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Detection of visual symmetries

JOHAN WAGEMANS
Laboratory of Experimental Psychology, University of Leuven, Tiensestraat 102, B-3000 Leuven, Belgium

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Abstract—This paper reviews empirical evidence for the detection of visual symmetries and explanatory theories and models of symmetry detection. First, mirror symmetry is compared to other types of symmetry. The idea that symmetry detection is preattentive is then discussed and other roles that attention might play in symmetry detection are considered. The major part of the article consists of a critical examination of the extensive literature about the effects on symmetry detection of several major factors such as the orientation of the symmetry axis, the location of the stimulus in the visual field, grouping, and perturbations. Constraints on plausible models of symmetry detection are derived from this rich database and several proposals are evaluated against it. As a result of bringing this research together, open questions and remaining gaps to be filled by future research are identified.

1. INTRODUCTION

Symmetry is everywhere: in natural objects, from crystals to living organisms, in manufactured articles of many kinds, and in art works from all cultures throughout the world and at all times (Washburn and Crowe, 1988). As pointed out by the editor of this Special Issue, it is no surprise then that biological vision systems have evolved adaptive strategies for perceiving such symmetries and utilizing them in all kinds of tasks. Pigeons discriminate and classify shapes on the basis of symmetry (Delius and Nowak, 1982). Animals at many phylogenetic scales use symmetry in mate selection (Moeller, 1992; Swaddle and Cuthill, 1993). Experimental evidence from human infants and young children demonstrates that symmetry receives ontogenetic priority as well (Bornstein *et al.*, 1981; Fisher *et al.*, 1981). Finally, computer-vision techniques have also been developed to detect symmetry and exploit it in all sorts of ways (Stevens, 1980; Kanade and Kender, 1983; Marola, 1989; Nalwa, 1989; Van Gool *et al.*, 1990, 1995).

Because all this suggests that symmetry is a salient visual property that must be detected efficiently and rapidly by the visual system, considerable research effort has been devoted to the study of the detection of visual symmetries in artificial and biological vision, by scientists in various disciplines from art to zoology, from the early days of visual science (Mach, 1886/1959) until now, and inspired by all kinds of theoretical approaches. Although this research tradition has provided us with a rich database of empirical findings and theoretical proposals, it has left open many questions. This paper brings some of this research together, to review what we know about symmetry detection and where gaps remain to be filled by future research. This review will focus only on aspects of symmetry perception related to its detection as such, not on the usefulness of symmetry in other tasks.

2. DIFFERENT TYPES OF SYMMETRY

Usually, symmetry is implicitly equated with mirror symmetry and most of the empirical studies of symmetry detection have been restricted to mirror symmetry. However, from a mathematical point of view, the class of symmetries is much richer (Weyl, 1952; Armstrong, 1988). Informally, symmetry means self-similarity under a class of transformations, usually the group of Euclidean transformations in the plane, that is, translations, rotations, and reflections (also collectively denoted by 'isometries'). Surprisingly few studies have explicitly compared the three pure types of symmetries or investigated the ways they interact when present together. In this section, the evidence is reviewed that the researchers' preoccupation with mirror symmetry reflects the fact that it is a more salient property for the visual system than the other symmetries.

For example, Julesz (1971) observed that detection of symmetry created by repetition (i.e. translation) or by point-reflection (i.e. 180 deg rotation) requires scrutiny, whereas perception of mirror symmetry (i.e. created by reflection) is effortless, rapid, and spontaneous. He also pointed out that the opposite is true in the auditory modality, where repetitions of melodic sequences are very easy to notice but mirror symmetries are not. The advantage of mirror symmetry over repetition has been confirmed in other, more systematic studies.

Corballis and Roldan (1974) designed two different tasks with the same simple stimuli (i.e. sparse dot patterns, arrowheads, and C-shapes) presented for 100 ms. In one task, subjects had to judge the relationship between the two pattern halves (as 'same' for translation or 'mirror' for reflection), whereas subjects in the other task had to judge each pattern as a whole (as 'symmetrical' for reflection or 'asymmetrical' for translation). In most of the conditions, a mirror-symmetry advantage was obtained. Bruce and Morgan (1975) asked subjects to detect small violations in reflected or translated line patterns and found that response times were generally faster for the mirror symmetries, except when the violations were near the edge of the patterns. This suggests that the salience of mirror symmetry is probably based on the ease of comparing spatially contiguous elements near the axis. In a systematic investigation of the effect of point-pair separation on the detection of translational symmetry, Jenkins (1983a) confirmed this intuition. His results may be compared with those of Tyler and Chang (1977), who showed that detectability of repetitive patterns declined with the square root of the number of repeats, in accord with ideal-observer predictions.

However, even when distance is controlled, there is often an advantage of reflection over translation. For example, when subjects have to compare two pseudo-random contours, the task is much easier when they are reflected than when they are translated, regardless of whether the contours are part of the same object or of two different objects (Baylis and Driver, 1995). An even more striking result was obtained in another recent study by Baylis and Driver (1994). They varied the number of elements in each half-pattern from 4 to 16 and found that the response-time functions were relatively flat for the detection of reflectional symmetry (i.e. 3 to 6 ms per element pair) and quite steep for the detection of translational symmetry (i.e. 25 to 40 ms per element pair). Although I would not go as far as Baylis and Driver (1994), who claim that this implies parallel versus serial computation of reflectional versus translational symmetry, respectively, these results do suggest collectively that there is something special about mirror symmetry which makes it an intrinsically more salient stimulus attribute than translational symmetry.

The special status of mirror symmetry seems supported by a couple of studies which have compared it with rotational symmetry. For example, Royer (1981) showed that symmetries created by 90 or 180 deg rotations were always much harder to detect than those created by reflections, regardless of the specific display type (i.e. dots, blocks, diagonolinear, or rectilinear line segments) and degree of practice. However, it remains to be seen whether this mirror-symmetry advantage would still hold when compared to rotational symmetries with smaller angles. A mirror-symmetry advantage was also obtained by Palmer and Hemenway (1978) in a study with closed polygons instead of discrete patterns, although subjects had to respond negatively to rotational symmetries, which might have affected the response times for other reasons. In other words, it appears hard to design a fair comparison and more work along the same lines seems warranted.

As far as I know, Kahn and Foster (1986) were the first to report a systematic investigation of the different types of symmetries created by translation, rotation, and reflection in dot patterns. Because they were interested in pattern recognition more than in symmetry detection, Kahn and Foster designed their experiments as 'same-different' discriminations to be made between two dot patterns, instead of global symmetry judgments of the whole configuration (which may cause important differences; see Corballis and Roldan, 1974). Although some specific differences between the three types of symmetry were found, the overall performance levels for all of them were quite good (d' between 1 and 2), considering the short exposures of 100 ms.

These reasonable levels of detectability for symmetries created by translation, rotation, and reflection were also obtained by Wagemans *et al.* (1993) in a study designed to test a specific model of symmetry detection (see later). In three separate experiments, the detection of symmetry in dot patterns was tested as a function of some transformation parameters (e.g. orientation, distance, angle), as well as some factors specifically manipulated to introduce or destroy higher-order structures that were proposed as being important in supporting efficient symmetry detection. In all conditions, d's for regular-random discriminations in dot patterns presented for 100 ms were generally above 1. Although no direct statistical comparisons between the three types of symmetry were made, the trends indicated that reflections were easier to detect than translations and rotations, which did not differ much. The same pattern of results was also obtained by Zimmer (1984), who used pseudo-random line drawings and different degrees of asymmetry as distractors for each type of symmetry (an experimental design which requires careful stimulus construction).

In summary, the different types of symmetry created by reflection, translation, and rotation can all be detected, although they are not equally salient. However, more direct comparisons in systematic, parametric studies are clearly needed. Because mirror symmetry seems to have a special status for the visual system, the remainder of the paper will focus on this type of symmetry only.

3. SYMMETRY AND ATTENTION

The salience of symmetry created by reflection about a vertical axis suggests that symmetry might be one of the privileged properties that are detected preattentively. Indeed, most symmetry-detection researchers have implicitly or explicitly adopted this view (e.g. Barlow and Reeves, 1979; Wolfe and Friedman-Hill, 1992; Locher and Wagemans, 1993). Experimentalists have developed two operational definitions of 'preattentive' to test this idea about the processing of stimulus attributes such as symmetry. In addition, there is some pertinent neuropsychological evidence.

First, following Julesz' (1981, p. 28) operational definition of a preattentive process as one in which an observer is able 'to perceive certain structures in the stimulus array when the stimulus is briefly presented — say for less than 160 ms', symmetric displays have often been presented at short exposure durations. This research confirms that symmetry can be detected preattentively (in Julesz's sense of the word) over a wide range of stimulus and viewing conditions. One can perceive symmetry in brief presentations of simple random shapes (at 25 ms; see Carmody *et al.*, 1977), in dot patterns (at 100 ms; see Barlow and Reeves, 1979; Wagemans *et al.*, 1991, 1993), in dynamic dot textures (at 40–50 ms; see Julesz, 1971; Hogben *et al.*, 1976), in other discrete patterns consisting of line segments at different orientations (at 10–125 ms; see Locher and Wagemans, 1993), as well as in complex abstract art displays (at 50–100 ms; see Locher and Nodine, 1989).

A second, perhaps more powerful, technique to assess preattentive processing has become very popular after Treisman introduced her feature-integration theory and the visual search paradigm to test it (Treisman and Gelade, 1980). In this paradigm, subjects have to search for a target in a display with a variable number of distractors. Response times are generally plotted as a function of display size and the slope of these functions is taken as an index of search efficiency. The basic finding is that targets defined by primitive features such as color or line orientation can be detected in parallel (i.e. independent of the display size), whereas more complex combinations such as conjunctions of color and form, or specific spatial relations between line segments seem to require a serial search process (as inferred from a linear display-size effect on response times). Because symmetry is critically dependent on the spatial relations between more primitive elements (such as dots or line segments), it seems to follow that symmetry must require attention to be detected. However, preattentive grouping processes can produce emergent properties and this might give local symmetry the status of a special feature (Treisman and Patterson, 1984; Pomerantz and Pristach, 1989). Moreover, more recent research has made it clear that conjunction search is often more efficient than predicted by a serial model (e.g. Wolfe *et al.*, 1989; Treisman and Sato, 1990; Enns and Rensink, 1991).

Inspired by studies showing that more global spatial relations between elements in a display affect the search efficiency (e.g. Moraglia, 1989; Nothdurft, 1992), the possibility that symmetry detection is preattentive in the sense of producing flat search functions has been tested in two studies. First, Javadnia and Ruddock (1988) showed that targets could be discriminated from distractors by parallel processing if they differed in symmetry (e.g. an E against Es where the symmetry was perturbed). More recently, Wolfe and Friedman-Hill (1992) have examined the role of the symmetry relations among display elements, which were line segments at variable orientations. Search for a target, defined as an element of a third orientation, was more efficient when the orientations of the background elements were symmetrical about a vertical axis (e.g. a 50 deg clockwise target against a background of 20 deg clockwise, CW, and 20 deg counterclockwise, CCW, distractors) than when they were symmetrical about an oblique axis (e.g. 20 deg and 80 deg distractors for the same target). However, both of these studies have their own limitations and more research along the same lines seems warranted, especially in light of other recent research suggesting that attention might play a role after all.

Driver *et al.* (1992) reported some results from a neuropsychological case study which are interesting in this respect. They investigated symmetry detection by a patient who failed to attend to the left side of objects throughout the visual field, resulting from brain damage centered on the right parietal lobe (i.e. the 'visual neglect syndrome'). As one would expect, this patient could not detect vertical symmetry in shapes (presented until a response was made), while he was able to detect horizontal symmetry. Interestingly, when asked which of two sets of shapes were seen as figures against a background, this patient clearly preferred the symmetrical shapes in much the same way as normal observers do (Bahnsen, 1928). As stressed by Driver *et al.* (1992), this result indicates that both the right and the left of each shape must be represented at some stage in the patient's visual system in a form that supports symmetry detection, at least covertly. The more general implication seems to be that symmetry can be detected preattentively, that is, prior to the attentional stage at which the patient's impairment leads him to neglect the left side of each shape when he is asked to make overt judgments about them.

Despite the operational definitions of 'preattentive' used in the experiments mentioned earlier, attention is involved in the sense that subjects always know when the stimulus is coming and where it will be presented. Moreover, in the first set of studies, subjects were explicitly instructed to detect symmetry. Recently, Rock, Mack, and their colleagues (Mack *et al.*, 1992; Rock *et al.*, 1992) have shown that this direction of attention to the array and to the task at hand is important. They demonstrated that many of the phenomena of grouping and perceptual organization studied by Gestalt psychologists do not occur in conditions of inattention, although they have since then been thought of as largely preattentive and automatic. In the cited studies, subjects had to perform a foveal task — line-length discrimination — while the stimulus was embedded in a field of other elements, or while it had an array of dots or a simple shape in its immediate neighborhood. Surprisingly, subjects could not answer simple questions such as whether the field was homogeneous or heterogeneous, how dense the array of dots was, or what shape the additional element had. Of course, this question could be asked only once to each subject in conditions of complete inattention, that is, independent of the attentional mechanisms activated by the intention to look for a certain stimulus. Despite the intrinsic limitations of this paradigm, it seems important to investigate whether symmetry can be detected under these conditions of inattention.

Another demonstration of the role of attention in symmetry detection has to do with the effect of orientation (see later). In an attempt to investigate whether the salience of vertical symmetry is based on the fixed neural architecture that supports the oblique effect in many other perceptual tasks (e.g. Appelle, 1972), Wenderoth (1994) recently manipulated the relative frequencies of different orientations in different blocks of trials. He found that the detection of mirror symmetry is best at the orientation which is at the mean of the frequency distribution. For example, when the 16 different orientations which were tested were vertical, horizontal, the two diagonals (45 deg and 135 deg), and 5, 10, and 15 deg CW and CCW deviations from diagonal, performance was best at diagonal instead of vertical or horizontal. The obvious explanation of this result is that the range of stimuli in a block of trials affects subjects' scanning or attentional strategies so that they focus on the symmetry axis with the greatest likelihood. This interpretation is congruent with Pashler's (1990) finding that cueing the subjects in advance about the orientation of the axis of symmetry produced a considerable increase in speed and accuracy.

In summary, there is overwhelming evidence that the percept of symmetry emerges seemingly effortlessly and automatically in a wide variety of conditions. However, the implications in terms of the role of attention are far from clear. Further research employing visual-search and inattention paradigms or other methods of manipulating attention seems important in this respect.

4. CHARACTERISTICS OF SYMMETRY DETECTION

Most of the studies on symmetry detection have investigated the effects of some major factors on the efficiency and speed of symmetry detection. This kind of research has yielded important information about the general principles of possible underlying mechanisms and the constraints within which they operate. Although these studies do not corroborate any specific model of how exactly symmetry is detected, they do provide powerful indications against the plausibility of some proposed models of symmetry detection. Four such explorations will be discussed in turn: the effects on symmetry detection of the orientation of the axis, the location of the patterns in the visual field, the grouping of the elements in the patterns, and perturbations of all kinds.

4.1. Symmetry and orientation

Since Mach's (1886/1959) observation that symmetry about a vertical axis is more salient than symmetry about any other axis, a large number of studies have quantified this advantage experimentally. Two basically different paradigms have been used to this end although neither addresses the issue of whether the vertical preference is based on a structural bias in the neural array or attentional preference for the vertical axis. In the first, introduced by Goldmeier (1937/1972), subjects are presented with a pattern with two axes of mirror symmetry, vertical and horizontal, and they have to indicate which of two test patterns with single symmetry, vertical or horizontal, best resembles the vertical-horizontal-symmetric reference pattern. The results clearly indicate a vertical symmetry advantage (Rock and Leaman, 1963; Fisher and Fracasso, 1987).

The second paradigm investigates the detectability of symmetry created by reflection about axes in different orientations, usually only vertical and horizontal and the two diagonals in-between. Generally, the results indicate that vertical symmetry is easier to detect (i.e. faster or better) than horizontal symmetry, which is easier to detect than diagonal symmetry (e.g. Palmer and Hemenway, 1978; Royer, 1981). However, a significant number of results do not fit this simple summary. In some studies, horizontal symmetry was not harder than vertical symmetry (e.g. Fisher and Bornstein, 1982), or horizontal symmetry was even easier (e.g. Jenkins, 1983b, Experiment 4; Pashler, 1990, Experiment 4). In other studies, diagonal symmetry was not harder than horizontal symmetry (e.g. Jenkins, 1985), or diagonal symmetry was even easier (e.g. Corballis and Roldan, 1975). Other work shows that the effect of axis orientation interacts with the effect of other variables such as the orientation of the individual line segments or their spatial grouping (Locher and Wagemans, 1993). The diversity of these results makes it difficult to support the hypothesis of a structural bias in the neural filters processing the symmetrical pattern.

Only a few studies have tested other oblique orientations in addition to the main diagonals. Barlow and Reeves (1979) reported a response-bias free measure of detectability (d') for one subject tested with eight different orientations, which suggested that vertical symmetry was easiest, followed by horizontal symmetry, followed by diagonal symmetry, and followed by other obliques (30 and 60 deg from horizontal, both CW and CCW). The difference between diagonal and other oblique orientations is not congruent with the neurophysiological evidence on the oblique effect, which suggests that the visual system's sensitivity for orientations decreases with larger deviations from vertical and horizontal (Appelle, 1972). Nevertheless, a similar pattern of results was reported in three more recent studies (Zimmer, 1984; Wagemans *et al.*, 1992; Wenderoth, 1994). However, Wenderoth (1994), by manipulating the range of orientations presented within a block of trials, showed that orientation preferences in symmetry detection could be biased or reversed at will to any selected orientation. Wenderoth's results suggest that a wide range of orientation effects in symmetry detection can be explained by attentional selectivity for particular axis orientations rather than biases in the neural array of orientation detectors.

4.2. Symmetry and visual field

A second set of factors investigated in some detail have to do with the location of the symmetric stimulus pattern in the visual field. Two kinds of manipulations have been employed: first, the contribution of different zones in a pattern to the global impression of symmetry; and, second, the effect of noncentral presentation of the pattern. Together with the orientation effects, these manipulations are interesting in as far as they test the importance of a symmetric projection to the visual system, which must be critical if the salience of vertical mirror symmetry depends on the vertical mirror symmetry of the neural architecture. This assumption has pervaded many of the ideas about symmetry detection since Mach's (1886/1959) early proposals (e.g. Julesz, 1971).

Most studies show that a restricted area around the axis is the most important one (e.g. Julesz, 1971; Bruce and Morgan, 1975; Barlow and Reeves, 1979; Jenkins, 1982) and that symmetry is easier to detect when the axis of symmetry is located at the point of fixation (e.g. Barlow and Reeves, 1979; Saarinen, 1988; Locher and Nodine, 1989). As with the orientation effects, however, several findings urge a qualification of this general statement.

First, with respect to the contribution of different zones, Barlow and Reeves (1979) measured the detectability of symmetry in displays in which only pairs of vertical slices of the dot patterns were symmetrical. The results showed that the symmetry is also detectable when the symmetrical dots lie only near the edge of each half pattern. In other words, the contribution of different zones does not decrease linearly with increasing distance from the symmetry axis. Instead, a U-shaped function was obtained with increased performance near the axis and near the edge of the pattern (see Wenderoth, 1995, for more recent evidence along the same lines). This is, of course, what one would expect on the basis of the positive results obtained with symmetric line drawings (e.g. Palmer and Hemenway, 1978) and filled polygons (e.g. Carmody *et al.*, 1977), which contain no internal features in the immediate neighborhood of the axis.

Second, with respect to the issue of central presentation, Julesz (1971) noted that the detection of symmetry in simple patterns like random shapes does not require that the center of the symmetry coincides with the fixation point of the eyes, whereas the opposite seems true for more complex patterns like dot textures. Based on this observation, Julesz concluded that symmetry detection operates at two levels: for patterns with low spatial frequencies, the symmetric relations are extracted globally, whereas a point-by-point comparison seems required for patterns with high spatial frequencies. A similar distinction has been incorporated in most subsequent theoretical proposals about symmetry-detection mechanisms (e.g. Bruce and Morgan, 1975; Palmer and Hemenway, 1978; Zimmer, 1984). In one of the few studies focused on the role of different spatial frequencies, Julesz and Chang (1979) showed that the sum of two random-dot arrays, one with vertical symmetry and one with horizontal symmetry, could simultaneously be perceived as two separate symmetrical patterns instead of a single random array when they are spatially filtered so that their respective power spectra are far enough apart (e.g. low-pass vertical symmetry and high-pass horizontal symmetry). In addition, they demonstrated that the low-band frequency channels contribute more heavily to the symmetry percept than the high-band channels do.

4.3. Symmetry and grouping

These and other ideas about spatial filtering (e.g. Watt and Morgan, 1985; Watt, 1987) receive indirect support from studies with symmetric patterns consisting of oriented line segments. Locher and Wagemans (1993) obtained results suggesting that the spatial grouping (e.g. clustering) of line segments determines the detectability of symmetry more than their individual identities (e.g. orientation relative to the axis of symmetry). The perception of symmetry might be the conscious concomitant of the output of filtering operations executed in parallel on a symmetric display, which make the locations of large-scale tokens (blobs) available before the figural identity of the elements. Different versions of this idea are widely spread among symmetry-detection studies (e.g. Barlow and Reeves, 1979; Royer, 1981; Jenkins, 1983b; Pashler, 1990; Locher and Wagemans, 1993).

In addition to the evidence discussed earlier, two other results argue against the idea of a point-by-point comparison of all the elements in a display. First, Troscianko (1987) has demonstrated that isoluminance does not destroy perception of random-dot symmetry. In the light of his view that the main effect of isoluminance may be an introduction of a small positional uncertainty into the neural representation of the stimulus, Troscianko interpreted this finding as evidence that exact position information is not essential for symmetry detection. Second, by comparing human performance with an ideal observer mechanism looking for all pairwise matches, Tapiovaara (1990) has convincingly shown that only a modest number of all possible point-by-point comparisons are made. This finding is, of course, what one could expect on the basis of the wide range of patterns used in symmetry-detection research. The results obtained in these studies do not seem to agree with the simple prediction that detectability of symmetry takes more time with an increasing number of pattern elements (see Baylis and Driver, 1994, for more direct evidence with filled polygons). Apparently, elements become grouped together and only a restricted number of groups are compared.

Nevertheless, there is some evidence that at least one featural characteristic, the luminance of the elements in relation to the background, determines the matching of symmetrically positioned elements. Zhang and Gerbino (1992) studied the detection of vertical symmetry in different kinds of opposite-contrast dot patterns. The background was always grey and dot-background contrast was varied in four different conditions: (i) same contrast for all dots, either black or white; (ii) black dots on the left of the axis and white on the right, or vice versa; (iii) half of the dots white and half black, with positive correspondence (white-to-white or black-to-black); (iv) half of the dots white and half black, with negative correspondence (white-to-black or black-to-white). Discrimination from similar noise patterns was equal in the first and third conditions and better than the second and fourth, a result which argues against a contrast-insensitive mechanism based on abstract-token matching (see also Tyler *et al.*, 1993). In other words, what enters the symmetry-detection mechanism seems more than mere spatial positions of completely abstract place tokens.

4.4. Symmetry and perturbations

In many of the forementioned studies, perturbations of all kinds have been used to assess the operating characteristics of the symmetry-detection mechanism. We tend to think that symmetry is abundant in our perceptual world (see Introduction); yet few instances of symmetry in natural objects are really perfect. For example, human faces are never perfectly symmetrical. This can be demonstrated quite easily by creating two symmetric variants of a picture of a face by reflecting the right half and the left half. The differences from the original picture are striking. Moreover, bilateral symmetry can be detected from general viewpoints, which suggests that the symmetry-detection mechanism is robust to the skewing transformation associated with non-frontal viewing positions (see later). All this seems to imply that symmetry is a canonical property which tends to be exaggerated by the visual system (Freyd and Tversky, 1984), much like orientations slightly off vertical or horizontal seem to profit from the special status of the cardinal orientations (see earlier). On the other hand, if symmetry really is special for the visual system, it might be important to signal minor deviations from it (especially in animals where they might be correlated with gene deficiencies; see the evolutionary biology references cited earlier).

Somewhat surprisingly, psychophysical research supports both of these apparently conflicting intuitions. On the one hand, many studies have used perturbations of symmetry to show how robust the detection mechanism is, whereas other studies, on the other hand, have required subjects to discriminate perfect from imperfect symmetries, a task subjects could do just as well. Notice that the major difference between these two types of studies lies in the task given to the subjects, not the stimuli *per se*. In the first, subjects have to distinguish perfectly symmetric or imperfectly symmetric patterns from completely random ones; in the second, subjects have to respond 'symmetrical' only to the perfectly symmetric ones. It is also interesting to note that some of the specific perturbations that have been used were related to more-or-less detailed proposals about potential mechanisms.

Within the first category of studies (with random distractors), Barlow and Reeves (1979) have performed seminal work by systematically testing the discriminability of random dot patterns and dot patterns with variable proportions p of symmetric pairs. With 100 ms exposures and 100 dots, d's were still around 1.0 with $p = 0.3$ or 0.4. This means that in dense patterns 30 or 40% of pairwise correspondences are sufficient to trigger the preattentive percept of symmetry. In another experiment, Barlow and Reeves (1979) smeared symmetry by reducing the accuracy with which pairs are placed. This was done by positioning one of the two dots of a symmetric pair randomly within a square area centered on the symmetric position, the size of which was varied in different steps. As one would expect, the performance level decreased with increasing size of the tolerance area, but subjects still performed at 75% correct with a square of 0.4 deg visual angle, which was 20% of the total width of the patterns displayed. Both of these results suggest that the mechanism for symmetry detection is remarkably robust.

More recently, the author and his colleagues (Wagemans *et al.*, 1991, 1992, 1993) have introduced a different type of distortion away from perfect mirror symmetry,

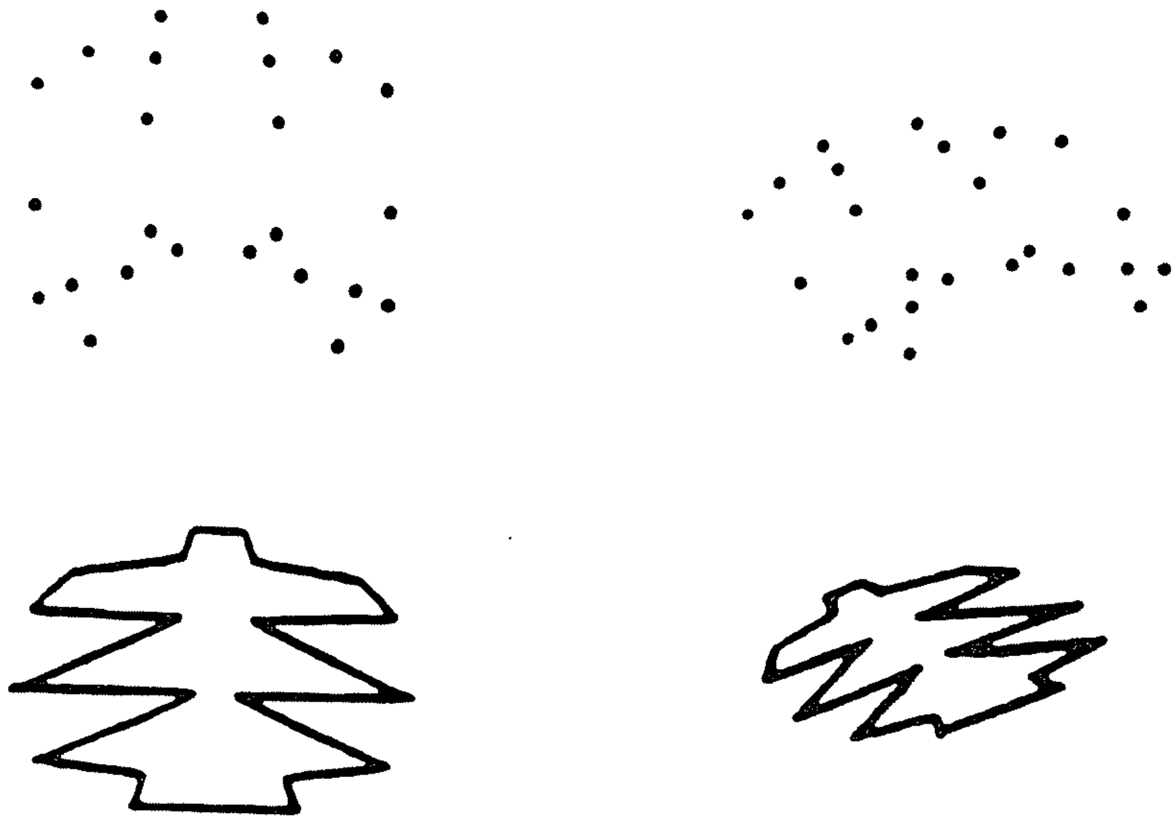

Figure 1. A dot pattern with bilateral symmetry as viewed head-on (left) and from a non-orthogonal viewpoint (right), giving rise to so-called 'skewed symmetry'. The bottom two panels show the same for a polygon. Skewing the symmetry is probably less disruptive here. From Wagemans (1993). Copyright 1993 by the American Psychological Association Inc. Adapted with permission.

which might have greater ecological significance. Whenever a perfectly bilateral symmetry is viewed from a nonorthogonal viewpoint, the actual projection on the retina is skewed symmetric (see Fig. 1 for some examples). This means that corresponding elements are not at orthogonal positions across the axis, but at an orientation which differs from 90 deg with an offset (i.e. the skewing angle) depending on the viewing position. In one set of experiments with unlimited presentation times, response times always increased dramatically with increasing skewing angle (Wagemans *et al.*, 1992) and in another set of experiments with 100 ms exposures, d' always dropped significantly, although seldomly to chance levels (Wagemans *et al.*, 1991). Similar effects of skewing were obtained in two other laboratories as well (Gerbino and Zhang, 1991; Locher and Smets, 1992). By specific additional manipulations in further research (see later), the impact of skewing could be reduced. Moreover, based on indications that skewed symmetry in polygons can be used for shape recovery much better than with dot patterns (Wagemans, 1992, 1993), it can be expected that skewing would be even less detrimental with polygons. Unfortunately, a symmetry-detection experiment with skewed symmetric versus random polygons still remains to be performed.

Within the second category of studies (with perturbed distractors), Barlow and Reeves (1979) reasoned that the remarkable degree of sensitivity to even small proportions of symmetry which they had obtained in the experiments mentioned earlier would be much less interesting if the visual system were unable to signal varying degrees of symmetry above that level (of say, 30 or 40%). This would indicate that the mechanism could only give ungraded, all-or-nothing symmetry responses to all stimuli with a sufficiently high degree of symmetry (i.e. above a certain threshold). Barlow and Reeves (1979) therefore repeated the experiment with variable degrees of symmetry but now asked subjects to discriminate them from one another instead of from completely random patterns. With a difference of 0.3 between the proportions p of symmetric pairs in the two stimulus categories to be discriminated (i.e. random from 0.3, 0.1 from 0.4, etc.), performance was reasonable ($d' = 1$) across the whole range. This result implies that symmetry is represented as a graded rather than a discrete all-or-nothing property. In a sense, this is the way it should be, if one considers the fact that completely random patterns are also quite rare. When symmetry is defined as self-identity under Euclidean transformations (see earlier), it is hard to design dot patterns or polygons in which the generalized autocorrelation (Uttal, 1975) would be zero. This approach of near symmetries has been fruitful (e.g. Farrell and Shepard, 1981; Zimmer, 1984).

Jenkins (1983b) introduced perturbations to test his proposal about the role of two types of regularities in bilaterally symmetric dot patterns. He observed that symmetric point pairs have the same orientation and collinear midpoints throughout the pattern. The purpose of his study was to determine the visual system's sensitivity to each of these factors. In one experiment, Jenkins required his observers to discriminate random-dot textures from equally dense patterns with uniformly oriented point pairs but a variable range within which the midpoints could be centered. As one would expect, performance dropped with increasing perturbation of midpoint collinearity, but even with a range of 4.4 deg of visual angle, it was still above 65%. This means that the visual system is able to detect orientational uniformity as such. In another experiment, subjects had to discriminate perfectly symmetric dot textures from patterns in which midpoint collinearity was perturbed. The results of this experiment showed discrimination performance of 85% correct with midpoint collinearity perturbations over a range as small as 0.07 deg of visual angle. This means that the visual system has a very high sensitivity to midpoint collinearity as well. As in Barlow and Reeves' (1979) study, these results indicate a remarkable robustness of the symmetry-detection mechanism against perturbations (as measured in an imperfect-random discrimination task), as well as a high sensitivity to minor deviations from perfect symmetry (as measured in a perfect-imperfect discrimination task). It is worth pointing out that a similar set of experiments with perturbations of orientational uniformity remains to be done.

In one study (Carmody *et al.*, 1977), subjects were given three response categories (symmetrical, random or mixed) and they were able to discriminate pseudo-random polygons of the three types surprisingly well, considering the very short exposure duration of 25 ms. However, the sensitivity for the mixed category was remarkably lower, which might have been due to biases to respond 'symmetrical' or 'random' more often. In a second experiment, the same patterns were presented but different two-alternative forced-choice tasks were used for two groups of subjects. One group had to respond 'target' only to the perfectly symmetric patterns and 'nontarget' to both other types of patterns. The second group had to respond 'nontarget' to the perfectly symmetric patterns and 'target' to both other types of patterns. The data showed higher detectability for symmetric patterns than for random patterns, which was in turn higher than for the mixed patterns. It would be interesting to repeat the same experiment with a slightly different task, that is, with perfectly symmetrical and mixed patterns as targets and only completely random patterns as nontargets. Additional manipulations of the exposure duration and the frequencies of each type of stimulus might reveal a pattern of detectabilities consistent with the idea that there is perhaps an initial bias to exaggerate symmetry (i.e. imperfect symmetry 'equals' symmetry), followed by more detailed processing which could signal deviations from symmetry if needed for the task at hand (see also Freyd and Tversky, 1984).

5. THEORIES AND MODELS OF SYMMETRY DETECTION

In the light of what we now know about symmetry detection from this review of the literature, how can we explain the way symmetry is detected by the visual system? Despite the long list of robust effects of several different variables known to affect symmetry detection, they have not led to a convergence upon one single, theoretically satisfying answer. However, several attempts to formulate possible mechanisms for symmetry detection in general or quite specific terms have been made in the past decades of symmetry research.

Palmer and Hemenway (1978) were among the first to propose a fairly general process model which seemed to be congruent with most of the empirical findings available at that time. In essence, they proposed a dual-process model consisting of a selection-evaluation cycle. First, a potential axis of symmetry would be selected by a rapid but crude analysis of symmetry in all orientations simultaneously. By establishing a perceptual frame of reference in the appropriate orientation, a detailed evaluation would then be performed by explicit comparison of the two pattern halves. This model explains why it takes longer to reject near and rotational symmetries than to identify perfect symmetries. Furthermore, by assuming that the initial axis selection is biased towards vertical and perhaps horizontal, this account is also able to explain orientational effects. Finally, by assuming a variable order of selection, the advantage of multiple symmetries (created by reflection about more than one axis) can be accounted for as well, since, on average, a symmetry axis would be selected sooner when there are more axes to choose from.

The distinction between two processes in symmetry detection, a fast, holistic process and a slow, point-by-point matching process, has been made by many other researchers too. For example, Julesz (1971) used it to explain the dissociations obtained between patterns dominated by low versus high spatial frequencies, respectively (see earlier). Bruce and Morgan (1975) used it to explain different types of symmetry-violation detection. Foster (1991, pp. 63–64) also proposed two kinds of operations for symmetry detection: one, a fast reversal of spatial-order information; the other, a potentially slower, progressive alteration of positional information. In addition, the possibility of two completely different processes, perhaps levels of processing, should always be borne in mind when considering possible conflicts between data obtained with different experimental procedures. For example, some paradigms seem to require subjects to perform a pointwise matching process (e.g. when response times are measured with sparse patterns and perturbed distractors), whereas others allow subjects to rely on their first impression (e.g. short exposure durations, dense displays, random distractors).

Despite its attractive characteristics, Palmer and Hemenway's model has two major problems. First, some effects that are explained by specific properties of the axis-selection process remain even when there is no need to select an axis. For example, the multiple-symmetry advantage was still present in an experiment in which subjects had to report on only one specific type of symmetry (e.g. vertical symmetry; see Palmer and Hemenway, 1978, Experiment 2). Palmer and Hemenway explained this by suggesting that the evaluation stage might be facilitated by the good Gestalt of the two pattern halves to be compared in the case of double or fourfold symmetry, but this seems to beg the question as to where the good Gestalt came from in the first place. Likewise, the vertical-symmetry advantage still remained when subjects were cued about the orientation of the symmetry axis (Pashler, 1990) and diagonal symmetry was still not easier to detect than vertical symmetry when the pattern was surrounded by a tilted frame which should bias the selection of the corresponding reference frame (Herbert *et al.*, 1994; Zimmer, 1984).

As noted by Royer (1981), a second, more serious, problem with the dual-process model is the difficulty in elaborating the nature of the crude but rapid analysis in the selection stage. In a sense, this kind of preattentive symmetry detection is the more basic process to be explained, because it seems most closely tied to the fixed functional architecture of the visual system and it is probably the one which affects other perceptual and cognitive processes. The pervasive role of symmetry suggests that we should look for an explanation of symmetry detection which has more general applicability than the selection-evaluation account, which is tailored only for symmetry-detection tasks. We know that symmetry affects many other processes, even if subjects are never asked to select and evaluate symmetry axes. An excellent example of this important distinction has been discussed earlier: Driver *et al.* (1992) have shown convincingly that symmetry can affect figure-ground organization in a patient with hemineglect, even though he was unable to perform above chance in an explicit symmetry-detection task.

The same problems appear to plague other proposed models as well. For example, based on a comparison between their subjects' performance levels against those of an ideal mechanism with absolute efficiency, Barlow and Reeves (1979) proposed that the symmetry-detection mechanism employed by the human visual system probably does not perform an exhaustive search through all possible pairs to find those that qualify as symmetric. Rather, the empirically obtained efficiency suggested that only 25% of the pairs were used in the discrimination tasks. In addition, the mechanism tolerated surprisingly large inaccuracy in the placing of the symmetric pairs, which led Barlow and Reeves to believe that the only thing the visual system does in detecting symmetry is to compare dot densities measured in relatively large areas placed symmetrically about the putative axis of symmetry, which reduces the number of comparisons to be made enormously (e.g. for 100 dots, from 4950 to 8). This seems to be an operation which can be performed quite easily by visual neurons with fixed receptive fields. However, this proposed mechanism cannot explain symmetry detection in patterns where density has been made homogeneous (e.g. Julesz, 1971, for high-density patterns and Wagemans *et al.*, 1991, for low-density patterns). In addition, the mechanism is not only tolerant and efficient, it is also quite versatile in the sense that it can also detect symmetry by reflection about axes that are not vertical and not central in the visual field. As admitted by Barlow and Reeves (1979), each different position and orientation of the axis seems to require a different set of comparisons and it is not at all clear how these are brought about. Again, to explain how all of these comparisons can be performed preattentively is quite difficult.

Another example is Jenkins' (1983b) distinction between three component processes involved in the detection of mirror symmetry in dense dot textures. Using perturbations of midpoint collinearity in three different discrimination tasks (see earlier), Jenkins obtained the following three major empirical results: (1) the orientational uniformity of dot textures can be detected, even when the pairs are distributed randomly over a large region; (2) the visual system can correlate points only when they are within a relatively narrow region around the axis; and (3) deviations from perfect midpoint collinearity can be detected quite accurately. In line with these findings, Jenkins proposed that the detection of mirror symmetry involves three different processes: (1) a process that detects orientational uniformity; (2) a process that fuses the most salient point-pairs around the axis into a larger feature; and (3) a process that determines whether that feature is symmetric. Assuming that each of these component processes responds differently to variations in axis orientation, Jenkins could explain what was known about symmetry detection without postulating the existence of a symmetrical neural organization centered about the fovea (as Mach, 1886/1959, and Julesz, 1971, had previously done). However, once more, these component processes could also be regarded as different strategies one can use depending on the discrimination task at hand, rather than a theoretically satisfying proposal of preattentive symmetry detection in general.

In order to understand the enormous efficiency, robustness, and versatility of the first, preattentive stage of global symmetry detection, one should take the pervasiveness of symmetry in other perceptual and cognitive processes seriously. This suggests that symmetry might be an integral part of the way the visual system encodes and represents visual patterns in general. Perhaps, perception of symmetry is nothing more than the conscious concomitant of the output of filtering and grouping operations which are executed in parallel on all visual displays, regardless of whether they are symmetric or not. This idea has been around for a while (e.g. Barlow and Reeves, 1979; Royer, 1981; Pashler, 1990; Foster, 1991; Locher and Wagemans, 1993), but it has never been spelled out in sufficient detail to be incorporated in a computational symmetry-detection model before Wagemans *et al.* (1993) did so in their so-called bootstrapping model.

Two robust or striking empirical findings have inspired this model. First, the fact that skewing affects symmetry detection so much (Gerbino and Zhang, 1991; Wagemans *et al.*, 1991, 1992; Locher and Smets, 1992) ruled out one class of symmetry-detection

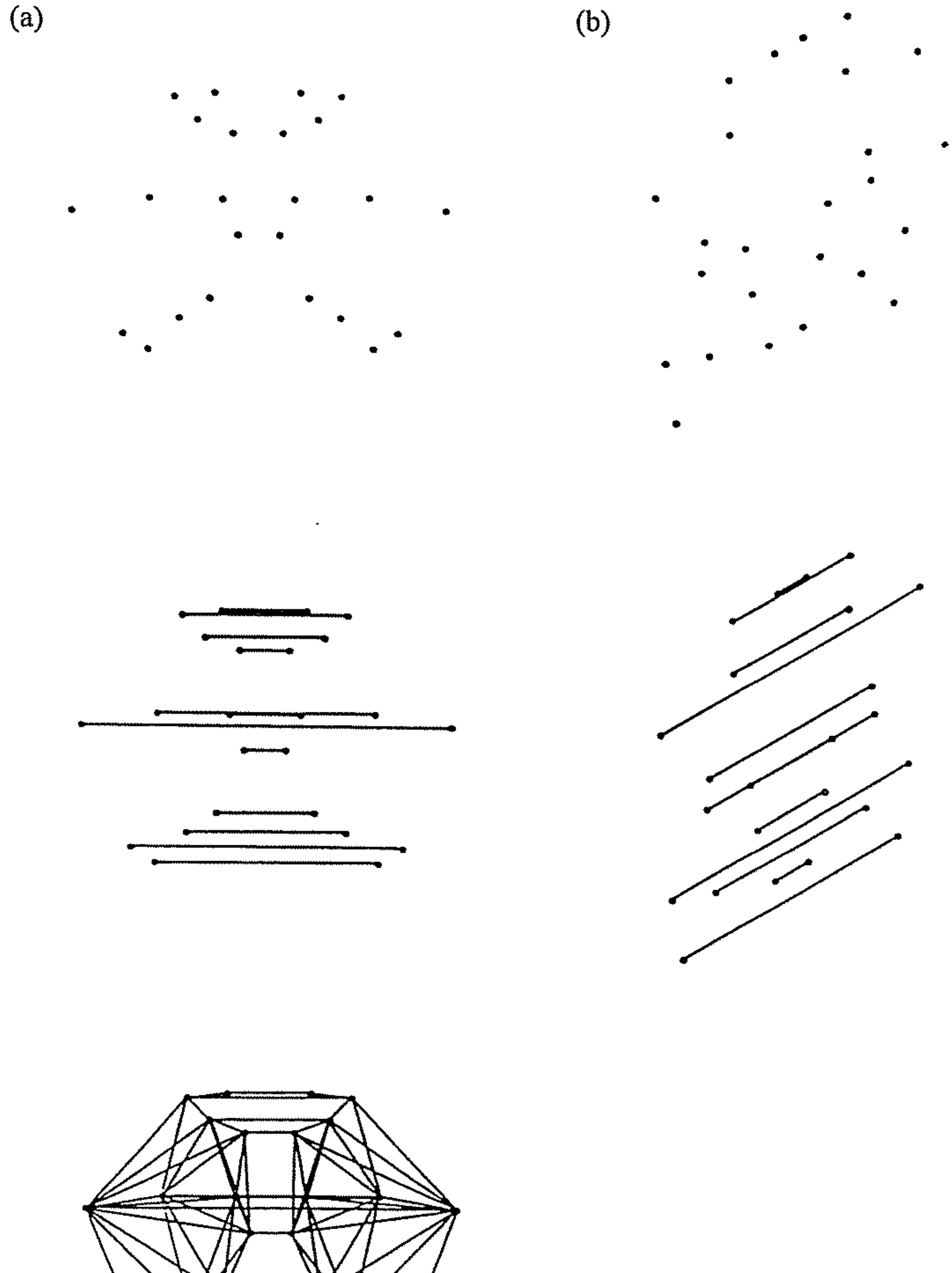

Figure 2. A dot pattern with (a) perfect bilateral symmetry and (b) skewed symmetry, together with their lower-order structure (i.e. virtual line parallelism) and, for the perfect bilateral case only, higher-order structure (i.e. correlation quadrangles). From Wagemans *et al.* (1993). Copyright 1993 by Pergamon Press Ltd.

models. Second, the fact that detection of single symmetry is easier when it is supported by a second symmetry along an orthogonal axis (Palmer and Hemenway, 1978, Experiment 2) suggested the plausibility of another class of models. The first class of models assumes that symmetry detection is based on first-order (or more generally, lower-order) regularities such as orientational uniformity and midpoint collinearity (Jenkins, 1983b), defined on point-pairs. Because skewed symmetry has exactly the same first-order regularities and is nevertheless much harder to detect preattentively, it is clear that symmetry detection relies on something else, perhaps in addition to it (see Fig. 2). Perfect bilateral symmetry differs from skewed symmetry in having regular second-order (or, more generally, higher-order) structures as well. The quadrilaterals formed between two symmetric point-pairs are symmetric trapezoids in perfect bilateral symmetry and irregular trapezoids in skewed symmetry. Likewise, double symmetry differs from single symmetry in having rectangles instead of trapezoids.

The basic assumption of the model by Wagemans *et al.* (1993) is that these pairwise correlations between the angles in these quadrilateral structures (which have been called 'correlation quadrangles' for that reason) facilitate the propagation of local pairwise groupings (called 'bootstrapping' for that reason). The idea is that quadrilaterals such as trapezoids specify a reference frame which suggests a unique direction within which other correspondences are much more likely to be found (see Fig. 3). In other words, the initial randomness in pairing elements in a pattern within some local neighborhood converges to systematicity much more easily, creating a coherent global structure more rapidly and more efficiently.

This proposal of a mechanism that allows local pairings to spread out throughout the whole pattern almost automatically seems to come close to capturing the essential nature of symmetry detection: In one sense, symmetry only exists as the total sum of pairwise correspondences in the complete pattern, whereas all available evidence suggests that the preattentive mechanism responsible for its detection is not performing such a point-by-point comparison. In addition, such a mechanism could explain the superiority of symmetry created by reflection compared to symmetry created by translation or rotation. Whereas the latter two have regular higher-order structures (in this case, parallelograms instead of trapezoids), they do not allow the same amount of bootstrapping, because there is no single direction of propagation.

The first study the author and his colleagues performed to investigate the plausibility of this account was to combine the two manipulations that inspired the proposal,

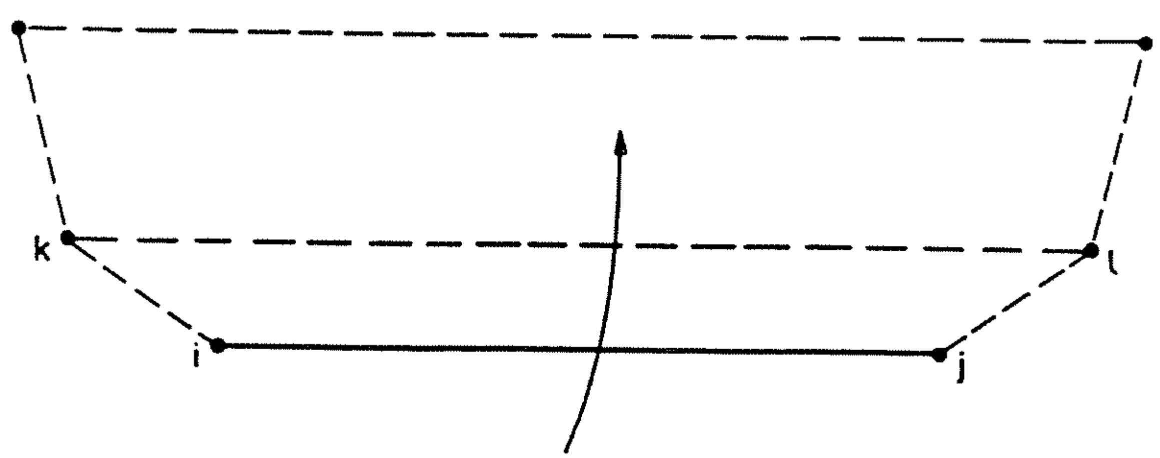

Figure 3. Bootstrapping. The correlation quadrangle formed between $(i, j)(k, l)$ suggests a direction in which to proceed. From Wagemans *et al.* (1993). Copyright 1993 by Pergamon Press Ltd.

introducing skewing and additional axes of symmetry at the same time. When dot patterns were flashed for 100 ms, increasing skewing angles caused decreasing detectability for single symmetries much more than it did for double symmetries, and skewing had almost no effect on quadruple symmetry (Wagemans *et al.*, 1991). In other words, what affects the preattentive symmetry-detection mechanism is not the degree of skewing as such, but the degree of remaining regular higher-order structures.

This idea was further tested in a study with three different types of symmetry in similar dot patterns (Wagemans *et al.*, 1993). In each of three experiments, parametric variations were introduced in the form of axis orientation and skewing angle for reflections, translation direction and distance for translations, and rotation angle for rotations. In addition, the presence of higher-order structures was always manipulated by introducing specific kinds of non-randomness in the pseudo-random dot patterns used to create the symmetries (e.g. equidistance in reflections, collinearity in rotations), or by introducing specific noise types (e.g. varying the translation distance within a pattern). In general, the results obtained in these three experiments provided strong support for the idea that detection of symmetry is easy when the pairwise correspondences are supported by regular higher-order structures and more difficult when lower-order regularity is all that is available.

In the same study, a possible implementation of the bootstrapping model was also proposed with two processes, a cost function to express the cost of different pairings and a probabilistic optimization procedure to converge on a globally optimal grouping solution. The general ideas of the model were incorporated in this specific implementation in the following way. First, the cost function used two components, one corresponding to first-order structure and one corresponding to second-order structure. Second, the optimization procedure allowed more rapid convergence based on bootstrapping. Although the implementation was not advocated as the only possible one, nice fits to the psychophysical results were obtained. Moreover, this implementation was spelled out in sufficient detail to qualify as a computational model, not just a conceptual approach.

Obviously, additional experiments are needed to test the model in its details and further elaboration is required to incorporate more of what we know about symmetry detection. For example, orientation effects are not part of the current model, but they could be incorporated quite easily, either as part of the cost function or as part of the optimization procedure. The same is true for effects of eccentricity, either as a simple increase in distance from fixation (different zones around the axis, see earlier) or as a displacement of the axis away from fixation (noncentral presentation, see earlier). Moreover, although the specific details of the model as they are now suggest that the model only works for high-spatial-frequency, low-density patterns consisting of discrete elements (preferably dots), something along the same lines could be developed for low-spatial-frequency patterns like dense dot textures or closed figures, by assuming that the model operates on the centroids of blobs or the vertices of polygons.

One other characteristic of this model which is worth mentioning is that it suggests a much wider applicability than has been assumed in previous symmetry-detection models. Wagemans *et al.* (1993) pointed out that bootstrapping based on higher-order structures appears a plausible mechanism in a wide variety of other tasks such as the detection of global structures in Glass patterns (e.g. Glass, 1969; Prazdny, 1986) and in vector graphs (Caelli and Dodwell, 1982). In addition, some specific results about perception of stereo (Akerstrom and Todd, 1988) and motion (Werkhoven *et al.*, 1990) suggest that a similar mechanism might underlie grouping or correspondence problems in many other areas as well. There are good reasons to suppose that the mechanism of symmetry detection is so general: simple transformations like translations, rotations, expansions and contractions occur each time when the observer or the object moves. It is not unlikely, therefore, that biological vision systems have evolved to detect the invariances in the resulting optic flow patterns (e.g. Lappin *et al.*, 1991). In any event, the potential scope of this mechanism stands in contrast to the specificity of previously available proposals which could count as 'models' of symmetry detection (Julesz, 1971; Palmer and Hemenway, 1978; Barlow and Reeves, 1979; Jenkins, 1983b; Foster, 1991).

Whether one single mechanism for all sorts of grouping tasks is possible, or whether, alternatively, the visual system might have developed multiple mechanisms, each devoted to one specific task, remains to be investigated in more detail. On the one hand, the special status which mirror symmetry seems to have for the human visual system (see above) suggests that we might have a special mechanism for its detection. Some researchers would go even further and propose several different mechanisms for the detection of reflection symmetry only. For example, Tyler *et al.* (1993) recently reported evidence that the perception of mirror symmetry imposed on a field of either static or dynamic noise, with either the same or opposite contrast in the two half-fields, seems to require three separate mechanisms, each with specific spatiotemporal properties. On the other hand, such a proliferation of multiple symmetry-detection mechanisms seems quite unlikely if one considers the many different types of symmetry to be detected and the large number of other grouping tasks which appear to employ similar correlational mechanisms (such as in motion or stereo). Clearly, more research is needed to find out whether the truth perhaps lies somewhere in the middle, with one general architecture for spatiotemporal grouping, the parameters of which can be fine-tuned or optimized for each specific task with which the visual system is confronted.

6. SUMMARY AND CONCLUSION

One way to summarize what is known about the detection of visual symmetries is by attempting to answer some specific questions. As one would expect with issues that have puzzled researchers for a long time, the answers are generally not simply yes or no. Probably the truth lies somewhere between the different extreme positions that have been taken in the past. Future studies should help us reveal the circumstances under which the visual system employs one strategy instead of another.

(1) Is mirror symmetry special? Yes, but this does not mean that visual symmetries created by other kinds of self-similarities such as translations or rotations cannot be

detected. The reason that symmetry created by reflection is more salient might have to do with the fact that it is the only type in which all local reference frames on a small number of elements are globally consistent. At least one model of symmetry detection suggests that it is this alignment that facilitates the fast and automatic propagation of local correspondences throughout the whole pattern, which appears to underlie the efficiency of symmetry detection in human vision.

(2) Can symmetry be detected preattentively? Yes, in the sense that symmetry can be detected easily in various displays presented very briefly (below 150 ms). Yes, in the sense that experiments with the visual search paradigm suggest that search efficiency is influenced by the symmetry relations between targets and distractors and among the distractors. However, these results do not mean that attention does not play a role in symmetry detection. For example, it is not clear what is the effect of directing the subject's attention to the array and the task at hand. Moreover, orientation effects can be attenuated or reversed by directing the subject's attention to particular orientations and scrutiny is often required for the detection of minor deviations from perfect symmetry.

(3) Is there an effect of the orientation of the axis of symmetry? Yes, but this does not mean that mirror symmetry can be detected efficiently only when the axis is oriented vertically. The general trends obtained in several studies suggest that, in the absence of biasing factors, symmetry is increasingly harder to detect when the axis is horizontal or near vertical, then diagonal or near horizontal, and, finally, in other oblique orientations. Note that this orientation function deviates from the classically reported oblique effect in two respects. First, near-vertical and near-horizontal axes are better, probably because they are close to the cardinal reference frame. Second, diagonals (45 deg and 135 deg) are better than other obliques, suggesting that they are references too. However, it is possible that many of the previously reported results are based on the mean orientation of the distribution of orientations used in a block of experimental trials.

(4) Is symmetric projection to the visual system necessary for the perception of symmetry? No. Although it becomes harder to detect mirror symmetry when the axis is displaced away from fixation, symmetry detection is still possible with non-central presentation. Together with the orientation effects, these results suggest that an explanation of the symmetry-detection mechanism need not be closely tied to the symmetric neural architecture that has sometimes been postulated.

(5) Does detection of mirror symmetry depend exclusively on pairwise correspondences between elements close to the axis? No. Although there is evidence to suggest that contiguous pointpairs contribute more heavily to the symmetry percept, other results indicate that they are not necessary. For example, symmetry still can be detected when there is no information about symmetry close to the axis, as in filled or wide polygons, or by replacing pairs close to the axis by random noise.

(6) Does symmetry detection rely on pairwise comparisons? Probably yes, but to a much lesser extent than assumed in some models of symmetry detection. For example, the symmetrically positioned elements do not have to match perfectly, either in their figural attributes, nor in their positions. Large perturbations of all kinds can

be tolerated. It is more likely that a small number of groups, possibly derived from low-pass filtering, are compared rather quickly and crudely. Alternatively, the massive parallelism of the system might allow a large number of 'comparisons' to be performed simultaneously, while still producing a stable global organization quickly and under serious degrees of local perturbation.

(7) Does this imply that symmetry detection is sloppy and gives a non-graded symmetry response to all stimuli with a certain level of symmetry? No. Despite its remarkable robustness against perturbations of all kinds, the symmetry-detection mechanism(s) also can be surprisingly precise, if the experimental task requires it. Small deviations from perfect symmetry can be detected. One way to compromise between these two apparently conflicting requirements of robustness and sensitivity is to have two mechanisms or operation modes: one, an initial, crude mechanism with a bias towards exaggerating symmetry, and the other, a secondary mechanism for checking the details. Whereas the first probably operates on the basis of a small number of large groups (clusters), the second requires intrinsically slower point-by-point comparisons. Of course, these two mechanisms (or modes of operation of the same mechanism) are at work in different viewing and task conditions. Such a two-mode account need not be in conflict with our bootstrapping model. It could well be the case that the first mode reflects an automatic, unconscious 'signal' based on the low cost of the grouping and the global characteristics of the minimal solution (acting like an emergent property), whereas the second mode would then reflect the conscious accessing of this representation to scrutinize its details.

(8) Do we have one single mechanism for the detection of all types of symmetry? Probably the answer is yes and no. Some studies suggest that we have several different mechanisms, even for the detection of mirror symmetry, and important dissociations have been reported. On the other hand, at least one mechanism of symmetry detection has been proposed which could also explain the detection of many other types of structure (e.g. in vector graphs, in Glass patterns), as well as more general grouping or correspondence problems (e.g. in stereo, in motion). It is worth looking at the possibility of one general architecture for spatiotemporal grouping with the potential of parameter-optimization for different tasks.

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