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Coordinate Frame for Symmetry Detection and Object Recognition

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Can subjects voluntarily set an internal coordinate frame in such a way as to facilitate the detection of symmetry about an arbitrary axis? If so, is this internal coordinate frame the same as that involved in determining perceived top and bottom in object recognition and shape perception? Subjects were required to determine whether dot patterns were symmetric. Cuing the subjects in advance about the orientation of the axis of symmetry produced a substantial speedup in performance (Experiments 1 and 3) and an increase in accuracy with brief displays (Experiment 2). The effects appeared roughly additive, with an overall advantage for vertical symmetry; thus, the vertical axis effect is not due to a tendency to prepare for the vertical axis. The cuing advantage was found to depend upon the subject's knowing in advance the spatial location as well as orientation of the frame of reference (Experiment 4). The fifth experiment provided evidence that the frame of reference responsible for these effects is the same as the one that determines shape perception: Subjects viewed displays containing a letter (at an unpredictable orientation) and a dot pattern, rapidly naming the letter and then determining whether the dots were symmetric about a prespecified axis. When the top-bottom axis of the letter was oriented the same way as the axis of symmetry for the dots, symmetry judgments were significantly more accurate. Thus, the results suggest a single frame of reference for both types of judgment. The General Discussion proposes a theory of how visual symmetry may be computed, which might account for these phenomena and also characterize their relation to "mental rotation" effects.

Symmetry of visual patterns is often very salient for human observers. This fact is rather puzzling, and it has engendered speculation beginning with the writings of Mach (1886/1959). Logically speaking, the mechanisms that detect symmetry must perform a fairly specialized computation in which properties of particular regions in an image are somehow compared with properties of regions located in corresponding positions across a candidate axis of symmetry (for discussions of these mechanisms, see Barlow & Reeves, 1979: Jenkins, 1983; Julesz, 1971). What determines which axis or axes will be considered in this computation? And how does this determination interact with other ongoing visual functions such as object recognition? Previous research has found that symmetry is best detected about a vertical axis and that this preference is not subject to voluntary alteration (Corballis & Roldan, 1975). By contrast, voluntary alterations in the frame of reference for perceiving a scene have been found to powerfully affect shape recognition (Rock, 1973). In this article, the relation between these phenomena is explored, in an attempt to characterize the role of voluntary factors in the determination of a candidate axis for symmetry detection, and their relation to the internal frame of reference for shape, first described by Rock (1973), is also explored. In the rest of the introduction, the relation of shape perception to orientation is reviewed, and some basic issues about the relation of symmetry detection and orientation are described.

Orientation and Shape Perception

The orientation in which a pattern is presented can dramatically change its perceived shape. Such effects can be observed in several different experimental situations. First, when objects must be identified by an upright observer, tilting the objects produces substantial deleterious effects on performance (e.g., Dearborn, 1899; Jolicoeur, 1985). One can immediately confirm this by viewing some written text or a photograph of a face, upside down, and attempting to read the text or determine the expression on the face. Second, if unfamiliar shapes are presented at orientations far from upright, the ability to recognize them later when presented in their normal upright orientation is often greatly reduced (Rock, 1973). These findings indicate that perception of shape for purposes of object recognition and visual memory cannot be based solely on descriptions that are invariant with respect to rotation. If it were, the speed of object identification should be unaffected by rotation, and an unfamiliar object presented twice should appear just as familiar however it is rotated when viewed a second time, because its rotationally invariant description would, by definition, be unaltered.

The examples cited earlier involve changes in both retinal and environmental orientation of objects. Which form of disorientation causes the problems? The answer appears to be both. The difficulty of reading inverted text is still apparent when the text is upright in the environment and the observer is rotated, a fact that anyone can, with slightly more effort, confirm. Retinal orientation, however, is not the only factor

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influencing perceived shape. Rock (1973) reported an elegant set of experiments that demonstrated the effects of additional, environmental factors. He concluded that although perceived shape depends upon the assignment of top and bottom to an object, this assignment can be affected by the axis of gravitational vertical and by the presence of a frame surrounding the object. For instance, in one experiment, subjects' heads were tilted 45° to the right before the subjects viewed some unfamiliar objects. Subjects then attempted to recognize the objects, with their heads upright. Recognition performance was best when the objects were tested at the same environmental orientation of their original presentation, even though this meant that the retinal image was therefore rotated 45° from the initial presentation. How can this be accounted for? Rock proposed that when the subjects' heads are tilted, the mental representation of the shape depends upon assignment of a coordinate frame to the object, which is influenced by the gravitational and other environmental clues to the vertical. When subjects are tested with their heads upright, this internal reference frame is still oriented upright in the environment. Therefore, performance is best if the objects are presented and tested in the same absolute orientation in the environment.

One can account for the observations just described by proposing that perception of shape depends upon the orientation of an internal coordinate frame that is shifted by gravitational and other clues—shifted to an orientation that may depart somewhat from the retinal vertical. (Such an account must include the qualification that this is possible only within limits, indicated by the poor recognition performance produced by extreme departures from the retinal vertical.) This proposal, however, is still incomplete, because it neglects the fact that the orientation of the frame of reference is subject to direct voluntary control. Thus, following the classical Gestalt psychologists, Rock (1973) observed that phenomenal shape can be voluntarily changed, as when observers attempt to "imagine" that a particular portion of the figure is the top. This voluntary designation can occur even when the designated top is uppermost in neither retinal nor gravitational coordinates. This is the phenomenon observed in the well-known diamond/square ambiguity: A square with its edges running horizontally and vertically can, at will, be seen as a diamond that points either to the upper right or the upper left. Rock's interpretation of these observations is that the assignment of top and bottom to the figure is ordinarily determined by environmental cues but that these cues can nonetheless be overridden by voluntary control.

In summary, then, subjective perception of shape—as indexed by object identification and recognition memory—depends upon the imposition of an internal frame of reference that assigns subjective top and bottom to an object. The major axis of this frame can, within limits, be rotated so that it departs from the retinal vertical. This rotation is subject to direct voluntary control, but in the absence of such control, it tends to be governed by environmental cues. (The term *rotation* is not meant to necessarily imply a continuous process or to assert any relation to the process commonly termed *mental rotation*; this issue is discussed in the General Discussion.)

Symmetry and Coordinate Frames for Object Recognition—Why Should They be Linked?

I turn now to orientation and the perception of symmetry. There are several reasons to suspect that the detection of symmetry might be tied to the perception of shape and object recognition for disoriented objects. The facility with which symmetry is detected is itself somewhat puzzling from a functional standpoint. As Barlow and Reeves (1979) pointed out, though, symmetry is an especially useful cue to the identity of many different sorts of animals, which suggests an obvious evolutionary advantage for visual systems that are sensitive to it. Symmetry detection may serve some other functions closely related to this; for example, as the early Gestalt psychologists suggested (Wertheimer, 1958), it may serve as a grouping principle, aiding in the segregation of an object from its background—again, particularly in the important case of animals. It should be noted that with animals, the symmetry axis generally runs from the top of the creature to its bottom.

Taken together, these considerations suggest two plausible reasons for suspecting that the frame of reference for object recognition and the optimal axis for detection of symmetry might be tied to each other. First, the fact that the presence of symmetry is often a cue to an object's identity suggests that if it is computationally difficult to test for symmetry about more than one axis at once, it would be sensible to focus the testing on an axis that was predetermined to be the likely top-bottom axis of the object. Second, the fact that natural symmetry generally occurs about a top-bottom axis suggests that if symmetry was detected before an object had been identified, it would be sensible for the frame of reference for shape perception to be aligned with the axis of symmetry so that subjective top and bottom are at opposite ends of the axis. A version of this idea is incorporated in Marr's (1982) sketch of a computational account of vision. In Marr's scheme, detection of symmetry is cited as a primary cue to the proper assignment of a object-based coordinate frame onto the 2½-D sketch of an object, which permits it to be recognized without regard to its orientation in the 2½-D sketch.

Symmetry and Orientation—Empirical Findings

These considerations, then, suggest plausible functional bases for linkages between symmetry and the frame of reference for object recognition, and vice versa. Plausible functions for linkages do not establish the actual existence of linkages, however, so 1 turn now to the empirical data. The starting point for considering the problem is the old observation that symmetry about a vertical axis is more salient than symmetry about a horizontal axis (Mach, 1886/1959). This salience has a corresponding effect in objective detection performance with random-dot patterns. Julesz (1971) suggested that random-dot symmetry could hardly be detected at all when the axis was not vertical. Barlow and Reeves (1979) showed this to be false but confirmed that vertical symmetries are the easiest to detect. This could potentially reflect a constraint that is not alterable by expectations (or possible changes in an internal frame of reference), or it might just reflect a tendency for the internal frame of reference to be aligned with the retinal vertical in the absence of influences to the contrary.

This question was investigated by Corballis and Roldan (1975), who looked at performance in a task requiring subjects to determine whether a pattern of dots was symmetric. The asymmetric patterns, requiring a negative response, consisted of a pattern translated rather than reflected across the axis of symmetry ("repetitions"). In the first experiment, the orientation of the axis of symmetry ranged from 0° (vertical) to 135°, by 45° increments. The orientation was varied randomly from trial to trial. Reaction times (RTs) for positive (symmetric) displays increased from about 825 ms to about 950 ms as the orientation varied from 0 (vertical axis of symmetry) to 90 (horizontal axis of symmetry). Corballis and Roldan's second experiment was essentially the same as the first except that the orientation of the axis was varied between blocks and thus allowed subjects to anticipate the orientation in advance. The results were very nearly the same as in the previous experiment, and they showed at least as great an effect of orientation of the axis on RTs. If subjects had been able to rotate an internal frame of reference to match the anticipated orientation of the symmetry, a major benefit should have been found. Corballis and Roldan concluded from these two studies that subjects are "unable to prepare mentally for a given orientation by rotating an abstract frame of reference" (Corballis & Roldan, 1975, p. 225). Other experiments reported by Corballis and Roldan indicated that when subjects tilted their heads, the optimal symmetry detection performance tracked the retinal rather than the gravitational vertical.

From these results, then, it appears that detection of symmetry operates most efficiently when the axis of symmetry follows the retinal vertical, pure and simple. This suggests that the voluntarily controllable internal frame of reference for shape perception, posited by Rock (1973) must be unrelated to the selection of a candidate axis for symmetry judgment, because the internal frame of reference for shape is subject to voluntary control. However, before accepting this conclusion, it may be worth noting a peculiar feature of the methods used by Corballis and Roldan (1975). Each of their dot displays included not only the array of dots but also a plainly visible line marking the axis (see Figure 1A for an example of their displays). In short, the display itself explicitly cued the subject to the actual orientation of the axis. In view of this aspect of the experiments, the conclusion attributed to Corballis and Roldan above should perhaps be modified. What the results really indicate is that subjects are unable to prepare mentally for a given orientation in a way that provides any benefit above and beyond whatever may be provided by the simultaneous presentation of the axis along with the pattern.

This opens up several possibilities. On the one hand, subjects may, as Corballis and Roldan (1975) concluded, be quite unable to usefully prepare for particular orientations of the axis. But one should consider, on the other hand, the following alternative. When the dots are presented, an initial stage of perceptual processing may be necessary to obtain a usable representation of the dots and their locations. This representation may be required prior to the initiation of the symmetry analysis itself. When the displays also contain a line marking the axis of symmetry, as in Corballis and Roldan's experiments, this initial registration of the dots may operate simultaneously with the determination of the orientation of the line marking the axis of symmetry. If the latter step generally took less time than the former, then reaction times should be unaffected by whether the axis of symmetry was known in advance. Thus, the results of Corballis and Roldan's experiments do not rule out the possibility that advance notification could actually allow subjects to prepare an internal frame of reference. However, it should be noted that even if this is the case, then Corballis and Roldan's results nonetheless do indicate something important: that at least some of the advantage for the vertical axis is due to intrinsic factors, rather than set. Otherwise, the vertical advantage would have been abolished in the blocked axis condition.

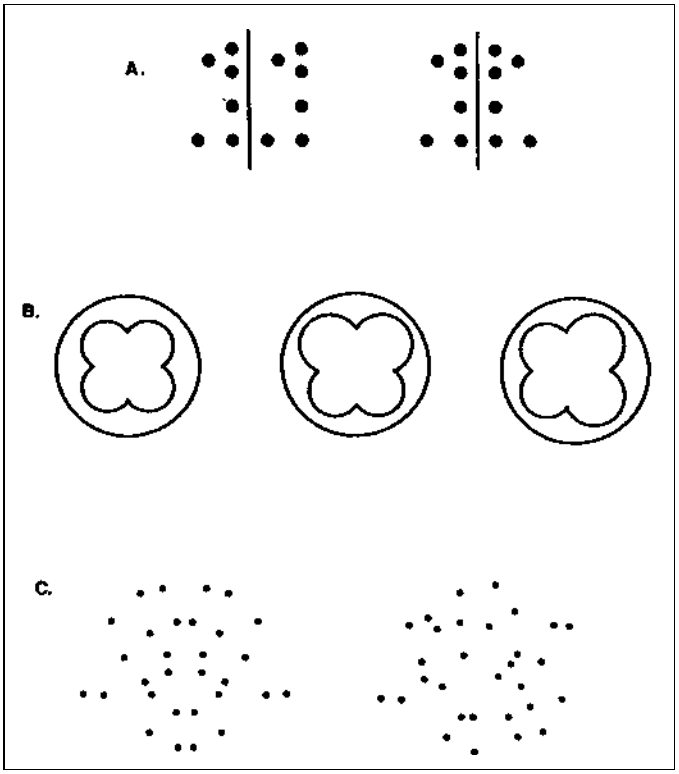


Figure 1. A: Symmetric and asymmetric figures from Corballis and Roldan. B: Comparison forms from Rock and Leaman. C: Approximate configurations of the symmetric and asymmetric displays in Experiments 1-4. (Displays in A are from "Detection of Symmetry as a Function of Angular Orientation" by M. C. Corballis and C. E. Roldan, 1975, *Journal of Experimental Psychology: Human Perception and Performance, 1*, p. 223. Copyright 1975 by the American Psychological Association. Printed by permission. Displays in B are from "An Experimental Analysis of Visual Symmetry" by I. Rock and R. Leaman, 1963, *Acta Psychologia, 21,* p. 174. Copyright 1963 by Elsevier Science Publishers, Physical Sciences & Engineering Division. Printed by permission.)

The second relevant line of research bearing on the issue of whether symmetry detection is affected by a voluntarily controllable frame of reference was reported by Rock and Leaman (1963). Those investigators asked subjects to decide whether the middle shape in Figure 1B or the right-hand shape appears more like the left-hand shape. Subjects overwhelmingly chose the middle shape. Rock and Leaman's account proceeds as follows: First of all, subjects' similarity judgments are primarily based on symmetry. The left-hand shape in Figure 1B is bilaterally symmetric. The symmetry of the middle shape about the vertical axis is a more salient symmetry than the symmetry of the right-hand shape about the horizontal axis. Thus, the former is seen as more similar to the left-hand shape than is the right-hand one, that is, more similar by virtue of having symmetry as a more salient feature. (This fits with the general observation, dating from Mach, 1886/1959, that symmetries about the vertical axis are more salient, and it fits with Corballis and Roldan's, 1975, findings as well.) The critical comparison, however, arose when Rock and Leaman had subjects view these three figures with their heads tilted 45°. Subjects still tended to select the middle shape as being more similar to the left-hand shape. Assuming that Rock and Leaman's account of the basis of the similarity judgments is correct, then if the salience of the symmetries were determined purely by the retinal orientation, subjects should have chosen the middle shape and the right-hand shape equally often. The results suggest, then, that symmetry detection is affected by an internal frame of reference, which is in turn generally governed by cues to environmental vertical, in just the way that shape recognition is.

The Rock and Leaman (1963) work is intriguing, but it is still far from conclusive, for several reasons. The method relies entirely on subjective measures rather than assessing symmetry detection performance directly. It seems plausible, but is hardly certain, that the similarity judgments are being determined by the relative salience of the horizontal and vertical symmetries. Even conceding this explanation for the subjects' behavior, the results do not tell us that the frames of reference for object recognition and symmetry detection are unitary, or indeed that the object recognition frame is being affected at all when subjects tilt their heads. At most, the results tell us that the symmetry frame, like the object recognition frame, can be influenced by gravitational or other clues to the environmental vertical.

The Present Approach

In order to understand the influence of frames of reference on symmetry detection, one needs to begin by determining whether symmetry detection performance is really unaffected by mental set, as Corballis and Roldan (1975) concluded. For that purpose, then, in the first three experiments I examined the detection of symmetry of dot patterns with or without providing subjects advance information about the axis of symmetry, in advance of each trial, either the axis itself or an uninformative warning pattern was presented to the subject. However, when the display itself was presented, the axis was never present.

There were several other deliberate departures from the methods used by Corballis and Roldan. First, displays here consisted of 30 small dots rather than the 12 large blobs used by Corballis and Roldan (1975, see Figure 1C for examples). Second, the nonsymmetric displays were simply random configurations of dots within the display boundaries rather than the repetition displays used by Corballis and Roldan. It seemed more straightforward to examine the detection of symmetry rather than the discrimination of symmetry from another form of pattern correlation within the display. Finally, advance notification was provided with cues rather than blocking of trials, in order to ensure that any set effects observed could be attributed to voluntary preparation per se rather than to possible "passive" intertrial repetition effects.

Experiment 1

In the first experiment subjects determined whether a display of 30 dots was symmetric. For the symmetric displays, there were four possible axes of symmetry, spanning the possible range in 45° increments. On half of the blocks of trials, the axis of symmetry was cued in advance of the display, by displaying a line marking the axis. In the cued blocks, the probability of the display being symmetrical was still always one half, but symmetric displays were always symmetric about the cued axis. In the uncued blocks, an uniformative warning stimulus was presented, consisting of all of the potential axes of symmetry superimposed, in order to ensure that temporal warning was not confounded with cuing of the axis. The different axis orientations were presented in mixed trials.

Method

Subjects. Thirty-four undergraduates at the University of California, San Diego, participated as subjects in the experiment, in partial fulfillment of a course requirement.

Apparatus and stimuli. Stimuli were presented on Princeton Graphics SR-12 monitors, controlled by IBM PC microcomputers (equipped with Sigma Design Color-400 boards, operated in 640 x 200 graphics mode). The displays were presented in green on a black background. The dot displays consisted of 30 dots, each measuring approximately 1 mm in height and 0.5 mm in width. The 30 dots lay within an imaginary circle 6.0 cm in diameter. Symmetric patterns were made by selecting 15 positions within the appropriate semicircle at random without any constraint and presenting them together with the points corresponding by mirror reflection. Asymmetric patterns were made by randomly selecting 30 positions from within the entire circle. Subjects viewed the displays in a lighted room from a distance of approximately 60 cm.

Design. The experiment was divided into 10 blocks of 40 trials each. Five of these blocks had informative cues indicating the axis of symmetry, and 5 did not. Within each block, half of the displays were symmetric, and half were not. The symmetric displays were equally often symmetric about four different axes: -45°, 0°, 45°, and 90° (0° being vertical). Each block of 40 trials consisted of 5 trials from each of the eight cells formed by combining axis with presence/absence of symmetry. A total of 850 observations per condition were thus collected from the 34 subjects. It should be noted that for the uncued asymmetric displays, the axis of symmetry is a dummy variable, in the sense that although individual trials were assigned to different cells according to axis, the axis had no effect on the nature of the display presented.

The order in which cued and uncued blocks were presented was counterbalanced: Equal numbers of subjects were randomly assigned to two groups; for one group, the even-numbered blocks were cued, and for the other group the odd-numbered blocks were cued.

Procedure. The subjects were given instructions in writing describing the task. The instructions stressed that responses should be made as rapidly and accurately as possible. They described the nature of the cues and their relation to the axes of symmetry, but they provided no explicit guidance on the use of the cues. Subjects were simply informed that when cues were present, "you will know the orientation of the axis of symmetry, if it is present." Prior to data collection, each subject worked through 48 practice trials, in two miniblocks of 24 trials each.

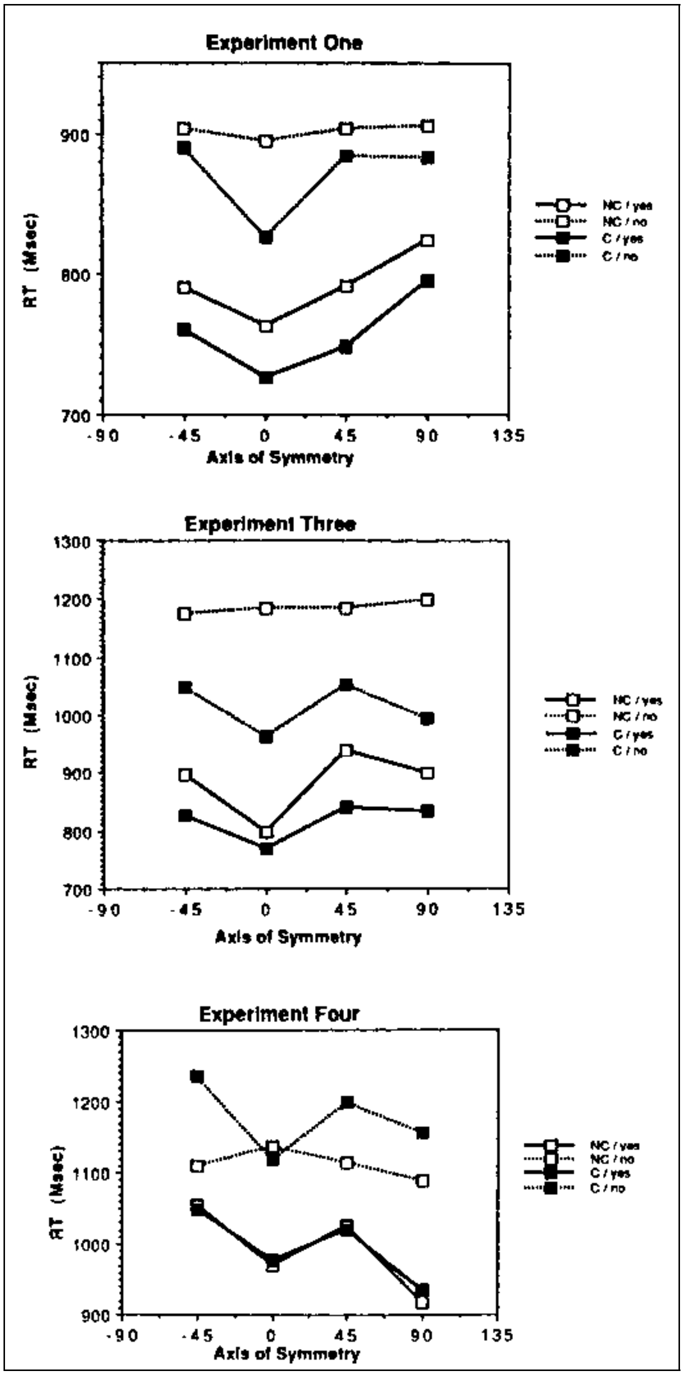
Each trial began with the presentation of a warning signal, which also provided axis information in the cued blocks. In the cued blocks, the signal was a line representing the axis of symmetry, extending outward from the center to the point where the line intersected an imaginary square, 2 x 2 cm, located in the center of the screen. On the no-cue blocks, the fixation consisted of all of these lines; it looked something like an enormous asterisk. This fixation point appeared at the center of the display for 1,000 ms; 150 ms after its offset, the dot display was presented. The display remained present on the screen for 150 ms. The subject responded to the display by pressing either the "n" or the "b" key on the keyboard with their right hand to indicate that symmetry was or was not present, respectively. If the subject made an error, a warning tone of 680 Hz was immediately sounded for 1 s. The intertrial interval between completion of one response and presentation of the cue for the next trial was approximately 1.6 s, not including the occasional error warnings. At the end of each block, the subject rested until he or she felt ready to resume. During this period feedback was provided in the form of average correct RT and percentage of errors for all of the blocks the subject had completed so far.

Results and Discussion

Response times under 200 ms or in excess of 2,000 ms were discarded. The data from one subject was discarded, because her RTs were grossly slower and more variable than the other subjects. Figure 2 (top panel) presents subjects' mean RTs for correct responses, as a function of axis of symmetry, symmetry presence/absence, and cuing. When no cue was presented and the display was not symmetric, the axis variable was a dummy variable, as noted above, and the minimal effects shown in the figure therefore indicate the reliability of the means. A three-way analysis of variance (ANOVA) was performed to examine axis by symmetry by cuing. The effect of cuing averaged 33 ms and was reliable, $F(1, 32) = 9.3$, $p < .005$. The negative trials were slower than the positive trials by an average of 111 ms; the effect was significant, $F(1, 32) = 86.7$, $p < .001$. The effect of axis of symmetry was also significant, $F(3, 96) = 8.9$, $p < .001$. Finally, there was a significant interaction of presence/absence and the axis of symmetry, $F(3, 96) = 3.3$, $p < .05$; inspection of the figure reveals that this primarily reflects the null effect of the (dummy) axis variable in the negative trials. No other effects or interactions were significant.

A separate ANOVA was performed to examine the positive trials alone. The effect of cuing was significant, $F(1, 32) = 8.4$, $p < .007$, as was the effect of axis, $F(3, 96) = 6.9$, $p < .001$. The interaction, however, was nonsignificant, $F(3, 96) = 0.3$, $p > .80$.

The error rates are shown in Table 1. Cuing produced an advantage in accuracy of 5.4%, which was significant, $F(1, 32) = 35.0$, $p < .001$. Responses were 6.2% more accurate on positive trials than on negative trials, $F(1, 32) = 10.8$, $p < .002$. The effect of axis of symmetry was also significant, $F(3, 96) = 9.7$, $p < .001$, a result reflecting more accurate performance with the 0° case and least accurate performance with the 90° case. Axis of symmetry interacted with cuing, $F(3, 96) = 7.7$, $p < .001$, and also with yes/no, $F(3, 96) = 15.3$, $p < .001$. Finally, the three-way Cuing x Yes/No x Axis interaction was also significant, $F(3, 96) = 7.9$, $p < .001$. All these interactions depend to some degree upon the fact that axis is a dummy variable on the negative uncued trials. An ANOVA



function of axis, cuing, and presence/absence of symmetry. (NC = no axis cue; C = axis cue; Yes = symmetry present; No = symmetry absent.)

Table 1
Percentage of Errors in Experiments 1, 3, and 4

Axis				
Group	-45°	0°	45°	90°
	Experiment 1			
No cue/yes	13.3	14.4	15.9	27.9
No cue/no	28.0	26.3	24.4	23.6
Cue/yes	12.7	10.9	10.6	21.6
Cue/no	24.5	9.0	25.6	15.5
	Experiment 3			
No cue/yes	8.2	5.1	7.4	12.9
No cue/no	10.5	7.4	8.8	7.8
Cue/yes	4.2	3.8	5.5	8.8
Cue/no	9.3	4.9	11.6	4.6
	Experiment 4			
No cue/yes	35.7	22.0	30.5	15.8
No cue/no	42.7	42.5	44.8	45.0
Cue/yes	30.0	28.3	32.7	10.5
Cue/no	39.5	15.3	33.8	37.7

was conducted on the data from positive trials only. The effect of cuing was significant, $F(1, 32) = 9.9$, $p < .005$, as was the effect of axis, $F(3, 96) = 11.5$, $p < .001$. The interaction was nonsignificant.

There are two main results of this study. The first is that cuing subjects about the axis of symmetry provides a substantial and highly significant advantage in the speed and accuracy of symmetry detection, contrary to Corballis and Roldan's (1975) conclusions. Although the difference might be attributed to several factors, the most likely cause seems to be the fact that the lines Corballis and Roldan used to mark the axes of symmetry were not presented in the displays used here. The second major result is the fact that the cuing effect is essentially the same regardless of the orientation of the axis of symmetry, for symmetric displays. This indicates that the advantage for the vertical axis is not due solely to a strategy whereby subjects tend to anticipate a vertical axis when they do not have advance information about the orientation. If it were, then this advantage would be eliminated by cuing.

Experiment 2

In order to confirm the results of Experiment 1, a replication of that experiment was performed, with very brief displays and with accuracy, rather than RT, used as the primary dependent variable. In general, comparable effects are observed in both situations, but exceptions sometimes occur, and when they do, they are often informative (e.g., Santee & Egeth, 1982). In particular, if the cuing advantage observed in the previous experiment was caused by effects on response selection, rather than perceptual processing, one would expect that the advantage would disappear when response selection is performed at the subject's leisure, and hence with near asymptotic accuracy. (Thus, Santee and Egeth observed inhibitory effects of response-incompatible flanker characters on a choice task in reaction time, but not in accuracy with data-limited performance.)

Method

Thirty-four undergraduates at the University of California, San Diego, participated as subjects in the experiment, in partial fulfillment of a course requirement. The apparatus and stimuli were identical to those used in the first experiment with the sole exception that the displays were presented only for 100 ms. The design was identical to that of Experiment 1 and provided 850 observations per condition over the whole experiment. The procedure differed from that of Experiment 1 only in that the written instructions stressed that accuracy was of paramount importance and response speed was of no importance.

Results and Discussion

Figure 3 presents the subjects' error rates as a function of presence or absence of a cue (C vs. NC), presence or absence of symmetry (yes vs. no), and the axis of symmetry and cuing, when present (-45°, 0°, 45°, and 90°). The advantage of cuing (15.8% errors vs. 23.9%) was highly significant, $F(1, 33) = 71.3$, $p < .001$. Subjects were also more accurate for symmetric displays (16.3% errors) than for asymmetric displays (23.4%), $F(1, 33) = 19.4$, $p < .001$. The interaction of the two was not significant. The effect of axis of symmetry was significant, $F(3, 99) = 17.2$, $p < .001$. The axis effect interacted with cuing, $F(3, 99) = 5.8$, $p < .002$, and with symmetry, $F(3, 99) = 2.8$, $p < .05$. The three-way interaction of cuing, symmetry, and axis was highly significant, $F(3, 99) = 14.1$, $p < .001$. This again primarily reflects the obvious finding that axis makes no difference for asymmetric uncued displays, because for these displays axis is in fact a dummy variable.

An analysis of positive trials revealed a significant effect only of cuing, $F(1, 33) = 19.9$, $p < .001$, and axis, $F(3, 99) = 6.7$, $p < .001$. The interaction was also significant, $F(3, 99) = 4.3$, $p < .006$, apparently due to the large cuing effect at + 45°.

The results show a very large cuing effect in accuracy, which mirrors the results of Experiment 1 with RT used as the primary dependent variable. There is a slight attenuation of

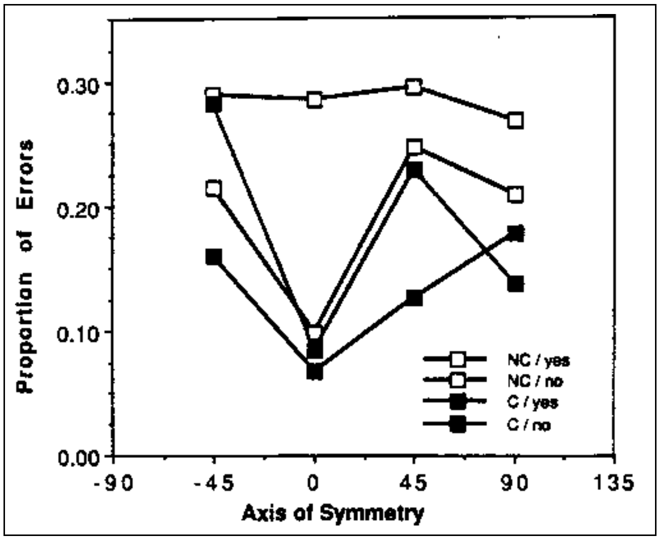


Figure 3. Mean proportion of errors in Experiment 2 as a function of axis, cuing, and presence/absence of symmetry. (NC = no axis cue; C = axis cue; Yes = symmetry present; No = symmetry absent.)

the effects of axis of orientation in symmetric displays when that axis is cued, but the effect of axis of orientation is still very large even for the cued displays. This indicates that the commonly observed vertical advantage (e.g., Barlow & Reeves, 1979) is not just due to a tendency to anticipate a vertical axis. In summary, then, the results basically replicate the findings of Experiment 1 and further reject Corballis and Roldan's (1975) claim that useful advance preparation for a particular axis of symmetry is not possible.

In the Results above, an interaction between cuing and axis in the error rates for positive trials was noted. This interaction takes the form of a substantially larger cuing effect for +45° axes. I cannot account for this effect, which is especially mysterious as the effect occurs for +45° axes but not for -45° axes; one would naturally have supposed these two conditions to be essentially identical.

Experiment 3

The previous experiments demonstrated that subjects' symmetry detection performance is considerably improved when they know in advance the axis of any possible symmetry. The first demonstrated this, with reaction time as the primary dependent variable; the second, with accuracy as the primary measure. However, the accuracy achieved in the first experiment was rather low, compared with that of subjects in Corballis and Roldan's (1975) study (or compared with the typical reaction time study). These high error rates are presumably due to the rather brief displays used in the first experiment. Given that the cuing effects were significant in both speed and accuracy, it is hard to understand how these error rates could undermine the conclusion; nevertheless, to be most certain of the generality of these cuing effects, it would be advantageous to observe them under conditions with low error rates. For that purpose, in the present experiment the displays remained available until the subject responded. Second, in the neutral no-cue trials in the previous two experiments the fixation point consisted of the union of the cues for all the axes. Although these cues provide no information about the axis, an anonymous reviewer pointed out that this neutral cue might possibly disrupt performance because it might seem to cue all of the axes rather than cuing none of them. Thus, the cuing effect in the previous experiments could conceivably reflect not a positive cuing effect but a detrimental effect of the neutral cues. In order to assess this possibility, the neutral cues in this experiment consisted of tiny crosses in the center of the screen.

Method

Twenty-two undergraduates at the University of California, San Diego, participated as subjects in the experiment, in partial fulfillment of a course requirement. The apparatus and stimuli were identical to those of the previous experiments except for the nature of the cues and the display duration. The neutral cues consisted of a tiny cross in the center of the screen (2 x 3 mm). The axis cues were as in the previous experiment except that the tiny cross was superimposed on them to mark the center of the screen. The displays remained present until the subject responded. The design was like that of Experiment 1. The procedure basically followed that of Experiment 1, with the following exceptions. First of all, the instructions stressed both speed and accuracy, but subjects were warned that they should not make too many errors. In addition, when subjects made more than 10% errors in a given block, the computer warned them to be more careful. The duration of the fixation point (neutral or informative cue) was 1,000 ms, followed by a blank interval of 500 ms. The time between the subject's response and the onset of the fixation point for the next trial was 1.4 s.

Results and Discussion

Response times under 200 ms or in excess of 2,000 ms were discarded. The data from 1 subject was discarded because of extraordinarily long RTs and high error rates. Figure 2 (middle panel) presents subjects' mean RTs for correct responses as a function of axis of symmetry, symmetry presence/absence, and cuing. When no cue was presented and the display was not symmetric, the axis variable was a dummy variable, and the minimal effects shown in the figure therefore attest only to the reliability of the means. A three-way ANOVA was performed to examine axis by symmetry by cuing. The effect of cuing averaged 119 ms and was reliable, $F(1, 20) = 30.3$, $p < .001$. The negative trials were slower than the positive trials by an average of 250 ms; the effect was significant, $F(1, 20) = 114.7$, $p < .001$. The interaction of cuing and positive/negative trials was significant, $F(1, 20) = 15.3$, $p < .001$. This reflects a larger cuing effect for negative trials (172 ms) than for positive trials (67 ms). The effect of axis of symmetry was also significant, $F(3, 60) = 19.1$, $p < .001$. The three-way Cuing x Symmetry x Axis interaction was significant, $F(3, 60) = 3.8$, $p < .02$. No other effects or interactions were significant.

A separate ANOVA was performed to examine the positive trials alone. The effect of cuing was significant, $F(1, 20) = 21.6$, $p < .001$, as was the effect of axis, $F(3, 60) = 18.4$, $p < .001$. The interaction, however, was nonsignificant, $F(3, 60) = 1.5$, $p < .20$.

The error rates are shown in Table 1. Cuing produced an advantage in accuracy of 1.9%, which was significant, $F(1, 20) = 7.6$, $p < .02$. Responses were 1.1% more accurate on positive trials than on negative trials, which was not significant. The effect of axis of symmetry was also significant, $F(3, 60) = 4.2$, $p < .01$, which reflects more accurate performance with the 0° case. Axis of symmetry interacted with presence/absence of symmetry, $F(3, 60) = 5.6$, $p < .002$, which reflects what seem to be rather different patterns of axis effects for symmetric and asymmetric displays.

This experiment differed from the first in employing a different form of noninformative cue and in making the display available until response. The cuing effects on response latencies are larger than those in Experiment 1. A comparison of the middle panel with the top panel in Figure 2 suggests that the longer display duration has basically magnified the effects of all variables, including presence of symmetry as well as cuing. At the same time, the effects of these variables on accuracy were apparently reduced. This pattern of changes fits well with the suggestions of Pashler and Badgio (1985) concerning effects of display duration on patterns of response latencies. As in the first experiment, error rates again showed some interactions between axis of symmetry and other variables that were not readily interpretable. However, the effect of cuing was nonetheless significant in error rates as well as RTs.

Therefore, the results strengthen the conclusions of the first two experiments: first, that substantial axis cuing effects exist and, second, that cuing does not eradicate the effects of axis of symmetry. Given the results of these three experiments taken together, this conclusion appears to be inescapable and to suggest that the methodological peculiarities of the Corballis and Roldan (1975) work must have prevented them from observing these cuing effects.

Experiment 4

The previous experiments have indicated that advance knowledge of the axis of symmetry produces a major facilitation for the detection of symmetry in dot patterns. In these experiments the advance information was sufficient to allow subjects to know not only the orientation of the axis of symmetry but also its exact location in the visual field. Does the detection of symmetry benefit only from full specification of the location and orientation of the axis, or would it benefit equally when the orientation alone was provided? If cuing affects a global frame of reference that applies across the whole visual field, one would expect a benefit from orientation information alone. On the other hand, if the frame applies to specific objects or locations, one would not. In Experiment 4, this question was addressed by providing subjects with a centrally located cue to the orientation of the axis but then presenting the display itself in a location chosen randomly from a wide range of positions to either the right or the left of fixation. Thus, on cued trials, the subject knew the direction of any axis of symmetry but not its location in the field. Displays were brief, and reaction time was the primary dependent variable, as in Experiment 1.

Method

Twenty-four undergraduates at the University of California, San Diego, participated as subjects in the experiment, in partial fulfillment of a course requirement. The apparatus and stimuli were identical to those used in the first experiment except for the placement of the dot displays. The cues were again presented at fixation, as in Experiment 1. However, the patterns of dots were randomly positioned either to the left or to the right of fixation. The center of the pattern was placed at a point somewhere along the following range: from 3.5 cm to 1.7 cm left of fixation and from 1.7 cm to 3.5 cm right of fixation. Thus, it was equally likely to be left or right of fixation, and given that, it was then randomly fixed in a spot along a 1.8-cm range of eccentricities. Exposure duration was set to 100 ms. The design was identical to that of Experiment 1 and provided a total of 600 observations per condition over the whole experiment. The procedure followed that of Experiment 1, and the instructions stressed speed.

Results and Discussion

Figure 2 (lower panel) presents the subjects' mean correct reaction times as a function of presence or absence of a cue (C vs. NC), symmetry or asymmetry (yes vs. no), and the axis of symmetry and cuing, when present (-45°, 0°, 45°, and 90°). The effect of cuing was not significant, $F(1, 23) = 3.5$, $.05 < p < .10$. The effect of symmetry/asymmetry was highly significant, $F(1, 23) = 80.5$, $p < .001$. The effects of cuing and symmetry interacted, which reflects a negative effect of cues for the asymmetric displays (-64 ms) and a negligible effect of cues for the symmetric displays (-4 ms), $F(1, 23) = 5.6$, $p < .03$. The effect of axis of symmetry was significant, $F(3, 69) = 13.0$, $p < .001$. This effect showed only a trend toward interacting with cuing, $F(3, 69) = 2.3$, $0.5 < p < .10$. The interaction of axis with cuing was not quite significant, but the three-way Cuing x Symmetry x Axis interaction was significant, $F(3, 69) = 4.0$, $p < .02$. The latter interaction reflects the fact that the cuing effect varies with axis for asymmetric displays but is uniformly negligible for symmetric displays.

The error rates were analyzed likewise, and the results are presented in Table 1. The effect of cuing was significant, $F(1, 23) = 22.2$, $p < .001$. The effect of symmetry/asymmetry was also significant, $F(1, 23) = 21.4$, $p < .001$. The effects of cuing and symmetry interacted, which reflects a much greater advantage of cuing for the asymmetric displays (12.1 %) than for the symmetric displays (0.6%). The effect of axis of symmetry was significant, $F(3, 69) = 16.5$, $p < .001$. This effect did not interact with cuing. $F(3, 69) = 2.2$, $p > .10$. The effect of symmetry interacted with axis, $F(3, 69) = 10.7$, $p < .001$. Finally, the three-way interaction of axis, symmetry, and cuing was significant, as in the previous experiments, $F(3, 69) = 10.5$, $p < .001$, which reflects at least partially the fact that axis is a dummy variable for uncued asymmetric displays.

In the current study the cues accurately indicated the orientation of the axis of symmetry, when symmetry was present, but they did not indicate the position of the axis, because the entire patch of dots appeared in an unpredictable position to the left or the right of fixation. This unpredictable eccentric placement of the dots seems to have had several basic effects. In the primary dependent measure—reaction time—the facilitative cuing effect observed in the previous study is basically abolished. In fact, cues actually slow subjects down in detecting the absence of symmetry, although they make these responses slightly more accurately as well. Perhaps cues cause subjects to proceed more carefully before responding. However, the most informative result seems to be the overall lack of a cuing advantage for detecting the presence of symmetry. Finally, overall performance is generally best for the 90° condition, whereas in previous experiments this condition was poor, relatively speaking.

What can be concluded from these results? First of all, to a first approximation these cues just do not produce the basic cuing advantage observed in the previous experiments. This suggests that in response to cues, subjects adjust an internal frame of reference that is applied to a specific object or location in the visual field, rather than adjusting a global parameter for top-bottom which would govern processing throughout the visual field. This experiment does not indicate whether subjects could have benefited from these central cues—presented in different locations from the dot patterns that they cue—had the subjects known in advance what the location of the dot patterns would be. It seems natural to assume that such knowledge would be sufficient to restore the cuing effects observed in the previous experiments, but perhaps it is necessary to perceive the cues in the same actual location as the expected symmetry axis. In either case, a strong hypothesis of the global frame of reference seems inconsistent with the results.

One obvious question posed by the results is what is going on at the 90° (horizontal) case. Positive responses are actually fastest in this condition, whereas in the previous experiments this was a relatively slow condition. This is probably due to the fact that, with displays that are symmetric about the 90° (horizontal) axis, the subject has available for inspection some corresponding dot pairs that are located quite close to the retinal midline. Hence, some corresponding dot pairs are acquired with higher acuity vision. On the other hand, with the other axes, in all cases of corresponding dot pairs, at least one dot is retinally quite eccentric. In a sense, then, peripheral factors are confounded with axis of symmetry in this experiment.

There are no such confounds for the cuing manipulation, however, so the main result of the present experiment is clear. When subjects do not know where the patch of dots will appear, they cannot derive much benefit from knowing the direction of any possible axis of symmetry. So whatever other properties the perceptual set revealed in the first three experiments may have, it does not appear to reflect a change in an internal perceptual parameter governing processing over the entire visual field.

Experiment 5

The previous experiments showed clearly that accuracy and speed in determining whether an array of dots is symmetric are substantially facilitated by providing subjects with advance information about the orientation and location of the axis of symmetry. How is the preparation for a symmetry axis related to the voluntary control of the internal frame of reference for shape perception, posited by Rock (1973)? The strongest relation the two processes might have could be identity, if assigning top and bottom to a figure for shape perception just is preparing to detect symmetry about the top-bottom axis. (One would naturally suppose that because axes of symmetry have orientation, but not direction, that assigning top to either end of the axis would include preparation for symmetry detection about that axis.) Another alternative, of course, is no relation at all: Preparing for a symmetry axis might be completely independent of object recognition. How can the question be addressed empirically? In this experiment I used what is basically a dual-task paradigm. Subjects attempt two tasks involving a single brief display: judging the symmetry of a set of dots and identifying a familiar character also presented in the display. If the two perceptual "sets" are identical, or inseparably linked, one should find better performance when the orientation of the two displays is appropriately related.

Subjects were presented with a brief (100-ms) display containing a character (letter or digit) and a dot pattern superimposed on it. They were required to make a speeded response to the character, responding depending upon whether it was a letter (U or E) or a digit (4 or 9). In addition, they were also required to determine whether the pattern of dots was symmetric about a prespecified axis; for this second response, accuracy, rather than speed, was the goal. When the dots were symmetric—half of the time—it was always about the prespecified axis, which remained constant for any given subject throughout the experiment. This axis was either -45° or +45° (with respect to vertical), for two different groups of subjects. For all the subjects, though, the characters were presented at orientations of -45°, 0°, and +45°, in mixed trials.

Because the task required subjects to monitor the pattern of dots for its symmetry about a fixed axis, it provided every incentive for subjects to keep the symmetry frame of reference oriented appropriately on all trials. The key question, then, was whether attention to a familiar object with its top-bottom axis oriented differently would involuntarily shift the internal frame for symmetry and thus impair performance compared with that when the two were oriented in the same way.

Method

Subjects. Sixteen undergraduates at the University of California, San Diego, participated as subjects in the experiment, in partial fulfillment of a course requirement.

Apparatus and stimuli. The apparatus was identical to that used in the earlier experiments. Stimuli were similar to those used in the first experiments except that each display contained (a) a letter or digit and (b) a dot pattern superimposed on it. The characters (U, E, 4, or 9) were drawn in bright red with lines of the same width as the dots presented for symmetry judgment. The characters measured about 1.2 x 2.8 cm high. The dot patterns consisted of 30 green dots arranged within a 6-cm imaginary circle, as in the previous experiments. The dots were superimposed on the characters in the pixel array. The fixation point in this experiment was just a line-drawn plus sign, about 1 cm in height and width. Exposure duration for the entire display (character plus dots) was set to 100 ms.

Design. The design was a mixed between/within-subjects design, with the fixed axis of symmetry (-45° or +45°) varied between subjects, and the remaining factors varied within subjects. The experiment was divided into 10 blocks of 36 trials per block. Each block contained equal numbers of six trial types, representing dot symmetry versus asymmetry by three character orientations. Thus, there were 60 trials per condition per subject, for a total of 480 observations per condition in the whole experiment. The character identity was chosen randomly on each trial without constraint.

Procedure. The procedure was similar to that of the previous experiments. The instructions stressed that the first response—to the character—should be as fast as possible. The response keys were the comma and period keys on the microcomputer keyboard, for letters and digits, respectively. Subjects made these responses with the index and middle fingers of their right hand. The second response—to the dots—was made at the subject's leisure, as accurately as possible. These responses were made with the index and middle fingers of the left hand, with the z and x keys used for symmetric and asymmetric, respectively. The computer, in fact, refused to accept a response to the dots received before a 250-ms interresponse interval had elapsed, to discourage hasty responding.

Results

Figure 4 presents the subjects' error rates to respond to the dots as a function of the orientation of the letter or digit, separately for the -45° symmetry group and the +45° sym-

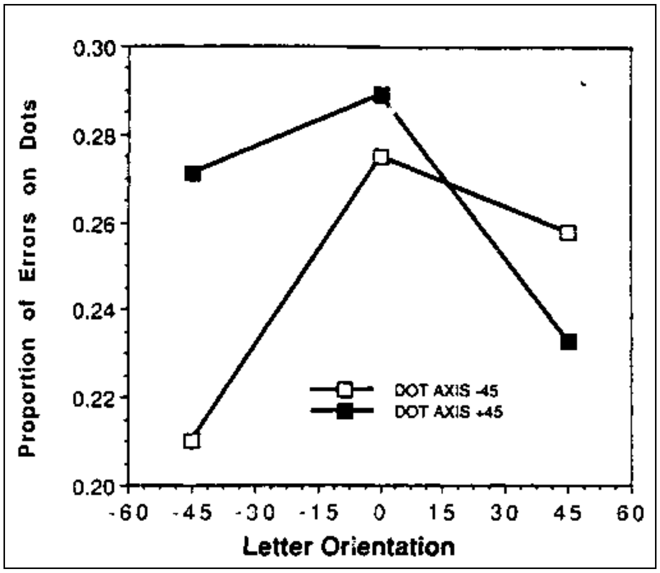


Figure 4. Proportion of errors in dot symmetry judgment (Experiment 5) as a function of orientation of the character superimposed on display. (Dot Axis -45 = group for which dot symmetry was always about -45° axis; Dot Axis +45 = group for which dot symmetry axis was always about +45° axis.)

metry group. The data show clearly that the lowest error rate occurs when the top-bottom axis for the letter is at the same orientation as the dot pattern (i.e., -45° and +45°, respectively). Table 2 presents this same symmetry error data broken down by symmetry and asymmetry of the display as well as orientation of the letter. The data were analyzed separately for the two groups.

For the +45° group, the effect of axis was significant, $F(2, 14) = 4.7, p < .03$. The effect of symmetry versus asymmetry of the dots was nonsignificant, $F(1, 7) = 2.7$, $p > .10$. The interaction of the two approached significance, $F(2, 14) = 3.55, .05 < p < .10$.

For the -45° group, the effect of axis was significant, $F(2, 14) = 7.4, p < .007$. The effect of symmetry versus asymmetry of the dots was nonsignificant, $F(1, 7) = 4.5, .05 < p < .10$. The interaction reached significance, $F(2, 14) = 9.2, p < .004$.

A planned comparison was performed to determine whether symmetry judgment error rates were reliably lower when the character orientation matched the symmetry axis than when it did not match. For each subject the error rates were computed for matching versus nonmatching axes and averaged across symmetric and asymmetric displays. (For this comparison, only nonmatching axes at +45° and -45° were included so that the actual orientation would be counterbalanced across the two groups of subjects). The difference was significant by sign test ($p < .01$) and also by t test ($t = 3.27, p < .01$).

Table 2
Percentage of Errors in Experiment 5

Axis of symmetry/ symmetry	Orientation of the character		
	-45°	0°	45°
-45°-yes	29.4	22.1	34.6
-45°-no	12.7	32.9	17.1
+45°-yes	37.9	29.2	31.5
+45°-no	16.2	28.5	15.2

Note. Data are percentages of errors on the symmetry judgment as a function of the axis of symmetry, whether symmetry is present, and the orientation of the character.

For the (first) responses to the character, response times outside the range from 200 ms to 2,000 ms were excluded as deviant. When the axis of symmetry was -45°, the mean RTs to the character were 810 ms, 812 ms, and 833 ms, for characters presented at -45, 0, and +45°, respectively. This effect of orientation was significant, $F(2, 14) = 5.1, p < .05$. When the axis was at +45°, the mean RTs to the character were 698, 681, and 673 ms, respectively. The effect of orientation was not significant here, $F(2, 14) = 2.6, .10 < p < .15$. For the latter group, there was also a significant, but rather odd, interaction between orientation and symmetry versus asymmetry of the dot display. This took the form of faster responses to characters paired with asymmetric displays at +45° but not at the other orientations. There was no trend in this direction in the -45° axis group of subjects, and I have no account of this effect to offer.

Discussion

The results of this experiment indicate that when the symmetry of some dots, and the identity of a familiar object, must be judged in the same brief display, performance depends upon the relation of the orientation of the two patterns. Specifically, performance is best when the top-bottom axis of the object corresponds to the axis of symmetry for the dots. (As noted earlier, there are exactly two ways this could happen for any axis of symmetry, because axes of symmetry are nondirectional.) The strongest and the most obvious account would be that the perceptual sets involved in both processes are one and the same—to prepare to detect symmetry about a given axis in an object just is to see a particular end of it as its top and a different end as its bottom.

Although the alignment effect is both substantial and highly statistically significant, it is graded rather than absolute: Symmetry detection is not reduced to chance performance when the two axes do not coincide. This suggests several possibilities. Even if subjects do have to align the same reference frame to two "settings" in turn, in the different axis condition this requirement may not affect symmetry performance drastically, simply because an adequate sensory memory for the dots is available well after the offset of the brief display. Experiments in which backward visual masks follow the dot patterns might test this account. A second possibility is that rather than one single frame of reference subserving both processes, there are instead two frames of reference, with each exerting an automatic "tug" on each other, which the subject cannot voluntarily overcome. Such an obligatory but graded mutual influence might be readily described within Hinton's (1981) connectionist account of recognition of disoriented objects.

A final possibility is that the identification of the character may not always require the single frame of reference to be completely aligned with the top-bottom axis of the object.

Characters are very simple objects, and they characteristically do not show very large effects of disorientation on time for identification (Corballis, Zbrodoff, Shetzer, & Butler, 1978; Jolicoeur, 1985). Thus, perhaps their identification proceeds to some degree before the frame of reference is completely shifted. An obvious way to test this account is to use more complex objects, instead of the characters used in this experiment.

The approach adopted here may have applicability to a variety of different questions about mechanisms underlying different kinds of perceptual sets. The approach of Experiments 1-4 above—in which perceptual set was investigated by looking at the effect of predictability along different dimensions—has been commonly reported (see, e.g., Egeth, 1977; Pashler, 1988). By contrast, the approach used in Experiment 5 is more novel, and it may be useful whenever two set effects have been identified and the question is whether they share an underlying mechanism.

General Discussion

This article has presented evidence in support of several points.

1. Contrary to the conclusions of Corballis and Roldan (1975), when an observer knows in advance the axis of symmetry in a figure, he or she can detect symmetry more efficiently at that axis.
2. This is not accomplished by a mechanism that sets a "global parameter" applying across the entire visual field, because the cuing effect was reduced when subjects were told only the direction of the axis and not its location.
3. The system responsible for this presetting effect is identical to, or at least closely and automatically tied to, the frame of reference for object recognition and, specifically, in such a way that identifying an object with a particular top-bottom axis produces optimal detection of symmetries about an axis of symmetry with the same orientation.

The cuing effects observed in the first three experiments speak against the conclusions of Corballis and Roldan (1975), who reported no effect of advance knowledge of the axis of symmetry. It seems likely that the difference is due to the fact that in their experiments the axis itself was always presented simultaneously with the dot displays. For the reasons discussed in the introduction, this could certainly obscure effects of advance knowledge. Although demonstrating the existence of a sizable effect of advance knowledge, the present experiments do not provide answers for all the interesting questions one might ask about the effects. For one thing, the cuing effects observed here might possibly reflect a voluntary preparation of a frame of reference that can occur only in the presence of the axis cue; that is, perhaps the preparation process induced by the cues could not operate without their presence. Another possibility is that the effects of these cues might be automatic rather than voluntary; perhaps the perception of the cues themselves is sufficient to pull the frame of reference. This question could be resolved by experiments in which the cues were presented but did not predict the axis of symmetry.

Another observation made in the first three experiments reported above is that although axis cues improve the detection of symmetry, they do not eliminate, or even apparently much reduce, the tendency for symmetry to be detected best about a vertical axis. This result disconfirms the suggestion that the basic advantage for vertical symmetries is due to a tendency for the frame of reference to be aligned vertically as a default. As mentioned in the introduction, this conclusion is also supported by the results of Corballis and Roldan (1975) despite the problems with their cuing procedures. These findings suggest that when subjects know that one of several different possible axes of symmetry may appear in the display, they do not align their frame of reference with the vertical (otherwise vertical cues would be redundant, and hence useless). Perhaps in such cases subjects align their frame of reference with different axes on each trial, or with the axis that appeared on the previous trial. It is also conceivable that subjects can maintain an uncommitted state with regard to the orientation frame of reference. In any case, the present results do not allow one to characterize the source of the vertical advantage that remains after cuing.

The three conclusions stated above are consistent with the observations made earlier concerning the possible functional role of symmetry detection in animal vision. The first of these suggestions was based on the fact that symmetry itself is often a cue to an object's identity. Because the primary examples of symmetry in the natural world involve symmetry about a vertical axis, then if an object's top and bottom are known in advance, it would make sense to focus any limited symmetry detection "resources" on the axis running in the top-bottom direction, to better identify the object. The results reported here are consistent with such a linkage. The only aspect of symmetry detection argued for here that seems not so obviously functional is the finding of Experiment 4—that preparation for a generalized axis orientation rather than a specific axis does not seem to be effective. Functional considerations might have led one to expect otherwise. Consider the case of a tilted observer, confronting a scene with poorly discriminable object boundaries but containing mostly upright objects. In such circumstances, symmetry may be a useful heuristic for object segregation; furthermore, the orientation of the most likely axis of symmetry is quite predictable from environmental and gravitational cues, even though the probable locations of the axis—the object midlines—are not predictable. Why not alter a global frame of reference? One possibility is that a global shift in the frame of reference is possible when vestibular and other cues indicate a deviation of the gravitational upright from the retinal upright, but perhaps it cannot be produced by conscious anticipation alone.

The second functional consideration raised above was that there seems to be good reasons for detection of symmetry about an axis to automatically rotate the frame of reference into line with that axis, because if symmetry is detected in advance of object recognition, this will provide useful information about the most likely top-bottom axis for the object. The present experiments did not provide a test for all the predictions of this idea, because in Experiment 5 it was the object recognition that was primary and concomitant effects upon symmetry detection that were measured. However, straightforward extensions of the methods of Experiment 5 could allow such hypotheses to be specifically tested. For instance, one could present symmetric figures—either attended or unattended—and also require recognition of a complex object in the same visual scene. Perhaps even unattended symmetries will produce an involuntary rotation in the internal frame of reference in the manner of Experiment 5.

Possible Involvement of Mental Rotation

Thus far, the assumption has been made that preparation for symmetry detection and object recognition at particular orientations is accomplished by rotating an internal frame of reference in advance. One might at this point raise another possibility: that the subject is instead preparing to rotate the particular pattern that is presented, rather than any frame of reference. On such an account, the cues in Experiments 1-4 might work by optimally preparing the system to rotate the dot patterns along a particular angular trajectory. In the fifth experiment, the recognition of a character at a particular orientation might be accomplished by rotation of the character, which could then be facilitating repetition of the same rotation operation for the dots and thereby improving recognition of symmetry at that same orientation.

It is not so clear, however, that the dichotomy between pattern rotation and reference frame rotation is very illuminating, because the concept of a reference frame, and the concept of an operation that continuously transforms an input to eliminate the effect of misorientation, are not necessarily mutually incompatible or even logically distinct. Consider the crudest possible analogy involving computer hardware. Rotation of a pixel array can be accomplished with parallel hardware that essentially computes a matrix multiplication operation on the array. If one inserts into a computer vision system a component that performs this computation, is one thereby rotating a frame of reference or preparing the system to rapidly rotate particular images that might be presented to it? Both descriptions seem to be reasonable.

A slightly different, but perhaps more fruitful, distinction would be between a discrete rotation of a static image, sampled at some moment in time, and continuous transformation of all incoming visual information, commencing as soon as the information arrives. Thus, on the one hand, there is the possibility that the system rotates "snapshots" of the scene and thereby provides corrected images to later processes on an intermittent basis. The alternative would be a correction process that continuously updates the corrected image for subsequent processes. It seems to require rather ingenious experiments to disentangle these possibilities. However, one commonplace observation that is perhaps suggestive is that observers do not seem to have any obvious difficulty in watching a movie or television with their heads tilted to a moderate degree; presumably, this requires continuous monitoring of many aspects of a changing scene. Careful examination of such situations might be illuminating.

In the discussion thus far, it has been argued that the apparent distinction between pattern rotation and frame rotation may not represent a useful distinction, whereas the distinction between continuous and discrete correction seems more useful. A related question is whether the phenomena observed here might reflect mental rotation in the same sense as that involved in the well-known " mental rotation effect" observed when mirror-image judgment tasks are performed with forms presented at various orientations (e.g., Cooper & Shepard, 1973). There has been disagreement in the literature concerning whether subjects can rotate a reference frame prior to presentation of the test stimuli in that task. Cooper and Shepard concluded that they cannot. This conclusion was based on the finding that when subjects were cued as to the angle of an upcoming test figure, they still showed the usual mental rotation slopes (unless they were also cued as to the specific identity of the test figure). Along similar lines, Koriat and Norman (1984, Experiment 1) found that the rotation effect was little reduced when characters were presented in the same orientation on two successive trials. This speaks against the possibility of a reference frame that gets rotated on each trial and then remains for some time in the orientation at which it was last employed. Other results seem to suggest that the story may be somewhat more complicated, however. Hinton and Parsons (1981) found that cuing basically eliminated the angle effects when the test letters used all faced the same direction (the letters were F, R, G, and L, facing rightward in this sense). As Hinton and Parsons acknowledged, however, this result does not require a general purpose reference frame that can be rotated so that object rotation will be unnecessary for mirror-image judgments in general, given the limitation on the stimulus set. Finally, Robertson, Palmer, and Gomez (1987) examined intertrial repetition effects, in the manner of Koriat and Norman. However, unlike Koriat and Norman, they did find some effect of the relation between the orientations of the figures presented on successive trials. The rather complex pattern of results observed by Robertson et al. seemed to them to suggest that performance may have been produced by a probability mixture of two strategies, one involving rotation of the pattern to the upright and the other involving rotation of a reference frame (this frame holding its last position from one trial to the next). Given these seemingly conflicting results, it is hard to reach any general conclusions about the role of reference frames in mirror-imagine judgments. Perhaps the most that can be said is that, given a cue, subjects cannot readily rotate a general purpose frame usable for the task but that neither does subjects' performance always reflect a rotation of the figure to the upright, either. Given that the cuing effects for symmetry judgments reported here were easily elicited with simple cuing, this may suggest that the mechanisms involved are different.

There are further empirical reasons for suspecting that the mental rotation involved in making mirror-image judgments, and the corrections necessary for recognition of misoriented objects, are performed by different systems. Farah and Hammond (1988) examined patterns of performance by a brain-damaged subject on standard mental rotation tasks requiring mirror-image judgments. The patient, who suffered posterior right hemisphere damage, was unable to perform these tasks but could recognize misoriented objects without apparent difficulty. Thus, compensation for misorientation in object recognition does not seem to rely on the same neural machinery as that involved in rotating an image to make a mirror-image judgment. Given the indications in the present article that the frame of reference for object recognition and that for symmetry detection are identical or at least yoked to each other, it seems reasonable to suspect that "ordinary" mental rotation is not involved in that operation either. McMullen and Jolicoeur (1988) also reported evidence suggesting the independence of disoriented object recognition and mental rotation, based on the effects of tilting subjects' heads while the subjects performed mirror-image judgments and object identification judgments (without cues). For mirror-image judgments, the effects of misorientation depended upon angular disparity from the environmental vertical; for object identification, it was angular disparity from the retinal vertical that determined performance (see also Corballis, Nagourney, Shetzer, & Stefanatos, 1978).

These lines of evidence suggest that the preparation effects observed here probably do not have the same origin as the well-known mental rotation effect involved in making mirror-image judgments. Why should this be? Several theoretical accounts have been presented for the apparent independence of mental rotation and perception of misoriented shapes. Hinton and Parsons (1981) proposed that object recognition may require assignment of an intrinsic frame of reference, itself either right handed or left handed. This assignment permits object recognition, but the handedness of the reference frame employed for recognition cannot itself be determined without rotation. Corballis (1988) proposed that shape recognition is accomplished with descriptions that are independent of both orientation and handedness (i.e.. rotating or mirror-reversing an image would not alter the shape descriptions extracted from the image), following up on an idea first proposed by Deutsch (1955). Given the assumption of orientation invariance, mental rotation is plainly unnecessary for object recognition. However, these initial shape descriptions do not suffice for discriminating mirror images. For that purpose, mental rotation is required in order to align a representation of the object with an egocentric coordinate system, in which left and right are distinguished.

The Corballis' (1988) account provides a seemingly plausible theoretical explanation for the independence of mental rotation and object recognition. Unfortunately, it is not so clear that it can explain the harmful effects of disorientation on object recognition (Jolicoeur, 1985) and the effect of designation of top/bottom on recognition memory for shapes (Rock, 1973), both of which seem to contradict the hypothesis of complete orientation invariance in shape recognition. A modification of this view, however, can not only reconcile it with the discomfirming evidence just cited but also yield a conjecture with implications for the basic nature of symmetry detection itself.

Modifying Corballis' Account: Implications for Symmetry Detection

Suppose one accepts Corballis' (1988) view that shape descriptors are independent of handedness, without agreeing that they are orientation invariant. Given this assumption, further suppose that the application of shape descriptors to an object is governed by a frame of reference that may be aligned with retinal, gravitational, or any voluntarily chosen axis. This can explain the basic observations of Rock (1973) concerning the role of top/bottom specification on shape description and the generally harmful effects of misorientation (e.g., Jolicoeur, 1985).

The assumption of handedness invariance accounts for why mental rotation is necessary in mirror-image judgments—in just the way Corballis proposed. But the assumption of handedness invariance without rotation invariance also has direct implications for the nature of symmetry detection itself and for the role of the frame of reference in symmetry detection indicated in the experiments reported above. Suppose that the computation of (handedness-invariant) descriptors at various spatial scales is followed by a stage at which neighboring regions are grouped together when these descriptors match. (Such a grouping process is widely postulated in accounts of texture segmentation, e.g., Beck, 1982; Caelli, 1985. and stems from the gestalt principle of grouping by similarity). Given the proposed handedness invariance of descriptors, symmetric patterns will have a distinctive kind of description: They will generate many pairs of adjoining identical shape descriptors at all spatial scales. Consider a symmetry random-dot display. At the coarsest scale, there might be only a relatively modest number of adjoining pairs spanning the entire symmetry pattern. Nearing the axis itself, there would be more and more such adjacent pairs at finer scales. Grouping mechanisms will therefore automatically bind together these regions. The subjective perception of symmetry may simply be the conscious concomitant of this pattern of increasingly dense pairwise linkages across a common axis. This provides a fairly natural account of why the portions of the image nearest the axis should be the most critical for symmetry detection (Julesz, 1971), because disruption along this line will eliminate the linkages of all scales. It could also explain why symmetry is detected more readily than repetition of the same pattern (Julesz, 1971): Symmetric displays generate numerous linkages at progressively finer spatial scales, whereas repetitions generate only a few linkages at the very coarsest scale.

This account of symmetry detection entails that the frame of reference for shape recognition and the frame of reference for symmetry detection must be one and the same, as the data reported here suggest they are. This unity is required because the account suggests that symmetry detection is just one pattern of grouping of the initial handedness-invariant shape descriptions. If the view suggested here is correct, it suggests that Wertheimer's (1958) characterization of symmetry as being first and foremost a principle of grouping was correct, but it also suggests that grouping by symmetry could actually be just a special case of grouping by similarity, given the assumption of handedness-invariant shape descriptors. Whereas models of symmetry detection usually posit a point-by-point matching process specifically designed to detect symmetry, the present conjecture suggests that grouping principles already required for other visual functions could accomplish most of the work involved in detecting symmetry. Obviously, more research is required to determine the validity of this conjecture.

Summary

In summary, then, the results of the experiments reported here suggest that visual symmetry detection can be voluntarily preset to operate most efficiently about a particular axis of symmetry. This presetting seems to consist in adjusting the internal frame of reference for object recognition so that the top-bottom axis for object recognition coincides with the expected axis of symmetry. Suggestions have been advanced about why this functional linkage between symmetry detection and shape perception makes good functional and computational sense, given some obvious aspects of the natural visual world. It was also suggested that the internal frame of reference reflected in these effects may have little to do with the well-known "mental rotation effect" observed in tasks requiring mirror-image judgments. A possible explanation for this independence was suggested in the form of a theory of how symmetry itself might be computed—by grouping pairs of handedness-invariant shape descriptors from fine to coarse scale across the axis of symmetry. The assumption that these shape descriptors are not orientation invariant, but instead are applied in a way that depends upon an internal frame of reference, could account for the present results, along with some others.

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