repetition of trials (R)	5	1.01	0.41	1.12	0.36
Subjects (S)	5	20.66	0.0001	413.12	0.0001
P×E	4	13.22	0.0001	0.62	0.63
P×ST	5	54.66	0.0001	16.19	0.0001
P×O	4	12.98	0.0001	3.14	0.014
E×ST	20	2.25	0.001	2.42	0.0001
E×O	16	1.14	0.31	1.27	0.21
ST×O	20	2.19	0.002	5.97	0.0001
P×E×ST	20	7.83	0.0001	2.57	0.0001
P×E×O	20	2.91	0.0001	2.25	0.001
P×ST×O	16	2.12	0.006	2.25	0.003
E×ST×O	80	1.57	0.001	1.23	0.082
P×E×ST×O	80	1.16	0.09	0.89	0.75

(2) An ANOVA performed on the RTs for trials in which there were correct responses produced results which parallel those presented in table 5 for the full set of RT data.

3.2.1 *Element type.* The combined effect of element type and symmetry type upon RTs and error rates are presented separately for symmetric and perturbed stimuli in table 6. As seen in this table, the obtained significant interaction between these factors was due to deviations in both of these performance measures for the Mi-5SU stimulus from other 5SU symmetric patterns which was not found for perturbed stimuli. With this exception, RTs are very similar for all element types within each level of symmetry type for symmetric patterns, as was found in experiment 1, and also for perturbed stimuli. This outcome provides additional evidence that local feature information was dealt with as components of the global percept in a way which ignored local properties. As previously concluded, this indicates that symmetry is encoded integrally.

Table 6. Mean values of response times (in milliseconds) and percentage error rates (shown in parentheses) for the interaction (pattern type × element type × symmetry type) found in experiment 2. See text for details of abbreviations.

Symmetry type	Element type					
	Pa	Pe	Ob	Mi	Do	mean
Symmetric patterns						
3SU	781 (37)	811 (54)	771 (48)	853 (41)	798 (49)	803 (46)
4SU	764 (23)	765 (27)	787 (37)	822 (42)	735 (32)	775 (32)
5SU	711 (14)	740 (18)	731 (23)	900 (48)	721 (23)	761 (25)
DU	701 (18)	733 (31)	658 (13)	729 (18)	755 (23)	715 (21)
SG	771 (24)	763 (28)	802 (39)	783 (31)	760 (22)	776 (29)
DG	753 (20)	744 (18)	727 (26)	724 (17)	751 (26)	740 (21)
Mean	747 (23)	759 (29)	746 (31)	802 (33)	753 (29)	
Perturbed patterns						
3SU	787 (30)	798 (18)	811 (34)	771 (19)	774 (32)	788 (26)
4SU	807 (36)	849 (32)	811 (37)	802 (25)	791 (35)	812 (33)
5SU	861 (42)	832 (36)	841 (47)	794 (32)	853 (46)	836 (41)
DU	877 (43)	849 (27)	863 (53)	853 (42)	828 (45)	854 (42)
SG	847 (46)	834 (48)	813 (36)	807 (39)	855 (51)	831 (44)
DG	832 (43)	838 (33)	836 (24)	857 (44)	855 (52)	844 (39)
Mean	835 (40)	833 (32)	829 (38)	814 (33)	826 (44)	

3.2.2 *Spatial arrangement of display elements.* Additional support for this assertion is provided by the finding that characteristics of symmetric patterns which enhanced perceptibility of symmetry interfered with detection of asymmetric elements embedded in an otherwise symmetric display. That is, aspects of symmetry type which contributed to faster responses to symmetric patterns were associated with slower responses to perturbed stimuli, and vice versa. Such interference effects would be predicted by integral encoding models.

As can be seen in table 6, an increase in number of element-pairs about a single axis reduced the RT for symmetric patterns but increased the RT for perturbed stimuli, with the difference between pattern types reaching significance for 5SU stimuli. In addition, a second symmetry axis in ungrouped as well as grouped symmetric patterns produced reliably faster responses for symmetric versus perturbed stimuli.

Similarly, those aspects of symmetry type associated with high error rates for symmetric patterns resulted in relatively fewer errors for perturbed patterns, and vice versa. Detection of symmetry significantly increased with the number of element-pairs about the axis of SU patterns, whereas detection of imperfect symmetry reliably decreased for the same conditions. Thus, the increase in collinear pairs about the axis of symmetric patterns enhanced the salience of symmetry, whereas the increase of both collinearity and 'randomness' in the form of noncollinear element-pairs in the region surrounding the axis of 5SU versus 3SU perturbed stimuli presumably added to uncertainty concerning the global organization of these patterns. This is indicated by both the slower RTs for the 5SU patterns and the near-chance levels of performance.

Furthermore, whereas grouped elements of all types significantly enhanced symmetry detection in SG and DG compared with 3SU stimuli, grouping reliably reduced the detection of perturbed symmetry in grouped patterns below the 3SU rate for all elements except oblique lines. Apparently the divergence from collinearity which resulted from the perturbation of pairs of clustered elements was not sufficient to enhance the salience of imperfect symmetry, at least under the conditions of the present experiment.

Royer (1981, experiment 2) asked sophisticated subjects to indicate whether patterns which remained in view until the subject made a response were symmetric or not. His stimuli consisted of asymmetric perturbations (referred to as 'conjugates' by Royer) of symmetric square-field patterns which he generated by moving four pattern-elements from their positions in the symmetric matrix. In line with the results of the present experiment, Royer found that when symmetric patterns had low error rates, their asymmetric perturbations had high error rates and vice versa. Taken together, these data demonstrate that spatial arrangement characteristics of symmetric patterns which enhance the percept of symmetry interfere with detection of asymmetric elements embedded in an otherwise symmetric display. As mentioned above, an interference effect such as this supports the conclusion that symmetry is encoded integrally.

In addition, the close correspondence in average RTs between symmetric and perturbed patterns, compared with the average RTs for random patterns in experiment 1 (means = 755 ms, 824 ms, and 1012 ms, respectively), suggests that the same visual processing occurs for perturbed and for symmetric patterns. This would be the case if an initial visual process somehow 'detected' a probable axis of symmetry from improbable ones to be tested for concordance. Then the near-symmetric axis would likely be the only one evaluated, and an exhaustive consideration of all axes, as is suggested by the RTs for random patterns in experiment 1, would be unnecessary.

3.2.3 *Axis orientation.* As seen in table 5, the variable axis orientation was involved in several significant interactions for both dependent measures. Examination of the data sets revealed that these interactions were due primarily to significant variations in performance resulting from combinations of axis orientation and symmetry type found for one pattern type but not the other. RT data indicate that subjects took significantly more time to respond to 3SU symmetric stimuli in the all-axis versus the vertical axis orientations (mean RT = 881 ms versus 775 ms); and DU symmetric patterns were responded to significantly more quickly than 3SU, SG, or DG patterns when they were positioned about the vertical axis (mean RTs = 682 ms versus 774 ms, 817 ms, and 780 ms, respectively). These reliable differences did not occur for comparable conditions involving perturbed patterns. Similarly subjects made significantly more errors in response to 3SU symmetric patterns in the all-axis than in the vertical axis condition; in response to 5SU perturbed patterns in the horizontal versus left-right diagonal orientations; and in response to perturbed DG stimuli in the left-right diagonal versus the vertical orientations. In each case, performance differences were not reliable for the corresponding condition for the second pattern type.

Despite these few fluctuations in performance due to axis orientation, no single orientation produced a processing advantage for either of the symmetric patterns, as was found in experiment 1, or their perturbations. Average RTs for the V, H, L, and R orientation conditions were, respectively, 745 ms, 751 ms, 759 ms, and 743 ms for symmetric patterns; and 811 ms, 838 ms, 796 ms, and 824 ms for their perturbed counterparts. Furthermore, RTs for patterns oriented about the V, H, L, and R axes in the all-axis condition for symmetric and perturbed stimuli (mean RTs = 764 ms, 783 ms, 779 ms, and 781 ms for symmetric stimuli, and 839 ms, 864 ms, 844 ms, and 863 ms for perturbed stimuli, respectively) were approximately the same as when subjects tested for symmetry about one of these axes within a block of trials. As was the case in experiment 1, advance knowledge of the orientation of the symmetry axis did not produce a processing advantage.

The findings concerning the impact of pattern type and axis orientation upon symmetry detection obtained in experiments 1 and 2 have been replicated by Locher and Smets (1992) for the ungrouped dot patterns. For display conditions similar to those in the present experiments (but in which additional factors were investigated) Locher and Smets found that symmetry detection accuracy, as determined by receiver operating curve analyses, was higher when the stimulus set contained symmetric and asymmetric patterns than when it contained perturbed dot patterns (mean = 0.882 versus 0.794). Furthermore, no significant difference in detection accuracy was observed for vertically versus horizontally oriented symmetric patterns (diagonal orientations were not studied), nor did advance knowledge of these two orientations produce a difference in detection accuracy. Each of these results reported by Locher and Smets was also obtained in the present work, in experiments 1 and 2.

3.2.4 *Effects of task on symmetry detection.* Results of both experiments provide evidence that judgments concerning the presence of symmetry were affected by the interplay of task and stimulus type, as was found by Corballis and Roldan (1974). They observed that these factors influenced the speed of decisions concerning pairs of symmetric or repeated patterns composed of either arrowheads or of C-shapes. When subjects were given same/mirror instructions, after 100 ms presentations they responded to Cs more rapidly than to arrowheads. However, when the subjects were asked to judge stimulus pairs as either symmetrical or asymmetrical, their RTs did not differ reliably. Corballis and Roldan speculated that "the same/mirror instructions encouraged perception of the individual symbols, while the symmetrical/asymmetrical instructions encouraged perception of each patten as a whole" (page 140).

In the present research, the same set of symmetric patterns was included in two different detection conditions, namely, symmetric versus random patterns in experiment 1 and symmetric versus perturbed patterns in experiment 2. Although overall error rates for the symmetric patterns in both experiments are very similar, comparison of the data in tables 2 and 6 reveals that the type of discrimination which was made differentially influenced performance outcomes for symmetric patterns. More errors were made in response to all of the symmetric SG and DG patterns when they were discriminated from their perturbed counterparts than when they were presented with random patterns. Thus, in experiment 1 grouping produced a significant reduction in errors for all such stimuli compared with ungrouped patterns, whereas only the difference between grouped and 3SU stimuli was reliable in the second experiment. With respect to single-axis patterns, more errors were made for Ob - 3SU and Ob - 4SU patterns when the stimulus set contained perturbed stimuli than when it contained random stimuli. On the other hand, symmetry was more perceptible in Mi - 3SU patterns when the stimulus set contained perturbed stimuli.

Because the symmetric stimuli used in both experiments were identical, and because well-trained subjects participated in both experiments, differences in performance between the two experiments are not likely to be the result of differences in visual encoding processes. Rather, they are presumably the result of the way the holistic structure was perceived and/or the way in which decomposition of the coded information occurred. The present data do not permit us to specify how the different tasks produced processing differences. What these findings make clear, however, is that the influence of task characteristics upon symmetry detection deserves serious consideration in the future.

3.2.5 *Data for individual subjects.* As previously mentioned, subjects differed with respect to overall RTs and number of errors for both types of patterns in both experiments. For example, average RTs in experiment 1 for the four naive subjects were 837 ms, 814 ms, 984 ms, and 1130 ms for symmetric patterns, and 897 ms, 1099 ms, 1256 ms, and 1528 ms for asymmetric patterns; and the average percentages of errors were 27%, 26%, 26%, and 31%, and 30%, 20%, 35%, and 25%, respectively. For the two sophisticated subjects, average RTs for symmetric and asymmetric stimuli were 637 ms and 633 ms, and 699 ms and 859 ms; average error rates for the same subjects were 15% and 16%, and 16% and 25%, respectively.

Despite overall differences between subjects, the pattern of results for the other factors included in the analyses was very nearly the same for all subjects, as was the case in experiment 2. Royer (1981) also found that sophisticated subjects were much faster at detecting symmetry than naive subjects, but that they exhibited the same relative speeds of detecting different symmetries. And, as found in the present study, Royer reported that symmetry detection performance of sophisticated subjects did not change with increasing practice.

Wagemans et al (1991) also reported that the pattern of results for their well-trained subjects was similar to that for naive subjects in each of four investigations of orientation effects upon symmetry detection. Taken together, these findings suggest that bilateral symmetry is not something the visual system has to learn to detect through a large number of 'practice trials'. Developmental work by Bornstein et al (1981) and Humphrey et al (1986), showing a processing advantage for symmetry versus asymmetry in infants, provides additional strong support for this conclusion.

4 General discussion

The results of the present experiments support the view that mirror symmetry is detected preattentively, presumably by some kind of integral code which emerges from the interaction between display elements and the way they are grouped spatially. Furthermore, our findings suggest that the holistic impression of symmetry is derived from grouped pattern information, and that group tokens, boundary or axis information, and virtual lines serve as input primitives in the construction of the global percept. Thus, it appears that symmetry may be coded by the same spatial grouping processes responsible for the full primal sketch, as conjectured earlier. This conclusion is consistent with the assertions of both Pashler (1990) and Royer (1981) that the subjective perception of symmetry is the conscious concomitant of the output of filtering operations executed in parallel on a symmetric display.

We use the notion of 'preattentive' as Julesz (1981, page 28) defined it operationally, namely, as a process which is able "to perceive certain structures in the stimulus array when the stimulus is briefly presented—say for less than 160 msec". Of course, it is possible to focus one's attention on a pattern when it is presented at a previously cued location. Therefore, our argument would be much stronger if subjects in the present experiments had not known precisely where the patterns would appear in the display field. However, the way we investigated the nature of preattentive perception by limiting stimulus duration has been widely used. One such study by Hogben et al (1976) is particularly relevant to the present discussion. By introducing a variable temporal delay between each dot and its partner in a sequentially plotted symmetrical dynamic point pattern, Hogben et al have shown that a single 100 ms stimulus burst is seen predominantly as having a random or symmetric structure specified by positional relationships within the last 50 ms of the burst. Presentation durations employed by Hogben et al (1976) and those used in the present research are well within the limit for effortless perception as defined by Julesz (1981) to allow symmetry detection to be called preattentive.

The present data are insufficient to specify the way in which the visual system derives the holistic representation that signals the presence of symmetry from filtered information. However, properties of the mechanism responsible for symmetry detection identified by the present studies and by other investigations described throughout this paper are consistent with assumptions and conceptualizations of the 'primal sketch' visual processing models of Marr (1982) and Watt (Watt 1988; Watt and Morgan 1985).

First, these models conceptualize the raw primal sketch as a type of bit net which specifies the precise positional information of primitives. Spatial relationships, such as collinearity and parallelism, are implicit in these positions. Thus, sensitivity to the collinearity of paired elements and features in symmetric images, a necessary component of symmetry detection, is 'built into' primal sketch processing.

Another issue of considerable importance to the flexibility and tolerance of a symmetry detection mechanism is the assumption in the filter models that large-scale groupings which contribute to the formation of the full primal sketch are generated from 'collections' of individual elements. In the MIRAGE model of Watt and Morgan (1985), for example, it is assumed that the rapid computation of spatial position and shape of the coarsely defined areas or groups at each scale is made with an associated nonspatial parallel analysis of finer details within the groups. Thus, the representation at each scale is not 'complete' because the position of each element is not individually represented. By limiting the number of elements which enter the process in this way, a rapid computation of a first approximation of the overall spatial organization of an image (of global symmetry in this case) is made possible.

Moreover, because the positions and numbers (within limits determined by scale size and stimulus characteristics) of elements are not individually represented in groupings, precise collinear alignment of concordant pairs is not necessary to signal the presence of symmetry. Thus, large-scale tokens in the hierarchy make possible the tolerance for smeared mirror symmetry reported by Barlow and Reeves (1979). In addition, use of these large-scale tokens might be one of the ways to realize the advantage of grouped pattern information over point-by-point matching observed by Julesz (1971), Barlow and Reeves (1979), and Jenkins (1983), and replicated in this study. Furthermore, because large-scale groupings may be based on spatial proximity and arrangement more than on figural similarity of elements, large-scale tokens may be composed of several different types of elements (eg dots, lines, blobs). Support for this assertion comes from the findings of the present research that RTs and error rates were, in general, comparable for patterns composed of dots or lines, and when lines were positioned in the same or mixed orientations.

In sum, it is not unlikely that the operations responsible for generation of the full primal sketch could automatically signal the presence of mirror symmetry of a pattern. One way in which hierarchical grouping processes might accomplish this is suggested by Watt and Morgan's (1985) MIRAGE model. In the MIRAGE system, an image is convolved with a range of $\nabla^2 G$ operators. According to this model, with the onset of a visual stimulus there is a very rapid progressive spatial scale hierarchical computation of spatial position for all levels of detail from fine to coarsely defined areas of the image (see also Watt 1987). The largest filter produces only one zero-bounded 'group' encompassing all pattern components. Increasingly smaller filters produce increasingly larger numbers of zero-bounded groupings.

Each filter, therefore, contributes independent samples of the retinal stimulus to the judgment of the full primal sketch representation of an image (ie to global symmetry in this case). Different-sized filters produce zero-bounded contours at each scale value, which reflect the collinearity and midpoint correlation of features that define the symmetry of an image. The subjective perception of symmetry may simply be the conscious concomitant of this 'spatial coincidence' among the features in the ouput of the different filters, which is captured in the combination signal indicating the presence of symmetry. Presumably, some minimal output value will indicate the presence of partial symmetry.

Investigators who have studied symmetry detection have each proposed two-stage models to explain their findings (eg Palmer and Hemenway 1978; Royer 1981). According to these dual process models, a potential axis (or axes) of symmetry, selected effortlessly during the initial stage of processing, is evaluated for the presence of symmetry by a second scrutiny process. Several researchers (eg Corballis and Roldan 1975; Palmer and Hemenway 1978; Royer 1981) who have observed that detection of symmetry about the vertical axis is faster than that about the horizontal axis, which in turn is faster than that about the diagonal axis, have interpreted their findings as supportive of a hierarchical serial evaluative process. That is, evaluation of axes is done in a specific order beginning with the vertical.

Results of the present experiment suggest that if features of a symmetric pattern produce a very salient percept of symmetry, as was the case for double-axis patterns composed of diagonal lines in this research, and the resulting signal indicating the presence of symmetry is 'strong', scrutiny of the pattern may be unnecessary or minimal. When scrutiny is required to make a judgment concerning the presence of symmetry, the data presented here suggest that it entails a simple sequential decomposition of the holistic representation of a pattern. Because the absence of symmetry in a pattern requires that it be asymmetric about every axis, a decision concerning the presence of asymmetry can logically be made only after an exhaustive examination of all axes for element-pair concordance. If axes are tested sequentially and exhaustively, detection time should be longer for asymmetric than for symmetric patterns, and detection time for random patterns should not be affected by the order in which orientations are scrutinized. Both of these conditions obtained in the present research.

Furthermore, if, as hypothesized earlier, the visual system can rapidly signal the presence of imperfect (perturbed) as well as perfect symmetry, and if a probable axis of symmetry in both types of patterns can somehow be detected as part of the global percept, then scrutiny of the perturbed pattern for concordance can be restricted to the axis about which concordant pairs are located. And, if detection of asymmetry requires an exhaustive sequential examination of the four orientations about which symmetry occurred in the present study, then the search for nonconcordance in random patterns should take approximately four times as long as the search for nonconcordant pairs about the single 'symmetry axis' of a perturbed pattern. This is what was found in the present investigation. Symmetry provided an average processing advantage of 69 ms over perturbed patterns in experiment 2, and a processing advantage of 257 ms over random patterns in experiment 1. Thus, the value for random patterns was approximately four times that for perturbed patterns, as would be expected if the evaluative process is sequential and exhaustive.

5 Summary and conclusions

Three important results were obtained in this research. First, with respect to the main purpose of these experiments, which was to explore the factors which determine the saliency of the global percept emerging from a particular spatial arrangement of local elements, the principal finding was quite clear. It is that the type of local elements (ie dots, line segments in different orientations, or a mixture of line segment orientations) does not matter as much as their relative spatial positions. Some specific kinds of display arrangements produced a highly salient percept of global symmetry. For example, clustering the elements together, or grouping them along the axis or in symmetric positions about two orthogonal axes, made the role of individual elements disappear completely (in a perceptual sense) even though they were a geometrical part of the pattern. On the other hand, when no salient global percept emerged because of the lack of these specific grouping factors, local randomness (eg mixed element patterns) was interpreted by the symmetry detection mechanism as sufficient evidence for disturbed or even absent global structure.

Second, orientational effects, which have frequently been reported in the literature, did not systematically influence the initial stage of global symmetry detection. As was the case for element type, if the global structure was very salient because of particular spatial groupings, axis orientation did not affect detection peformance, nor did advance knowledge about it. Only when a patten required more processing time, such as in cases where stimuli were composed of mixed elements or when local perturbations had to be detected, did a vertical axis or advance knowledge of any other axes seem to facilitate the evaluative stage of symmetry detection.

Third, some of the effects obtained with respect to the previously mentioned factors seemed to be influenced by specific task requirements. Whereas the same symmetric stimuli were used in experiments 1 and 2, the way they were processed clearly depended on the kind of stimuli from which they had to be discriminated. In experiment 1, where completely random patterns were used as response alternatives, all kinds of spatial groupings produced significantly fewer errors in the detection of symmetry. In experiment 2, where local perturbations of symmetric patterns had to be detected, most of these grouping-dependent facilitation effects disappeared. One obvious explanation is that the mechanism responsible for the preattentive detection of global symmetry, which is clearly influenced by spatial grouping, could not operate in the same way in experiment 2 because more local properties had to be examined before a response could be generated.

The second and third sets of findings just described require further research to clarify the factors which influence detection performance. Nevertheless, as stated above, a useful theoretical integration of the whole set of results seems to suggest itself in terms of primal sketch visual processing models such as those of Marr (1982) or Watt (1987), which allow a crude representation of relative positions to be derived during the initial stage of perceptual processing. Furthermore, because these models include important scale issues such as a hierarchy of concrete-to-abstract tokens (Marr 1982) or a coarse-to-fine strategy (Watt 1987), they naturally allow the detection of a global structure such as symmetry, which is critically dependent on the relative positions of individual elements, to be influenced by their spatial grouping without implying the detailed processing of local figural properties.

This account fits nicely with the principal finding of this study that large-scale groupings based on spatial proximity and arrangement can easily override the effects of local element properties. Although the role of spatial grouping has been suggested previously (eg Barlow and Reeves 1979; Pashler 1990), this specific result has never been reported before, because interactions between element type and spatial grouping have not been studied systematically. The most important conclusion to be drawn from this study, therefore, is that mirror symmetry may not require a special mechanism for its detection. Rather, symmetry may be but one of the salient regularities of a visual display which is automatically signalled by preattentive grouping that occurs during the early visual processing of all stimuli.

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