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Johan Wagemans, Luc Van Gool, Géry d'Ydewalle

Institutions: Katholieke Universiteit Leuven

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Johan Wagemans [a] , Luc Van Gool [a] & Géry d'Ydewalle [a]

[a] University of Leuven, Belgium

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Orientational Effects and Component Processes in Symmetry Detection

Johan Wagemans, Luc Van Gool, and Géry d'Ydewalle

University of Leuven, Belgium

In previous research on symmetry detection, factors contributing to orientational effects (axis and virtual lines connecting symmetrically positioned dots) and component processes (axis selection and pointwise evaluation) have always been confounded. The reason is the restriction to bilateral symmetry (BS), with pointwise correspondences being orthogonal to the axis of symmetry. In our experiments, subjects had to discriminate random dot patterns from symmetries defined by combining 12 axis orientations (every 15°) with seven reflection angles (0°, yielding BS, and three clockwise and counterclockwise 15° steps, yielding skewed symmetry, SS). In Experiment 1, with completely randomized trial order, a significant interaction between axis and skewing angle was obtained, indicating that classically observed orientational effects are restricted to BS and that the orientation of the pointwise correspondences is important. These basic findings were replicated in three subsequent experiments, which differed in that they used blocks containing patterns with the same axis (Experiment 2), virtual lines orientation (Experiment 3), or their combination (Experiment 4). Based on a comparison between the results obtained by these manipulations, we suggest a possible reason for the failure of preattentive symmetry detection in the case of dot patterns with SS.

Requests for reprints should be sent to Johan Wagemans, Laboratory of Experimental Psychology, University of Leuven, Tiensestraat 102, B-3000 Leuven, Belgium (e-mail address: fpaas10@blekul11.bitnet).

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Much research has been done on symmetry detection in general and, more specifically, on the influence of the orientation of the axis of symmetry and the role of possible component processes. Despite the large number of studies (references will be given below), there are only few well-established facts. With respect to the effects of orientation, the only thing that seems clear is that symmetry about a vertical (V) axis is preferred and is easier to detect (faster and more accurate) than symmetries in other orientations. The relative ordering of the horizontal (H) and oblique (O) orientations is surrounded by an as yet unsettled controversy between research indicating an *oblique effect* (H better than O) and research indicating a *mental rotation effect* (O better than H). With respect to the component processes, most theorists seem to defend a two-process model postulating a first stage, in which a possible axis is selected by a rapid and crude process that is applied globally to the whole pattern, and a second stage, in which the symmetry is assessed by a slow and detailed point-by-point comparison process. Apart from this principal distinction, there is no agreement on the details of these component processes (e.g. how the global selection process works exactly).

In addition to this lack of detailed knowledge, everything that is known at the present time has restricted applicability because only detection of bilateral symmetry had been studied. Contrary to the widespread assumption that bilateral symmetry (especially in V orientation) occurs quite frequently in a normal visual environment (e.g. Barlow & Reeves, 1979), perfect bilateral symmetry is a rather rare visual event. First of all, most of the perceived symmetries (e.g. of a human face) are not perfect mathematical synmmetries, in the sense of exact pointwise correspondences. Furthermore, even if there were perfect bilateral symmetry in the world, it would only seldomly be projected as such to the visual system. In fact, the only situation in which it does result in a bilateral symmetry on the retina is when the symmetry is viewed from an orthogonal viewing position. From a more general viewing position, bilateral symmetry (BS) is projected to *skewed symmetry* (SS) in the image plane (see Figure 1).

In computer vision, the presence of SS in the image is, therefore, used as a cue to infer BS in the world (e.g. Kanade & Kender, 1983; Stevens,

FIG. 1. Skewed symmetry as the result of a non-orthogonal projection of bilateral symmetry (adapted from Kanade & Kender, 1983).

1979) and algorithms have been proposed to derive constraints on the orientation (slant and tilt) of a non-orthogonal plane from the direction and angle of the skewing (e.g. Barnard, 1983; Friedberg, 1986; Hakalahti, 1983). As far as we know, the human sensitivity to SS has never been tested formally and systematically (some informal observations are made by Attneave, 1982, and Stevens, 1979). Nevertheless, it seems to be a prerequisite for a biological visual system to be able to detect symmetry in non-orthogonal planes in order to use this kind of non-accidental property in object recognition (as proposed recently by Biederman, 1987, and Lowe, 1987).

The experiments presented here studied the detection of SS because it is an interesting generalization of BS and because it offers a resolution of some of the problems about orientational effects and component processes outlined above. To show why this is so, the literature on both of these research traditions is reviewed in rather greater detail.

Orientational Effects

Since Mach's (1886, 1959) observation that V symmetry is more salient than symmetry about an axis that is oriented differently, a number of studies have attempted to quantify this advantage experimentally. Two basically different paradigms have been used. In the first, the subject has to select one of two test patterns, a V symmetric and an H symmetric one, that most resembles the doubly (V–H) symmetric standard pattern. The experimental results obtained with this paradigm indicate that V symmetry is preferred over H symmetry (Fisher & Fracasso, 1987; Goldmeier, 1937, 1972; Rock & Leaman, 1963). This has been called the *Goldmeier effect*.

The second paradigm investigates the detectability of the symmetry about axes in different orientations. To measure the detectability, both performance level (% correct responses, number of errors, *d*'s) and response times (RTs) have been used. In most research, only four different orientations have been tested: the two main axes, V and H, and the two diagonals (D) in-between, right (R) and left (L), 45° clockwise (CW) and counterclockwise (CCW) from V, respectively. The most common finding with this paradigm is that V symmetry is easier to detect than H symmetry, which is easier to detect than L or R symmetry (Palmer & Hemenway, 1978; Royer, 1981). This result has been called the *oblique effect* (for a review of this effect in different domains, such as line orientation discrimination, see Appelle, 1972; Essock, 1980).

However, the picture becomes much less clear when one takes a closer look at the literature. In fact, one finds almost every possible ordering of the detectability of the symmetry about different axes. In some studies, one does not find significant differences between V and H symmetry (Fisher & Bornstein, 1982) and higher detectability of H symmetry has even been obtained (Jenkins, 1983, Experiment 4; Pashler, 1990, Experiment 4). In other studies, one does not find significant differences between H and L or R symmetry (Jenkins, 1985), and higher detectability of L and R symmetry has even been obtained (Corballis & Roldan, 1975). The latter finding has been interpreted as a *mental rotation effect* (for a review of this effect in different domains, see Shepard & Cooper, 1982). Indeed, the fact that the time needed to detect the symmetry about a certain axis increases with the angle between that axis and the V orientation seems to suggest that the subject has to rotate the pattern mentally to a V orientation.

With respect to the orientational effects, we have two aims in this study. First, we want to investigate the detectability of symmetry about a larger number of axes. As far as we know, the study of Barlow and Reeves (1979) is the only one testing more than the four basic axes. With respect to the controversy between the oblique effect and the mental rotation effect, this might contribute considerably, because intermediate axes would permit an examination of the linearity of the effect of departure from V, implied by the mental rotation account, with greater statistical reliability. Furthermore, if an oblique effect really determines the detectability of symmetry at different orientations, axes oriented 15° or 30° CW or CCW from V or H should yield different detectability than the main diagonals (for some of the evidence for this, see e.g. Appelle, 1972; Atkinson, 1972; Dick & Hochstein, 1989). Specific evidence for a bias towards the main obliques in the estimation of the orientation of dot patterns has been found (Lansky, Yakimoff, Radil, & Mitrani, 1989). Barlow and Reeves (1979) observed increasingly lower detectability of symmetry about axes in V, H, D, and other O orientations, but their study was somewhat restricted because only one subject was tested at the essential levels (i.e. 30°, 45°, and 60°), and only d's calculated. It would be interesting to replicate their results using more subjects in an RT study.

The second purpose of our experiments is to disentangle two potentially relevant orientations. The first is the orientation of the axis of symmetry, defined as the straight line connecting the midpoints between the symmetrically positioned elements. The second factor is the orientation of the pointwise correspondences, eventually represented by the so-called *virtual lines* (Stevens, 1978) connecting the symmetrically positioned elements. Intuitively, it might seem clear that the orientation of the axis determines the experimental results. However, because in BS the virtual lines connecting the symmetrically positioned elements are always orthogonal to the axis of symmetry, it is logically possible that their orientation is the psychologically relevant one. Some empirical data seem to support this suspicion.

For example, there is clear evidence for the importance of a small zone around the axis of symmetry (Barlow & Reeves, 1979; Jenkins, 1982; Julesz, 1971). It indicates that the elements positioned closer to the axis of symmetry—or, in other words, those that are connected by shorter virtual lines—contribute more to the global impression of symmetry. Based on the fact that the strength of a virtual line decreases with increasing distance between its endpoints (Stevens, 1978), this finding seems to offer some indirect support to the relevance of virtual lines in symmetry detection. Likewise, the results of studies testing BS versus repetition, indicating higher detectability of the former (Bruce & Morgan, 1975; Corballis & Roldan, 1974; Julesz, 1971; Kahn & Foster, 1986), have been explained by the longer average distances between translated vis-à-vis reflected elements.

A second example of empirical evidence arguing for the potential contribution of virtual lines to the orientational effects in symmetry detection, comes from Bornstein's research. In one of his habituation studies with four-month-old infants, he manipulated the separation between the two symmetric pattern halves (Bornstein & Krinsky, 1985). The orientational effects on the habituation rates disappeared when the separation increased. In a study with pre-school children and adults, he investigated the way in which four-, five-, or six-element symmetric arrays are reproduced (Bornstein & Stiles-Davis, 1984). Two symmetry-based strategies were distinguished: side-by-side reproduction (axis-based) and point-by-point reproduction (virtual-line-based). The choice for one of these strategies interacted with the orientation of the patterns in a statistically significant way. By adults, both strategies were used equally often for V and H symmetry, whereas the side-by-side strategy was clearly preferred for the D symmetry. The interaction effect of orientation with the relative importance of axis versus virtual lines seems to argue strongly for a more detailed investigation of both potentially relevant factors.

Jenkins' (1983) study is the one that is most directly focused on the issue of axis versus virtual lines in symmetry detection. The principal aim of his investigation was to determine the visual system's sensitivity to orientation uniformity (i.e. of the virtual lines) and midpoint collinearity (i.e. the definition of the axis). In addition to the manipulation of the task, he varied the orientation of the patterns (V in Experiments 1–3, H in Experiment 2). In summary, his results showed that when the axis was the most important factor to the task (i.e. in Experiment 3, testing the detection of perturbation of midpoint collinearity), V was superior to H. In contrast, when the virtual lines were the most important factor to the task (i.e. in Experiment 1, testing the sensitivity to orientational uniformity), H was superior to V. This interaction of orientational effects with the relative importance of axis and virtual lines encouraged us to investigate it in greater detail.

Component Processes

Starting from the observation that the detection of symmetry in simple patterns (e.g. amorphic shapes) is basically different from that in complex patterns (e.g. dot textures), in the sense that the latter requires that the centre of symmetry coincides with the fixation point of the eyes whereas the former does not, Julesz (1971) concluded that symmetry detection operates at two levels: for patterns with low spatial frequencies, the symmetric relations are extracted globally; in contrast, for patterns with high spatial frequencies, the symmetric relations are extracted by a point-by-point comparison process. Since this pilot work, a number of authors have suggested similar distinctions between different stages or component processes of symmetry detection. Moreover, they have investigated these component processes experimentally.

Bruce and Morgan (1975) studied the detection of violations in symmetric and repeated patterns using different distances between the location of the violations and the axis. On the basis of their complex pattern of results, with symmetry being easier than repetition in most cases but not always, they suggested a distinction between two successive stages: (1) a rapid and global comparison between elements around the midline, and (2) a conscious scanning strategy in which the elements in the two pattern halves are successively compared to detect the violations. Jenkins (1982) proposed a similar distinction on the basis of three experiments investigating the contribution of different zones around the axis of symmetry. In perfectly symmetric patterns, the presence of an immediately perceptible "cluster" or "feature" in the middle of the pattern is readily interpreted by the subjects as the location of the axis of symmetry because it appears symmetric. In patterns in which this central symmetric zone is absent, the symmetry in the rest of the pattern can only be detected by a point-by-point comparison process.

Palmer and Hemenway (1978) most explicitly suggested a process model with two functional components, selection and evaluation, to account for their set of experimental data on the detection of single and multiple mirror symmetry and rotational and near symmetry in polygons presented in different orientations. To start with, Palmer and Hemenway explained the difference between their own results on orientational effects, indicating an oblique effect ($RT_V < RT_H < RT_D$), and Corballis and Roldan's (1975), indicating a mental rotation effect ($RT_V < RT_D < RT_H$), by the absence or the presence, respectively, of an explicitly drawn axis of symmetry. They interpreted this as evidence for a stage in which a potential axis has to be found prior to testing symmetry about it and for the bias of this stage towards V. This suggestion was corroborated by the fact that the orientational effects were very similar for the rotational and near symmetries (a result that was not replicated by Kahn & Foster, 1986, however). It must be noted that this selection process does not follow a simple fixed order (V → H → D). Palmer and Hemenway suggested that the first stage of axis-selection follows a variable order, based on the considerably higher detectability (shorter latency and smaller error rate) of multiple symmetry. On the average, a symmetry axis will be selected sooner when multiple axes are present from which to choose.

Recently, Pashler (1990) attempted to characterize the role of voluntary factors in the determination of a candidate axis for symmetry detection by presenting the subjects an axis cue before each experimental dot pattern. This manipulation resulted in a substantial and highly significant advantage in the speed and accuracy of symmetry detection in general. In addition, the same orientational effects were found with or without cuing. According to Pashler, this result indicated that the higher detectability of V symmetry is not caused by a mere strategic choice of the subjects for a V axis in the absence of advance information.

In summary, the experimental results on component processes in symmetry detection have been interpreted in terms of a two-process account: (1) A possible axis is selected by a rapid and crude process that is applied globally; (2) then, the symmetry is checked by a slow and detailed point-by-point comparison process. However, it is not clear how these two processes can be functionally independent, because one can only find the axis of symmetry by detecting that the elements are positioned symmetrically about it. More specifically, two routes to the detection of BS can be followed. On the one hand, one can detect the midpoint collinearity that is characteristic of a display with BS, find the highly plausible axis, and test the symmetry about it, by checking point-by-point in the orientation orthogonal to the axis. On the other hand, one can detect the orientational uniformity that is also characteristic of a display with BS, find the virtual lines, and postulate an axis orthogonal to the virtual lines and dividing them in equal halves.

Futhermore, the relation between these component processes and the orientational effects is not clear. Although Palmer and Hemenway (1978) have made a serious effort to clarify this relation, the intriguing results of Jenkins (1983), discussed above, indicate that it is worthwhile to investigate the issues of axis and virtual lines in more detail. Using SS permits both this necessary disconfounding of axis and virtual lines in studying orientational effects and this desirable disentangling of selection and evaluation as component processes in symmetry detection.

GENERAL METHOD

The same general method was used in all four experiments. The only difference between the experiments concerned some aspects of the procedure, which will be described below.

Subjects. Six subjects participated in each of the four experiments. The first author and a collaborator took part in all experiments. For these subjects, the order of participation in the four experiments was determined randomly to avoid systematic order effects. In addition, four different naive observers volunteered in each experiment. The naive subjects were undergraduate students who participated in partial fulfillment of a course requirement. They also received a small amount of money (about £1.00 per hour) for their efforts. All observers had normal or corrected-to-normal vision.

Stimuli. The stimuli used in all four experiments were patterns consisting of 24 dots. Half of the patterns were completely random, the other half were symmetric (bilateral or skewed). The *symmetric dot patterns* were constructed in three phases. In the first phase, a random collection of 12 dots was used to create BS about one of the four basic axes (V, H, L, and R). Some constraints on the locations of the input dots were introduced to obtain a pattern with homogeneous density (e.g. minimal interdot distance). In a second phase, the symmetric dot patterns were rotated through an angle of 15°, both CW and CCW, so that the BS occurred in 12 different orientations (see Figure 2A); for example, a bilateral V symmetry could be rotated into a symmetry about an axis of 105° (0° indicates H). When an SS had to be generated, a third phase followed. A CW or CWW skewing of one of three angles (i.e. 15°, 30°, or 45°) was performed around the symmetry axis (see Figure 2B). The combination of the 12 levels of orientation of the axis and the seven levels of skewing yields a total number of 84 kinds of symmetry. In each condition, 10 different patterns were generated. Examples of the symmetric dot patterns can be found in Figure 3A.

The general principle of stimulus generation of the *random dot patterns* was as similar to the one for the symmetric patterns as it could be. The constraints on the randomization of the dot locations were the same. The skewing transformation was also applied to the random dot patterns, because the circular area in which the dots are located (and to which the subject's attention had to be divided) is transformed to an elliptic one in the case of SS, the elongation axis of which is exactly intermediate between the orientation of the axis and the orientation of the virtual lines, so that the perceived orientation of the dot patterns does not differentially detract from either of these factors. Work by Lansky, Yakimoff, and their colleagues showed that human observers are quite good in estimating the orientation of an elliptic dot pattern (e.g. Lansky, Yakimoff, & Radil, 1987; Lansky et al., 1989). Therefore, in order for the form of the stimulus zone not to be a potential cue for the decision on the randomness and regularity of the pattern constituted by the dots located in the zone, the random patterns were always made to have the same stimulus fields as their

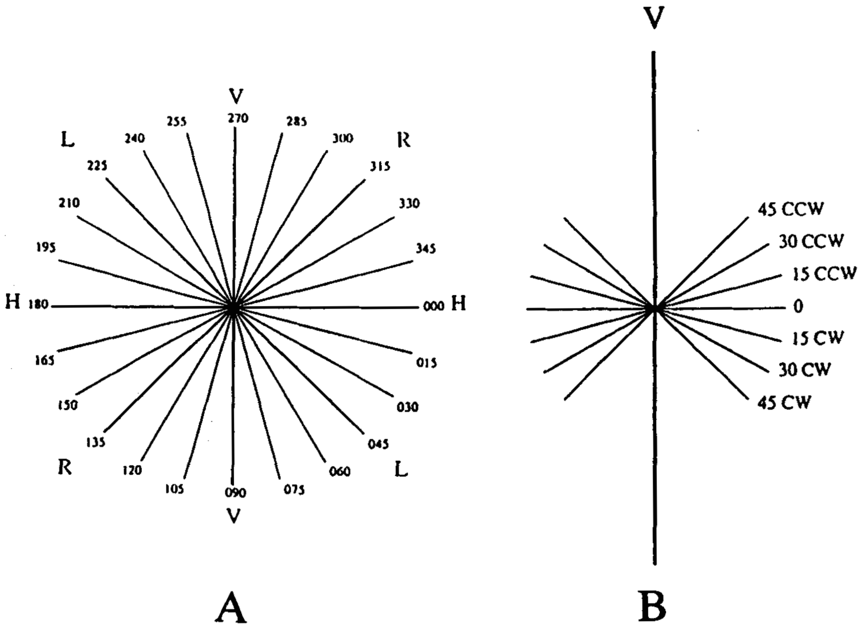


FIG. 2. Details about the manner in which the dot patterns were generated. (A) Twelve axis orientations were used (i.e. all 15° divisions of a circle); horizontal (H) is indicated by 0°. (B) Seven skewing angles were used for all axis orientations (only the vertical axis is shown): three 15° angles, both clockwise (CW) and counterclockwise (CCW), in addition to 0° skewing (resulting in bilateral symmetry).

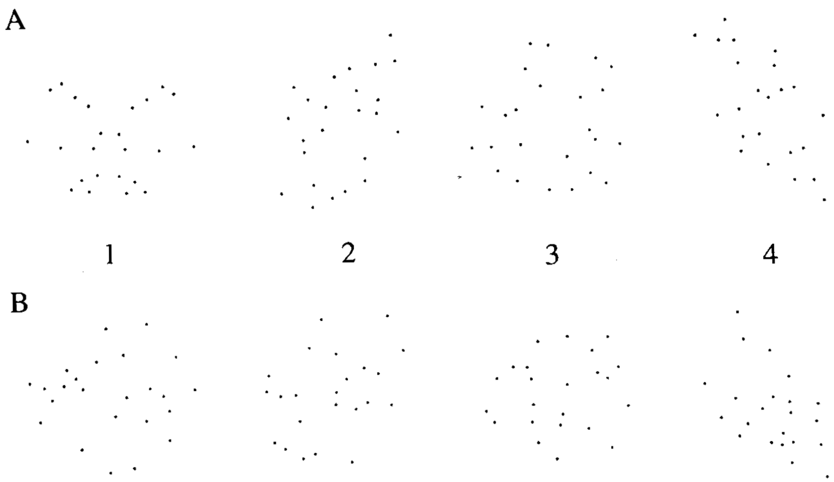


FIG. 3. Examples of the experimental dot patterns. (A) Four symmetric patterns: from left to right: (1) Axis = 90°, Skew = 0°; (2) Axis = 90°, Skew = −30°; (3) Axis = 105°, Skew = 0°; and (4) Axis = 75°, Skew = 45°. (B) Four corresponding random patterns.

symmetric counterparts. This also results in 84 kinds of random patterns. As with the symmetries, 10 different random patterns were generated in each condition. Examples of the random dot patterns are given in Figure 3B. The total number of experimental stimuli to be generated was 1680 (i.e. 12 × 7 × 2 × 10). In addition, in each condition two symmetric and two random patterns were generated to be used as practice stimuli.

Apparatus. The dot patterns were generated by a C program on a SUN-3 Workstation with a Motorola MC 68881 floating-point board. Stimulus presentation was automated by a different program on an Intel-386 system with a mathematical coprocessor and an AT&T-Truevision VISTA-card. Stimuli were presented on a raster display (BARCO, type CDCT-6351B) in PAL mode with a 50-Hz temporal resolution and a 740 × 578 spatial resolution, non-interlaced. The stimuli were presented as black dots against a homogeneous gray background in a completely darkened room. Screen borders were covered by a black cardboard with a circular aperture to reduce orientational cues. Subjects were seated at a distance of 114 cm on a chair with adjustable height to align their eyes with the centre of the screen. At that distance, the individual dots and the whole patterns subtended a visual angle of 5.7 min arc and 5°, respectively. Forehead- and chin-rests were used to prevent head rotations.

General Procedure and Task

Before starting the experiment, the subjects were instructed about what was meant by regularity (the notion of symmetry was avoided because naive subjects equate it with BS) by showing them four examples (one BS and one SS about a V axis, and two SS about two differently oriented axes). The examples were shown on paper and time was given to explore the dot patterns sufficiently to detect the presence of the symmetry.

The subjects were told that they would be shown a larger number of random and symmetric dot patterns, randomly intermixed, that had to be judged as regular or not. The YES/NO answers had to be made as quickly and accurately as possible by pressing one of two keys on a response panel (the identity of which was counterbalanced between subjects). The patterns remained on the screen until one of the response keys was pressed. Responses and RTs (measured from stimulus onset) were recorded and instantaneously evaluated by the computer, so that immediate feedback could be given. A correct answer was, after a short interval of 500 msec, followed by a 1000-msec high-frequency tone (750 Hz), a false response by a 1500-msec low-frequency tone (100 Hz). The only reason why this feedback was provided was to keep the motivation and arousal of the subjects at an optimal level. Secondary learning effects resulting from this feedback were averaged out by randomizing block and trial orders per subject. Before each stimulus pattern, a fixation pattern was presented for 500 msec. This was a black circle (0.5 cm diameter) in the centre of the screen. It allowed the subjects to fixate the centre of the dot pattern when it was presented immediately thereafter, without providing them with orientation cues (which would be the case with the classic fixation cross).

Following the description of the task and the procedure, subjects received a practice session with 15 trials (randomly chosen out of the total collection of 1680 experimental patterns). The main reason for this practice session was to show the subjects how the patterns would look on the screen and to allow them to get an impression of the difficulty of the task (i.e. especially with the largely skewed symmetries). When subjects did not see the regularity in the pattern when there was one, the experimenter indicated how the symmetric dots belonged together. After this practice session no further instructions were given.

The total number of experimental trials was divided into smaller blocks that could be run without a break. The manner of blocking the trials was different for the four experiments (see below). In the beginning of each block of trials (70 or 20), a small number of practice trials (14 or 4) was given. The patterns for these practice trials were not the same as the experimental ones, but they were representative of the block in which they were contained. Patterns that were responded to incorrectly were repeated at a random position in the remainder of the block. After a block of trials, the subject could choose to have a short break. Several blocks of trials were run in a 1-hr session. Most subjects took one or two short breaks in each session and needed five or six sessions to complete all trials. Sessions were distributed over several days. The order of trials within a block and the order of blocks was randomized for each subject separately.

Blocking in Different Experiments. In Experiment 1, all experimental patterns were divided in blocks of 70 trials constituting a completely randomized selection of the larger population. In other words, the subjects had no information whatsoever about the level of the manipulated factors to be expected. In each trial, they had to restart the search for an orientation of axis and virtual lines. In the three other experiments, blocks contained patterns with a common characteristic. In Experiment 2, two blocks of 70 experimental trials and 14 practice trials were made for each level of axis orientation. Within the blocks, therefore, the orientation of the axis was constant, whereas it changed between the blocks. In Experiment 3, the same was done for the orientation of the virtual lines, whereas Experiment 4 contained 84 blocks of 20 patterns, 10 random and 10 symmetric ones for each symmetry condition. The purpose of these manipulations will be made clear in the discussions and introductions between experiments.

Data Analyses. Only the data for the symmetric patterns were analyzed. Two sets of data—RTs and error rates—were available. Because the patterns that were responded to incorrectly were repeated in the rest of the block, there was always an RT associated with a correct response, so that equal cell numbers could be used in all analyses. As a consequence of the same procedure, the number of errors per pattern could, in principle, vary from zero to infinity. In practice, however, the average numbers of errors for each condition varied only between zero and one or two. A zero means that all patterns were responded to correctly from the first presentation; if all patterns of a particular condition had to be repeated once, or half of the patterns twice, the average number of errors would equal one. We cannot report percentages because of this feature of the procedure (there is no fixed denominator to compute the fractions).

An ANOVA with the two experimental factors (orientation of the axis, henceforth *Axis*, with 12 levels, and skewing angle, henceforth *Skew*, with 7 levels) as within-subjects variables was performed on the data sets (RTs and error rates) of all subjects. For each subject, the average values across 10 repetitions were entered in this analysis. The effects of the orientation of the virtual lines (henceforth *Virtual Lines*, with 12 levels) which results from the combination of axis and skew, were analyzed in separate one-way ANOVAs (with means across 70 repetitions).

In addition to the ANOVAs analyzing the general effects, some more specific analyses such as trend analyses were performed. Furthermore, the mental rotation and oblique effects were tested by a priori comparisons. Two alternative mental rotation accounts are viable. First, it might be that all orientations different from V are mentally rotated back to V, but only CCW, so that an orientation of 75° has to be rotated over 165° (see Figure 2A). Although this might seem a strange option, we think it is not more so than the alternative that assumes the shortest route (CW or CCW). For how does one know in what direction one has to rotate unless one knows the axis orientation already? But then mental rotation is simply superfluous. A second, more often assumed variant of this account would be a mental rotation back to V, but both CW and CCW, so that an orientation of 75° has to be rotated over only 15°. Both of these mental rotation accounts, further denoted by *Full Mental Rotation* and *Shortest Mental Rotation*, respectively, were tested by selecting different contrast coefficients.

Likewise, two alternative oblique effects are viable. First, one can test the following order of increasing difficulty: V, H, main obliques (45° and 135°), and other obliques (15°, 30°, 60°, 75°, 105°, 120°, 150°, and 165°). A second, equally plausible variant of an oblique effect would predict that 75° and 105° behave somewhat like V, and 15° and 165° behave somewhat like H (Dick & Hochstein, 1989). This variant would result in the following order of increasing difficulty: V ± 15°, H ± 15°, main diagonals (45° and 135°), and remaining obliques (30°, 60°, 120°, and 150°). Again, both of these oblique effects, referred to as *VH Effect* and *VH ± Effect*, respectively, were tested by selecting the appropriate contrast coefficients. In interpreting the psychological relevance of the statistical significances associated with all of these trend analyses and a priori comparisons, one has to pay attention to the rank ordering of the means. It might be that a particular effect (e.g. Shortest Mental Rotation) is statistically reliable, but not supporting the prediction, because the implied rank order is reversed (e.g. H better that O better than V).

EXPERIMENT 1

We have three aims with this experiment. The first is to examine the effects of the orientation of the axis on the detectability (error rates and RT) in dot patterns with BS at more levels than in all previous studies. In particular, we are interested in the relative difficulty of symmetries about axes that are intermediate between the four basic axes (V, H, L, and R), because this allows a more specific test of the contrasting oblique and mental rotation effects. On the basis of the literature reviewed above, we expect that the results will support the oblique effect account. The second aim of this experiment is to determine the relative contribution of axis and virtual lines to the orientational effects in symmetry detection by an independent manipulation of both factors. Some of the data reviewed above indicate that the effect of the virtual lines connecting the symmetrically positioned elements might be stronger than suggested by the present literature, which has neglected to consider it separately.

The third and final aim concerns the component processes in symmetry detection. In studies of BS, the two most often distinguished component processes are selection of a possible axis and evaluation of symmetry about it. As indicated above, the problem with this account is that the postulated component processes seem to be cooperative. In SS, the two component processes are not so mutually reinforcing. Because the virtual lines are not orthogonal to the axis of symmetry, finding the axis does not guarantee the orientation in which the symmetric positions can be checked. Likewise, finding the virtual lines does not guarantee that there is an axis orthogonal to their orientation. In other words, a third component process seems to be necessary in the detection of SS. When the axis-based route is followed, one has to find the orientation of the virtual lines to know in which orientation one has to check for pointwise correspondence. Alternatively, when the virtual-lines-based route is followed, one has to find the orientation of the axis that runs somewhere through them. The purpose of this experiment is to explore the effects of this additional component process.

In general, we expect an increase in the time that is required to detect SS. Moreover, due to the increased uncertainty, higher error rates are also expected.

Results

Response Times. The average RT across all correctly responded symmetric patterns and all subjects is 3242 msec ($SD = 1631$). This gives an idea of the difficulty of the task. The overall two-way ANOVA yields a significant main effect of Skew, $F(6, 30) = 15.26$, $p < 0.00001$, and a significant Axis × Skew interaction effect, $F(66, 330) = 4.34, p < 0.00001$. The main effect of Axis is not significant [$F(11, 55) = 1.30, p > 0.24$]. The significant Axis × Skew interaction effect is caused by the fact that the effect of the orientation of the axis was completely different at different levels of the skewing angle. As described in the General Method section, the predictions of the mental rotation and oblique effects have been tested separately for the case of Skew = 0° (i.e BS) by a priori comparisons with different contrast coefficients. Full and Shortest Mental Rotation were not statistically significant [$F(1, 5) = 3.94$ and 3.67, both $p > 0.10$]. More reliable were the oblique effects, $F(1, 5) = 11.78$ and 6.07, $p < 0.05$ and 0.06, for the VH and VH ± Effect, respectively.

The one-way ANOVA on the total data set shows a reliable effect of Virtual Lines, $F(11, 55) = 5.90, p < 0.00001$. In Figure 4A, the results for the different orientations of axes (solid line) and virtual lines (dotted line) are plotted together to make a visual comparison easier. Trend analysis reveals only one significant trend in the effect of Virtual Lines, namely, the quadratic effect, $F(1, 5) = 26.54$, $p < 0.005$. This means that the RTs for the correct identification of patterns with BS and SS increase linearly as a function of the deviation of the virtual lines connecting the symmetrically positioned elements from H, CW, or CCW.

Error Rates. The average number of errors made per pattern across all levels of axis orientation and skewing angle and across all subjects is 0.63 ($SD = 0.31$). This gives an idea of the general difficulty of the task (e.g. this error rate could be the result of all subjects requiring 63% of the patterns to be repeated once to be able to classify them correctly). The overall two-way ANOVA yields significant main effects of Axis, $F(11, 55) = 2.04, p < 0.05$, and of Skew, $F(6, 30) = 19.53, p < 0.00001$, as well as a significant Axis × Skew interaction effect, $F(66, 330) = 6.99$, $p < 0.00001$. Again, the effect of the orientation of the axis is completely different at different levels of the skewing angle. For the patterns with BS (i.e. Skew = 0°), the mental rotation effects were not significant [$F(1, 5) = 3.87$ and 3.74, both $p > 0.10$]. In contrast, the oblique effects

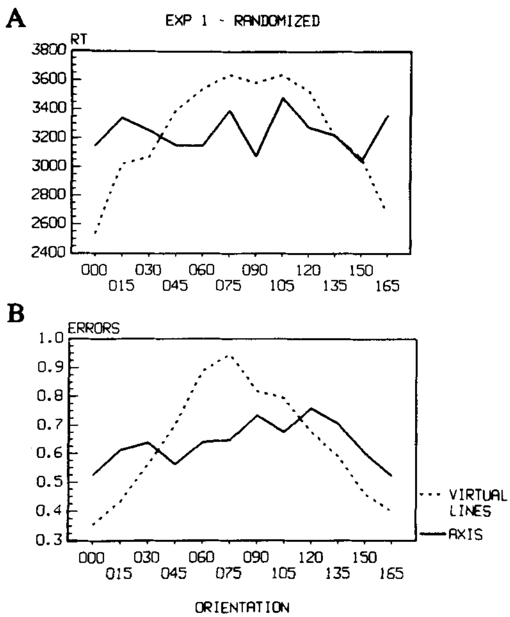


FIG. 4. Effects of the orientation of axis (solid lines) and virtual (dotted) lines in Experiment 1 (with randomized trial order). (A) Results for response times (RT measured in msec). (B) Results for error rates.

were reliable, $F(1, 5) = 11.99$ and 8.56, both $p < 0.05$, for the VH and VH ± Effect, respectively.

The one-way ANOVA on the total set of error data shows a reliable effect of Virtual Lines, $F(11, 55) = 12.49$, $p < 0.00001$ (see Figure 4B, dotted line, and compare with the solid line for the effect of Axis). Trend analysis shows that the effect of Virtual Lines is mainly quadratic and somewhat quartic, $F(1, 5) = 23.82$ and 14.13, $p < 0.01$ and 0.05. This means that the number of errors made for the identification of patterns with BS and SS increases linearly as a function of the deviation of the virtual lines from H, CW, or CCW, except for the V orientation, which yields better results than expected on the basis of linearity.

Discussion

Perhaps the most surprising result of this experiment is that the RT to detect BS and SS in a dot pattern does not depend on the orientation of its axis. Moreover, although the effect of the axis on the error rates is significant, it is different from previous research in that the H patterns yield the smallest error rates. Thus, it seems that the classically found orientational effects on symmetry detection (i.e. as measured with RTs and error rates) can be made to disappear or be changed completely by skewing the symmetry. Indeed, when the effects of the axis are sorted out for the different levels of skewing angle, it appears that the most commonly found orientational effects are replicated for the patterns with BS: V is easier than H, which is easier than O. More specifically, with respect to the first aim of this experiment—namely, to test the issue of mental rotation versus oblique effect at more levels of the axis-orientation variable—it is clear that the intermediate axes (15°, 30°, 60°, etc.) behaved more as expected on the basis of the oblique effect account than on the basis of the rival mental rotation hypothesis.

With respect to the second aim of this experiment—namely, to determine the relative contribution of axis and virtual lines to the orientational effects in symmetry detection—the results are very straightforward. When both factors are manipulated independently by using SS in addition to BS, the orientational effects of the virtual lines on RTs and error rates are much stronger than those of the axis (see Figure 4 for a direct comparison). More specifically, the symmetry of a dot pattern is harder to detect (i.e. it requires more time and it causes more errors) when the virtual lines connecting the symmetrically positioned dots deviate more from H, both CW and CCW. As an example, the average RT for the patterns with V virtual lines is about 1000 msec longer than for the patterns with H virtual lines, and the error rates were something like three times higher.

Apart from the role of SS in disconfounding the orientational effects of axis and virtual lines, it is clear that skewing has also an important contribution to the study of component processes in symmetry detection (i.e. the third aim of this experiment). In fact, the large increase on RTs and error rates caused by skewing can be seen as evidence for an additional component process, which takes a lot of time, something like 1000 msec for every 15° angle deviation from orthogonality, both CW and CCW, and is very error-prone, doubling or even tripling the number of errors made per pattern. Preattentive detection of symmetry is completely disrupted by skewing.

EXPERIMENT 2

Unlike Experiment 1, where the trials were completely randomized across all factors in the design, we now use blocks of trials with the orientation of the axis being constant within the blocks and varying between the blocks. This manipulation serves two purposes. First, with respect to the orientational effects, we want to find out if the results of Experiment 1 are due to the procedure that forced the subject to search for an axis and for an orientation in which the point-by-point comparisons have to be made (i.e.

the virtual lines) for every individual trial separately. Perhaps the effects of axis orientation diminish or change because the third component process is more demanding. Using BS only, Pashler (1990) has shown very recently that the orientational effects remain the same even after cuing the axis.

Secondly, with respect to the component processes, Experiment 2 permits an estimation of the duration of one of the classically postulated component processes, namely the selection of a possible axis (e.g. Bruce & Morgan, 1975; Palmer & Hemenway, 1978; Royer, 1981). If the blocks contain only random patterns and symmetric patterns with a particular axis orientation, and if a block of experimental trials is preceded by a small series of practice trials allowing the subjects to know the orientation of the axis to be expected, then the component process of selecting a potential axis about which the symmetry has to be checked is simply superfluous. The reduction in RTs to be expected, therefore, can be considered as a valid estimate of its duration. In his experiments on the detection of BS, Pashler (1990) has found cuing effects of 33 msec in a paradigm with short presentation time and of 119 msec with unrestricted exposure duration. Of course, this estimate cannot be generalized to the detection of SS. In addition to the effect of this blocking manipulation on RTs, we expect a decrease of the error rates because of the reduction in the number of error-prone component processes.

Results

Response Times. The average RT across all symmetric trials is 1682 msec (SD = 712). The overall two-way ANOVA yields reliable effects of Skew, $F(6, 30) = 11.04$, $p < 0.00001$, and the Skew × Axis interaction, $F(66, 330) = 3.36$, $p < 0.00001$, but not of Axis [$F(11, 55) = 1.50$, $p > 0.15$]. As in Experiment 1, the interaction implies that the effect of the axis orientation is different depending on the level of the skewing angle (which is confirmed by trend analyses). The predictions of the mental rotation and oblique effects have been tested separately for the patterns with BS. As in Experiment 1, the former are not reliable [$F(1, 5) = 3.24$ and 3.08, both $p > 0.13$], in contrast with the latter, $F(1, 5) = 68.41$ and 8.05, $p < 0.001$ and 0.05, for Full and Shortest Mental Rotation and VH and VH ± Effect, respectively.

The one-way ANOVA on the total data set yields a reliable effect of Virtual Lines, $F(11, 55) = 3.84$, $p < 0.001$ (see Figure 5A, dotted line and compare with the solid line representing the Axis effect). The trend analysis reveals only one reliable trend, namely, the quadratic one, $F(1, 5) = 6.58$, $p < 0.05$. As in Experiment 1, this means that there is a linear increase in the RTs caused by the increase in the deviation of the orientation of the virtual lines from H, both CW and CCW.

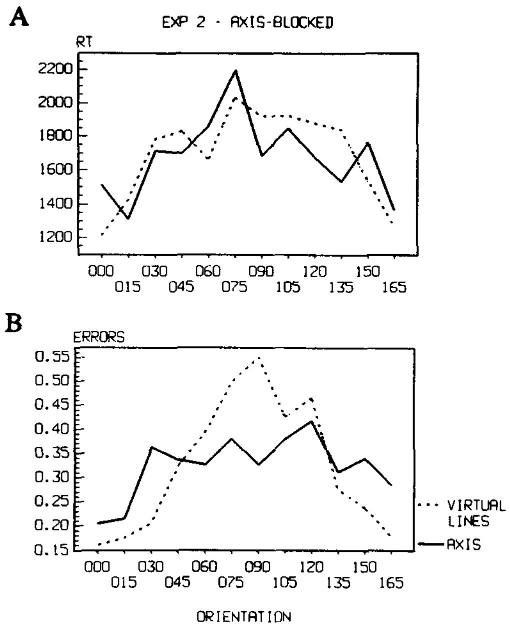


FIG. 5. Effects of the orientation of axis (solid lines) and virtual (dotted) lines in Experiment 2 (with axis blocking). (A) Results for response times (RT measured in msec). (B) Results for error rates.

Error Rates. The average number of errors made per symmetric pattern is 0.32 (SD = 0.22). The overall two-way ANOVA shows significant main effects of Axis, $F(11, 55) = 1.99, p < 0.05$, and of Skew, $F(6, 30) = 13.18$, as well as a reliable interaction effect, $F(66, 330) = 3.98$, both $p < 0.00001$. With Skew = 0° (i.e. BS), the Shortest Mental Rotation and the VH Effect are statistically significant, $F(1, 5) = 7.90$ and 18.44, $p < 0.05$ and 0.01, respectively, in contrast to the VH ± Effect, which is only marginally significant, $F(1, 5) = 6.03$, $p < 0.06$, and Full Mental Rotation, $F < 1$.

The one-way ANOVA on the error data set indicates a reliable effect of Virtual Lines, $F(11, 55) = 5.90$, $p < 0.00001$ (see Figure 5B, dotted line, and compare with the solid line for the Axis effect). Trend analyses show that the effect of Virtual Lines is quadratic and quartic, $F(1, 55) = 10.66$ and 3.63, both $p < 0.05$.

Discussion

The main purpose of grouping the trials into blocks with constant axis orientation was to investigate whether the effects of orientation found in Experiment 1 were due to some peculiar procedural details. In general, however, the same conclusion is reached in Experiment 2: the orientational effects that have been found in previous research are restricted to BS only. In a set of patterns including non-zero skewing, the orientational effects change drastically. Overall, H patterns yield the best results (i.e. shortest RTs and lowest error rates), with the other axis orientations causing a foremost linear increase in both dependent measures with increasing deviation from H, both CW and CCW. Note, however, that there is an important exception to this, caused by the fact that V patterns are easier than expected on the basis of a linear relation between deviation from H and the dependent measure. Furthermore, at different levels of the skewing angle, the rank orderings of the axis orientations are fundamentally different. When the data are sorted out for BS only, it appears that V patterns yield the best results again, followed by the H patterns and the O patterns.

A more specific goal of Experiment 2 was to find out whether the relatively larger contribution of the virtual lines to the orientational effects that were found in Experiment 1 could be made to disappear by axis blocking. Inspection of Figure 5 allows a direct comparison of the relative contributions of axis (solid lines) and virtual lines (dotted lines). As can be seen, for the RTs (see Figure 5A), the differences caused by the orientation of the axis are more or less as large (though not reliably) as those caused by the orientation of the virtual lines. So, the contribution of the axis can be enlarged by blocking the trials accordingly. However, for the error rates (see Figure 5B), the effect of the orientation of the virtual lines is still much more pronounced than that of axis orientation.

With respect to the component processes in symmetry detection, the decrease in average RT and error rate caused by axis blocking in Experiment 2 can be used to estimate the relative contribution of axis selection (i.e. the first component process). Indeed, the fact that the symmetric patterns in a particular block of trials all have the same axis orientation makes the process of selecting a potential axis superfluous. This reduces both the RTs and the error rates considerably. Although the exact value cannot be taken too literally, the difference between the mean RTs in Experiment 1 and 2 (i.e. 1560 msec) can be interpreted as an estimation of the duration of selecting a potential axis, given this particular set of experimental circumstances.

EXPERIMENT 3

In Experiment 3, we manipulate the orientation of the virtual lines between blocks, keeping it constant within blocks. The decrease in RTs and error rates that should result from this blocking (compared with Experiment 1) will reveal the duration and error-proneness of the component process necessary to find the orientation of the virtual lines (i.e. the orientation of the point-by-point comparisons to be made to check the symmetry after having selected a potential axis). Furthermore, it is interesting to see what happens with the relative contribution of the orientation of axis and virtual lines. In principle, two changes are plausible and not mutually exclusive. On the one hand, it might be that the effect of axis orientation increases because the main aspect of the patterns that has to be found to detect the potential symmetry is the axis that might be connecting the midpoints of the uniformly oriented virtual lines. On the other hand, it might be that the effect of virtual-line orientation increases, because it is possible to focus one's attention more consciously to it as a cue enabled by the blocking. This possibility is quite likely, given the fact that the orientation of the axis has this kind of cuing effect in Experiment 2 (especially on the RTs).

Results

Response Times. The average RT for the correctly responded symmetric patterns, across all kinds of symmetry and all subjects, is 2683 msec ($SD = 1350$). The two-way ANOVA on the RT data shows significant effects of skew, $F(6, 30) = 11.66$, and of the Axis × Skew interaction, $F(66, 330) = 3.06$, both $p < 0.00001$. The main effect of axis does not reach significance [$F(11, 55) = 1.40, p > 0.19$]. As in the previous experiments, the effects of the orientation of the axis are quite different at the different levels of the skewing angle. The prespecified comparisons to test the mental rotation and oblique effects all yield reliable results (although the latter are more pronounced) when the patterns with BS are considered separately, $F(1, 5) = 9.86$, 11.25, 26.00, and 50.03, $p < 0.05$, 0.05, 0.005, and 0.005, for Full and Shortest Mental Rotation and for VH and VH ± Effect, respectively.

The ANOVA with Virtual Lines as a factor yields a reliable effect, $F(11, 55) = 4.73, p < 0.0005$ (see Figure 6A, dotted line and compare with the Axis effect, solid line). Trend analysis shows that the effect of the orientation of the virtual lines is quadratic with marginally significant linear and sextic components, $F(1, 5) = 10.28$, 6.32, and 5.34, $p < 0.05$, 0.06, and 0.07, respectively. Notice the decrease in the RTs associated with the patterns with V virtual lines.

Error Rates. The average error rate for the symmetric patterns, across all kinds of symmetry and all subjects is 0.36 ($SD = 0.19$). The two-way ANOVA shows that all effects are reliable: $F(11, 55) = 3.21, p < 0.005$, for the main effect of Axis, $F(6, 30) = 20.97, p < 0.00001$, for the main effect of Skew, and, finally, $F(66, 330) = 2.77, p < 0.00001$, for their

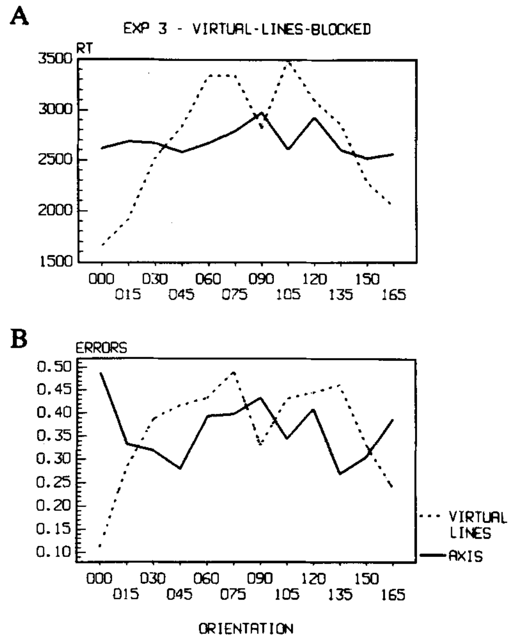


FIG. 6. Effects of the orientation of axis (solid lines) and virtual (dotted) lines in Experiment 3 (with virtual lines blocking). (A) Results for response times (RT measured in msec). (B) Results for error rates.

interaction. For the patterns with BS, a priori comparisons reveal that only the oblique effects are reliable, $F(1, 5) = 7.64$ and 6.98, for the VH and VH ± Effect, respectively, both $p < 0.05$.

The one-way ANOVA shows a significant effect of Virtual Lines, $F(11, 55) = 3.77, p < 0.001$ (see Figure 6B, dotted line and compare with the results for Axis, solid line). Trend analysis specifies that the effect of Virtual Lines is foremost quadratic and linear, with small cubic and quartic components, $F(1, 5) = 26.11$, 25.08, 12.19, and 4.40, $p < 0.005$, 0.005, 0.02, and 0.09, respectively. The latter trend is caused by a decrease in the error rates for patterns with V virtual lines.

Discussion

In general, the kinds of effects found in Experiment 3 are similar to those observed in Experiments 1 and 2. Once again, it appears that the orientational effects that have been reported in the literature are restricted to BS. For the larger set of symmetric patterns (i.e. with non-zero skewing), the effects of axis orientation on RTs disappear, and they change dramatically for the error rates (i.e. V and H patterns yield the most errors).

With respect to the more specific aims of this experiment, it is interesting to consider the effects of blocking the orientation of the virtual lines. As in Experiment 2, the effect of axis orientation is reduced in comparison with Experiment 1. This might appear somewhat surprising, because the virtual lines have a constant orientation in a particular block of trials which still requires subjects to find an axis (i.e. the straight line connecting the midpoints of the uniformly oriented virtual lines). However, as suggested above, the increased importance of axis orientation in Experiment 2 may be caused by the axis blocking, which allows the subjects to focus on the orientation of the axis more consciously. The plausibility of this interpretation is enhanced by the fact that a similar increase in the importance of the orientation of the virtual lines is found in Experiment 3 with the blocking on that factor.

Still further evidence for the attention-regulation effect is provided by a quite subtle difference between the pattern of results in the first two experiments and in Experiment 3. In Experiments 1 and 2, the effect on RTs and error rates caused by the orientation of the virtual lines is almost purely quadratic, or, in other words, a linear increase in the dependent measure is associated with the deviation of the orientation of the virtual lines from H, both CW and CCW. In Experiment 3, however, the quadratic trend is accompanied by reliable higher-order components caused by the decrease when the patterns contain V virtual lines. This relative V advantage, which is clearly visible in the dotted lines in Figure 6, is completely absent in the comparable Figures 4 and 5. It seems that the oblique effect (worse performance for the orientations different from V and H) is playing a larger role when the attention is focused on the particular orientation.

Another principal aim of blocking the orientation of the virtual lines was to quantify the contribution of the third component process, namely, the selection of the orientation of the point-by-point comparison process (i.e. the one that is absent when only BS is studied). Both the RTs and the error rates were reduced by using blocks with constant instead of completely randomized virtual-line orientation. The fact that the reduction for the RTs is smaller in Experiment 3 than in Experiment 2 might seem contrary to the data on the relative contribution of the orientations of axis and virtual lines to the orientational effects. However, the reduction in the error rates caused by the blocking is similar in Experiments 2 and 3. This indicates that, although the process of selecting the orientation of the point-by-point comparisons does not take a great deal of time, it is an important source of errors being made.

In fact, this is consonant with the status of the virtual lines in dot patterns. First, dot patterns allow a huge number of virtual lines to be "constructed", and the chances that some dots are "connected" incorrectly (i.e. not with their symmetrically positioned partner) are considerable, especially in patterns with large skewing angles. In addition, although our visual system is well equipped for orientation measurement (e.g. finely tuned nerve cells devoted to it in several different cortical areas), it is quite natural to assume that this orientation measurement is much harder with virtual lines defined by two dots (endpoints) only. As a consequence, two virtual lines being—within a quite broad range—more or less parallel by accident might already be taken as a possible orientation for the point-by-point comparisons. In summary, blocking the orientation of the virtual lines does not yield a large reduction in RT, because not much time is normally devoted to its selection, whereas it does produce a large decrease in error rate, because its selection is normally very error-prone.

EXPERIMENT 4

The comparison of the data from Experiment 2 (axis blocked) and 3 (virtual-lines blocked) with those of Experiment 1 (random order) has suggested that blocking on each factor enlarges its effect. On the other hand, these manipulations make certain component processes superfluous—namely, the selection of an orientation of axis and virtual lines for the point-by-point comparison, respectively. Naturally, this leads to a significant decrease in RTs and error rates. Although the combination of these patterns of results might appear somewhat contradictory, it was suggested above that it is interpretable in terms of attention focusing. In Experiment 4, we investigated the effects of blocking factors (axis and virtual lines) at the same time.

Results

Response Times. The average RT for the correctly responded symmetric patterns, across all kinds of symmetry and all subjects, is 1808 msec ($SD = 785$). The two-way ANOVA yields (more or less) reliable results for all effects: $F(11, 55) = 1.88$, $p < 0.07$, for the main effect of Axis, $F(6, 30) = 10.19$, $p < 0.00001$, for the main effect of Skew, and $F(66, 330) = 2.51$, $p < 0.00001$, for their interaction. The effects of the orientation of the axis are specified by separate a priori comparisons for the patterns with BS. These tests show that only the oblique effects are reliable, $F(1, 5) = 42.83$ and 12.82, $p < 0.005$ and 0.05, for the VH and VH ± Effect, respectively.

The ANOVA with Virtual Lines as a factor, once again, yields a reliable effect, $F(11, 55) = 4.12$, $p < 0.0005$ (see Figure 7A, dotted line and compare with the solid line for the Axis effect). Trend analysis shows that the Virtual Lines effect is linear, quadratic, and quartic, $F(1, 5) = 8.49$, 9.00, and 8.25, respectively, all $p < 0.05$.

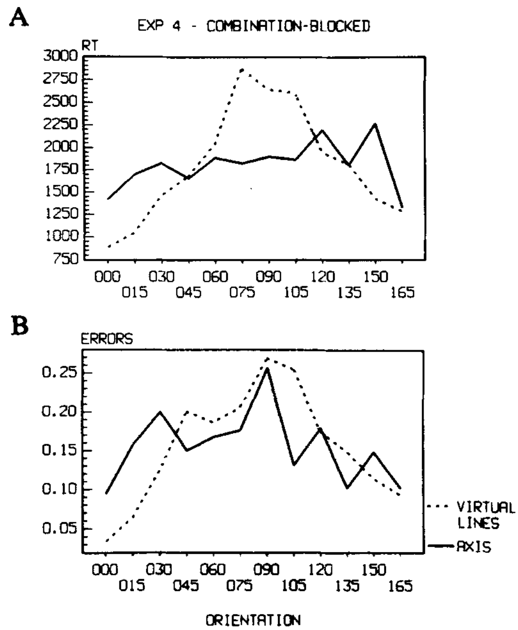


FIG. 7. Effects of the orientation of axis (solid lines) and virtual (dotted) lines in Experiment 4 (with combination blocking). (A) Results for response times (RT measured in msec). (B) Results for error rates.

Error Data. The average error rate for the symmetric patterns, across all kinds of symmetry and all subjects, is 0.15 ($SD = 0.12$). The two-way ANOVA with Axis and Skew shows that all effects are (more or less) reliable: $F(11, 55) = 1.92$, $p < 0.06$, for Axis, $F(6, 30) = 9.30$, $p < 0.00001$, for Skew, and $F(66, 330) = 2.54$, $p < 0.00001$, for their interaction. Despite the small error rate for the patterns with BS, the comparisons testing mental rotation and oblique effects yield one significant result, $F(1, 5) = 17.57, p < 0.01$, for the VH Effect. This is due to the fact that whenever an error is made, it occurs for bilaterally symmetric patterns with the symmetry axis oriented obliquely.

The one-way ANOVA reveals a reliable effect of Virtual Lines, $F(11, 55) = 3.64$, $p < 0.001$, shown in Figure 7B (dotted line), where it can be compared with the Axis effect (solid line). Trend analysis indicates that the Virtual Lines effect is quadratic with a small linear component, $F(1, 5) = 11.62$ and 5.09, $p < 0.05$ and 0.08, respectively. The quadratic trend means that more errors are made as a function of the deviation from H of the orientation of the virtual lines, both CW and CCW.

Discussion

The basic effects found in the previous experiments are once again replicated. First, the classically observed orientational effects are restricted to BS. Averaged across all skewing angles, the effects of axis orientation are different from those found in the literature (e.g. highest error rates for V). Furthermore, the effects of axis orientation are completely different at different skewing angles. Moreover, the effect of the orientation of the virtual lines is again very pronounced. All this indicates that the confounding between the two orientations (axis and virtual lines) in the studies restricted to BS is unjustified.

More interesting are the specific results of the combination blocking (Experiment 4) in comparison with the blocking on the separate factors (Experiments 2 and 3) and the absence of blocking (Experiment 1). With respect to the orientational effects, it appears that the blocking on two factors results in increased effects of both. As suggested above, this is probably due to the fact that subjects are able to focus their attention on the factor that is blocked. The results of Experiment 4 show that it is possible to focus on both factors simultaneously. In principle, both effects could also increase as a result of focusing on both factors alternatively from trial to trial. However, this alternative is rather unlikely, given that the increase in Experiment 4 for the effect of axis orientation is comparable to Experiment 2, whereas the increase for the effect of the orientation of the virtual lines is comparable to Experiment 3.

With respect to the component processes, the only one that is required in Experiment 4 is to check whether the dot patterns contain a specific orientational uniformity (i.e. virtual lines) and midpoint collinearity (i.e. axis), the orientations of which are known. Therefore, the subjects in Experiment 4 do not have to select a potential axis orientation nor the orientation in which to make the point-by-point comparisons (i.e. the virtual lines). The reduction in the dependent measures caused by this combination blocking is quite large, though smaller than expected on the basis of additivity of factors. For the RTs, the grand mean of Experiment 4 is even somewhat larger than in Experiment 2. However, the exact values of the RTs cannot be taken too literally as estimates for the duration of component processes, especially because the smaller number of trials (only four) in the practice block may have been insufficient to provide the subjects with accurate knowledge of the exact condition.

GENERAL DISCUSSION

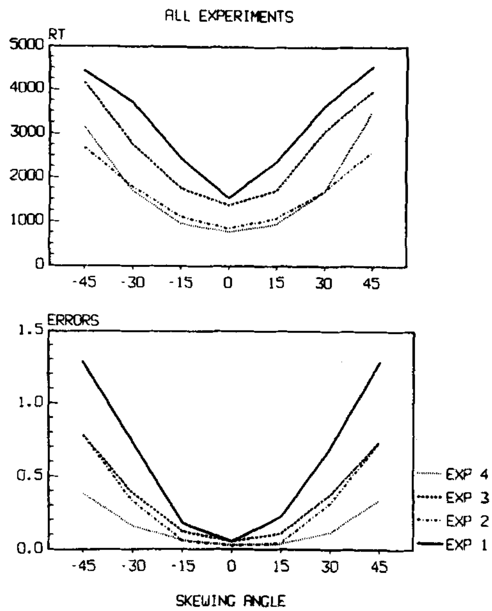
We here present some comparisons between the four experiments graphically as a kind of summary of the data, useful for reference purposes in the discussion. In line with the main purpose of this study, the discussion focuses on orientational effects and component processes in symmetry detection and the use of skewing with respect to these issues.

Skewing

The major new variable introduced in this set of experiments is skewing angle. We have used this manipulation to disconfound two potentially contributing factors to the orientational effects on symmetry detection (i.e. axis and virtual lines) and to disentangle the role of several component processes in symmetry detection (i.e. axis selection and point-by-point evaluation). As shown in Figure 8, where the results of the four experiments are brought together, the effect of this variable is dramatic, on the RTs (Figure 8A) as well as on the error rates (Figure 8B).

Averaged across experiments, the RTs (expressed in msec) to detect the symmetry in a dot pattern, for skewing angles varying from 45° CCW over 0° to 45° CW, are 3611; 2485; 1563; 1131; 1522; 2515; and 3648; respectively. This means, roughly, that the RTs increase by approximately 500 msec for the first 15° skewing and by approximately 1000 msec for every additional 15° increase in the skewing angle. Averaged across

A



B

FIG. 8. Effects of skewing angle on response times (RT measured in msec, represented in A) and errors (B) for all experiments. The comparison between experiments shows that blocking has a small effect for bilateral symmetry (i.e. Skew = 0°) and a gradually larger effect for skewed symmetry (i.e. Skew > 0°).

experiments, the respective error rates are 0.809, 0.397, 0.100, 0.034, 0.098, 0.373, and 0.773. This means that the number of errors being made in detecting SS in a dot pattern almost triples with each 15° skewing angle.

It is interesting to see that the differences between the experiments become larger with increasing skewing angle. For the RTs on patterns with BS, the difference is less than 1000 msec, whereas it becomes more than 1500 msec for Skew = 15° and more than 2000 msec for Skew = 30° or 45°. This increasingly larger difference between experiments is even more pronounced with the error rates. Having a cue about the orientation of axis, virtual lines, or even both, helps particularly when the patterns contain SS, especially with the large skewing angles, but it does not seem to make a big difference for BS. The focusing of attention to a particular characteristic in a display (e.g. the orientation of the axis or the virtual lines) appears to play only a minor role in the detection of BS.

Orientational Effects

One of the aims of this study was to investigate the detectability of BS with the orientation of the axis manipulated at more levels than in previous investigations. Averaged across experiments, the rank ordering of axis orientations according to accuracy data clearly supports an oblique effect, as found by Barlow and Reeves (1979). When the axis was oriented V, not a single error was made (out of a total number of 240, i.e. 10 patterns × 6 subjects × 4 experiments). The next fewest errors were made when the axis was H (i.e. 0.0040), followed by the error rate obtained when the axis deviated only slightly from V (i.e. by 15°, both CW and CCW), namely, 0.0125. Next, the error rates were 0.0395 for the diagonals (L and R), 0.0460 for the axes deviating slightly from H, and, finally, 0.0520 for the other oblique orientations (i.e. 30°, 60°, 120°, and 150°).

Although axis orientations show a somewhat different rank ordering according to RTs, the basic trends remain the same: the V patterns were easiest (746 msec), followed by the small deviations from V (937 msec) and the H patterns (954 msec). The other orientations yielded much longer RTs: 1294 msec for the main diagonals, 1259 msec for the axes deviating slightly from H, and, finally, 1222 msec for the other oblique axes. The latter values are not in the right order to be in agreement with the fine oblique effect predictions (cf. introductory section), but the gross trends in the RT data are certainly not supportive of the mental rotation account (Corballis & Roldan, 1975). In addition, even the fine predictions are corroborated by the error data, so it seems fair to conclude that the effect of axis orientation on the detectability of BS follows an oblique effect instead of a mental rotation effect. Furthermore. this conclusion is supported by all experiments separately, in the sense that all RT data sets show highly reliable oblique effects as tested by the prespecified comparisons (cf. General Method section).

An additional purpose of this study was to determine the relative contribution of axis and virtual lines to the orientational effects on the detection of symmetry. We used SS to permit a disconfounding of both factors. In line with some of the indirect evidence reviewed above (e.g. Bornstein & Stiles-Davis, 1984; Jenkins, 1983), the effect of virtual lines is important enough to be studied separately. In fact, the effect on the RTs and the error rates caused by the orientation of the virtual lines is more pronounced than the one caused by axis orientation; this is immediately clear when comparing the dotted lines with the solid lines in Figures 4–7. Both for the RTs (A panels) and the error rates (B panels), the curves for the axis orientation (solid lines) are much flatter than those for the orientation of the virtual lines (dotted lines). Statistical evidence confirms this visually obtained conclusion. In addition to the fact that the effects of the orientation of the virtual lines are more pronounced, they are much more stable also. In the eight available data sets (RTs and error rates for four experiments), all Virtual-Line effects systematically show the same linear increase for all orientations deviating from H.

Comparing the results of the different experiments is revealing about the processes that contribute to the orientational effects. In Experiments 1 and 3, in which the subjects' attention was not cued to the orientation of the axis, this factor does not show reliable results for the RTs to detect the symmetry about that axis. Only in Experiments 2 and 4, in which the blocks contained patterns with constant axis orientation, have statistically significant effects on the RTs been observed. Therefore, it appears that, at least for the more general situation of non-zero skewing angles, the effects of axis orientation depend on a process of attention focusing. A similar effect occurs for the effects of the orientation of the virtual lines: in addition to the quadratic trends that are obtained very systematically, higher-order components are observed caused by the decrease for V-oriented virtual lines in the RTs in the experiments where that orientation is cued (i.e. Experiments 3 and 4).

It must be noted that, even in the cases where axis effects do occur (as with all error data), they are quite inconsistent. It seems that almost all relative rank orderings of the different axis orientations can be obtained (e.g. lowest error rates for H in Experiment 1 and for O in Experiment 3, highest error rates for V in Experiment 4, etc.). This confirms what could be expected from a closer look at the literature (e.g. Fisher & Bornstein, 1982; Jenkins, 1983, 1985; Pashler, 1990): the orientational effects on symmetry detection are not as simple and as universal as implicitly assumed when only a rough summary is given.

Still further evidence for the latter conclusion is provided by the fact that the effects of axis orientation are completely dependent on the skewing angle. In all experiments, the Axis × Skew interaction effect is highly reliable. A simple summary of this interaction, averaged across experiments, is represented in Figure 9. In addition to the fact that the effects of axis orientation on RTs (see Figure 9A) and error rates (see Figure 9B) are fundamentally different for BS (solid lines) and SS (both CW, thin lines, and CCW, dotted lines), it is interesting to see that they change quite predictably. The curves for CW and CCW skewing angles cross exactly at 90° (i.e. V axis), and they show a small but significant decrease at 45° (i.e. L axis) for the CCW skewing angles and at 135° (i.e. R axis) for the CW skewing angles. This is caused by the fact that the orientation of the virtual lines gradually approaches V in those cases. As noted above, this can be advantageous, particularly when attention is being paid to it (as in Experiment 3). The same task dependency had been observed previously (e.g. Jenkins, 1983).

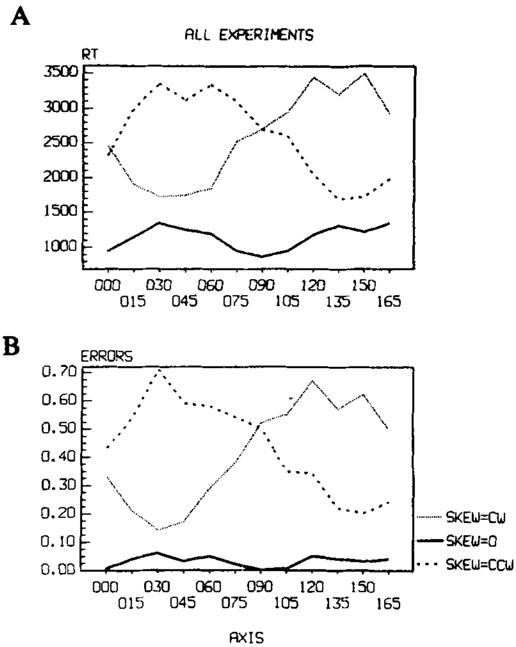


FIG. 9. Effects of axis orientation at different levels of skewing angle on response times (RT measured in msec, represented in A) and errors (B). Notice the difference between the effects at Skew = 0° (i.e. bilateral symmetry, solid lines) and the effects at clockwise (CW, thin lines) and counterclockwise (CCW, dotted lines) skewing angles (averaged across 15°, 30°, 45°), and the particular effects when the axis is 45°, 90°, and 135°. The results are averaged across experiments.

Component Processes

The review of the literature in the introduction showed that the distinction between two component processes, a global selection of a potential axis and a local point-by-point comparison to evaluate the symmetry about it, is a very common one. However, we noted that the details of this distinction and the manner in which the global stage operates exactly, are absolutely unclear, because two mutually reinforcing routes seem plausible. In the virtual-lines-based route, the orientational uniformity of the virtual lines that is characteristic of a symmetric display (Jenkins, 1983) is detected first, and a potential axis is postulated orthogonally to it. In the axis-based route, the axis defined by the midpoint collinearity that is also characteristic of a symmetric display (Jenkins, 1983) is detected first, and virtual lines indicating the orientation in which the point-by-point comparisons have to be made are postulated orthogonally to it. This description does not preclude the fact that both subprocesses must be cooperative in a sense, because the one cannot do without the other. On the one hand, to detect the orientation of the virtual lines implies "knowledge" about the way the elements are to be "connected"—hence, an axis about which the elements are positioned symmetrically. On the other hand, to detect the midpoint collinearity defining the axis requires that the symmetric positions have already been detected.

We have attempted to disentangle these cooperating subprocesses by introducing skewing in the displays. In SS, the selection of a potential axis does not automatically lead to a postulation of an orthogonal orientation for the point-by-point comparison process. Alternatively, the orientation of the axis of symmetry is not immediately given once the orientational uniformity of the virtual lines has been detected. An additional component process is required in the detection of SS—namely, the detection of the orientation in which the point-by-point comparisons have to be made when following the axis-based route, or, when following the virtual-lines-based route, the detection of the orientation of the axis that runs somewhere through them non-orthogonally. As indicated above, the effect of this third component process on the RTs and the error rates for the detection of the symmetry is quite large. Roughly, it causes an increase in the RTs of 1000 msec for every 15° skewing angle, and it makes the detection of the symmetry about three times more error-prone.

Although the exact quantitative values obtained in the different experiments cannot be taken too literally, it does seem clear that the estimation for the contribution of the selection of an orientation for point-by-point comparisons (on the basis of Experiment 3 something like 500 msec) is significantly smaller than the increase of approximately 1000 msec for every 15° skewing angle (based on the average across all experiments), attributed to this additional component process. It appears that skewing is doing more to symmetry detection process than simply adding another component process.

Towards an Explanation of Symmetry Detection

Based on the observation that skewing has an effect on the detection of symmetry that is larger than a mere addition of a component process and different from its effect on the processes that can be regulated by attention focusing (i.e. the selection of an orientation of axis and virtual lines), our suggestion is that skewing is disrupting the preattentive stage of global axis selection. The reason why this is so might be as follows: in BS, the elements are positioned in such a way that not only the individual elements are in symmetric positions about the axis. The virtual lines formed between two elements belonging together not because of the symmetry but because of their proximity have the same length and orientation as their corresponding virtual lines at the other side of the symmetry axis. This means that in BS the normal grouping processes that take place automatically lead to the detection of symmetry, because the possible relations confirm one another based on the Euclidean invariances in line lengths and orientations.

In SS, however, the Euclidean invariant relations between the element pairs in a dot pattern disappear as a consequence of the skewing. The remaining invariances, such as parallelism and collinearity (i.e. those under pure affine transformations), do not seem to be sufficient to enhance the symmetry detection. Skewing appears to be disruptive for the normal position-based grouping, because all distances and angles can be different. This failure of the preattentive grouping that normally occurs as a first stage in symmetry detection (as in all other perceptual processing, for that matter) forces the visual system to look explicitly for correspondences, which is much harder (takes more time and leads to more errors). Of course, with more natural connected instead of fragmented displays, other sources of information (such as convexity, which is also affine invariant) might be used.

Our data on the difference between BS and SS are not the only evidence for the role of invariants-based grouping in symmetry detection. The fact that multiple symmetry shows an advantage over single symmetry (e.g. Palmer & Hemenway, 1978; Royer, 1981) even when the subject's attention is devoted to the detection of a particular single symmetry (e.g. about a V axis) corroborates this line of reasoning. In addition, results obtained with different types of patterns such as vectorgraphs are indicative of the same principles (e.g. Dodwell & Caelli, 1985).

This account is, generally, in agreement with a recent suggestion by

Pashler (1990, p. 162): "that grouping principles already required for other visual functions could accomplish most of the work involved in detecting symmetry". However, his more specific proposal about a mechanism that requires confirmation of groupings at all spatial scales is quite unlikely given the facts about symmetry detection and spatial filtering (e.g. Julesz & Chang, 1979). Our suggestion is more closely related to work by Foster (1978; Foster & Kahn, 1985; Kahn & Foster, 1986), postulating that a fixed association exists between local features and the relations specifying the orientation and distance of one local feature to another.

Naturally, more work is needed to substantiate the above claim. In current research, we are developing a more specific and quantitative model of symmetry detection, explicitly based on the importance of invariances in the distances between elements in a display and the angles formed between element pairs. In addition, further research investigates the general role of grouping processes in symmetry detection (Locher & Wagemans, 1991) and, more specifically, the use of Euclidean and affine invariants (Wagemans, Van Gool, & d'Ydewalle, 1991).

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