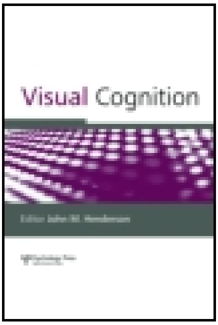


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# Parallel computation of symmetry but not repetition within single visual shapes

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# Parallel Computation of Symmetry but Not Repetition within Single Visual Shapes

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Visual symmetry is highly salient to human observers. Indeed, Mach (1885) observed that symmetry is more salient than repetition in the contours of a shape. We find that symmetry within a single shape can be detected in parallel, whereas repetition is apparently detected by a serial process. Subjects were required to judge whether a pseudorandom block-shape was symmetrical (Experiment 1) or had repeated contours (Experiment 2). When present, these relations arose around either vertical or horizontal axes of elongation, which were unpredictably intermingled. In both cases, symmetry judgements were scarcely affected by the number of discontinuities along the contours to be compared, whereas repetition judgements showed substantial delays when there were more discontinuities. These results are consistent with parallel encoding of a part-description for shapes, in accordance with Hoffman and Richards' (1984) curvature-minima rule.

Visual symmetry is highly salient to human observers, especially when it arises about a vertical axis. This sensitivity to symmetry has been commented upon by many philosophers and early writers on perception. For example, Pascal (translated, 1950, p. 491) asserted that "symmetry is what you see at a glance". The

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present paper examines the mechanisms of symmetry perception and considers their implications for theories of visual shape coding in the two-dimensional domain.

There are many grounds for believing that symmetry is a useful visual attribute. Koffka (1935) noted that symmetry may be an especially helpful cue for figure–ground segregation. Clear experimental evidence now exists to show that symmetrical shapes do indeed tend to be seen as figures against asymmetrical background (e.g. Driver, Baylis, & Rafal, 1992; Rock, 1983). As many objects and organisms are inherently symmetrical, such segmentation may signal the location of objects in the visual scene. Note, however, that symmetrical objects will not project a perfectly symmetrical image unless they are directly facing the observer. On the other hand, human observers can be almost as sensitive to skewed symmetry as to exact symmetry (Wagemans, Van Gool, & d'Ydewalle, 1992).

A related perspective on the importance of visual symmetry comes from computational approaches to vision. These characterize symmetry as a "non-accidental" image property, because it is very unlikely to arise by chance in an image in the absence of a symmetrical object in the distal image-source. Several authors (e.g. Biederman, 1987; Lowe, 1987) have argued on computational grounds that the visual system should be especially sensitive to such properties. Marr (1982) proposed specifically that symmetry is an important non-accidental cue for determining the principal axis of a shape, prior to deriving an object-centred description relative to this axis.

These many functional arguments for the importance of visual symmetry do not address the nature of the processes that detect it. A common introspection has been that visual symmetry is derived effortlessly. Mach (1885) in particular noted that observers detect symmetry with exceptional ease, finding even the detection of repetition within a visual pattern more difficult. This seems paradoxical because repetition only involves the repositioning of image-features, whereas symmetry involves a similar translation plus a reflection of those features. The advantage of symmetry over repetition has been confirmed experimentally by Fitts, Weinstein, Rappaport, Anderson, and Leonard (1956), Julesz (1971), Corballis and Roldan (1974), Bruce and Morgan (1975), Chipman (1977), and more recently by Baylis and Driver (in press). It could be taken to suggest that, unlike detection of exact repetition, symmetry perception often does not require a serial point-by-point comparison. Bruce and Morgan (1975, p. 240) seem to foreshadow this proposal in suggesting that whereas "repeated patterns have to be scanned line-by-line . . . symmetric patterns might be analysed by a more global process". In fact, the existing evidence for the proposal that symmetry is detected in parallel, but repetition by a serial process, is indirect and rather inconclusive.

Julesz (1971) found that a 50-msec exposure was sufficient for the perception of symmetry in dense random-dot patterns, provided subjects fixated the axis of symmetry. It seems implausible that this rapid and reportedly "effortless" perception depended on any serial point-by-point comparison. On the other hand, this study did not include a systematic examination of either exposure duration or the number of symmetrical elements. In any case, symmetry detection for dense textures of this kind may be a special case. Julesz (1971) showed that detection of textural symmetry depends upon fixation of the symmetry-axis, but this does not apply for symmetry detection within simple two-dimensional shapes. Thus detection of textural symmetry may involve different mechanisms from the detection of figural symmetry. Indeed, Wolfe (1992) showed that there are many differences in the information that can lead to effortless texture-segmentation, or to preattentive visual search with individual shapes. In this paper, we focus on symmetry perception between contours, following several arguments for the primary role of contours in shape perception (e.g. Biederman, 1987; Marr, 1982).

Wolfe and Friedman-Hill (1992) recently reported that symmetry affects parallel stages of visual search that are widely considered to be preattentive (e.g. Treisman & Gormican, 1988). Search for a target-line with a unique orientation was more efficient when distractor-lines (but not the target) formed a background texture that was symmetrical about a vertical axis. Conversely, search became more difficult when the target was part of a symmetrical texture involving some of the distractors. These results imply that symmetry detection can arise in relatively early stages of vision that operate in parallel across the visual field. However, they do not reveal the nature of the contrast between symmetry perception and repetition detection (Bruce & Morgan, 1975; Mach, 1885). Moreover, symmetry in these experiments took a very simple, indeed minimal, form involving mirror reflections of oriented straight lines in dense texture displays. As noted above when discussing Julesz's (1971) work, it may be misleading to extrapolate from such texture displays to the case of symmetry perception for complex shapes.

Preliminary evidence that symmetry in complex shapes can have preattentive effects comes from a neuropsychological case-study of a neglect patient with brain-damage centred on the right parietal lobe (Driver et al., 1992). The patient, C.C., displayed object-centred hemineglect—that is, he failed to attend to the left side of objects throughout the visual field. Despite this severe attentional deficit, he tended to see symmetrical shapes as figures against asymmetrical grounds. Thus, the patient showed the usual effect of symmetry around the vertical on figure-ground segmentation, as described by Rock (1983) for normal observers. This intact effect of symmetry on figure-ground segmentation demonstrates that both the right *and* the left of each shape must have been represented at some stage in his visual system. As the patient neglected the left side of each shape, the implication is that symmetry between the sides of these shapes must have been derived preattentively. However, such an argument for preattentive symmetry detection is indirect, relying on the premise that the complex disabilities in left neglect (see Bisiach & Vallar, 1988, for review) can be reduced entirely to the absence of normal attention for left-sided information. Thus, although there are many studies that suggest that symmetry detection may be preattentive, none is entirely conclusive.

We turn now to the further hypothesis that, although symmetry detection may be effortless and parallel, repetition detection is not. Until now, this hypothesis has been based solely on the commonly observed difficulty of detecting repetition as compared with symmetry (e.g. Baylis & Driver, in press; Bruce & Morgan, 1975; Chipman, 1977; Corballis & Roldan, 1974; Fitts et al., 1956; Julesz, 1971). For example, Bruce and Morgan (1975) investigated the difference between symmetry and repetition detection using relatively sparse texture displays. Subjects had to judge whether these displays were "regular" (i.e. symmetrical *or* repeated) or "violated" (a slight departure from either symmetry or translation). In most of their experiments, there was a clear advantage when judging displays that were symmetrical or had small violations of symmetry. This result is *consistent* with parallel symmetry detection versus serial repetition detection, but it falls well short of conclusively establishing such a qualitative difference between the tasks. To do so would require systematic variation of the number of elements to be compared, which was not implemented.

The advantage for symmetrical displays in Bruce and Morgan's (1975) study declined when the violating elements were constrained to appear in the periphery of the display rather than in the central fixated region. This aspect of their results might be taken as evidence that symmetry detection does *not* fully operate in parallel across the visual field but relies to some extent on a checking procedure favouring elements around the midline axis of symmetry. Indeed, this was Bruce and Morgan's conclusion. They argued that the advantage for symmetry judgements over repetition is largely an artefact of the spacing of corresponding elements, which necessarily fall further apart for repeated textures than they do for symmetrical textures around the midline. However, Bruce and Morgan's (1975) results on this issue are inconclusive, as distance of the violating elements from the axis of symmetry was confounded with their retinal eccentricity. Peripheral violations of symmetry may have been harder to detect than more central violations simply because of limits in acuity or spatial resolution with increasing eccentricity (see Saarinen, 1988). The existence of such limits is perfectly consistent with the operation of a parallel process.

In sum, many existing data from psychophysics, (Julesz, 1971), cognitive psychology (Wolfe & Friedman-Hill, 1992), and neuropsychology (Driver et al., 1992) are *consistent* with the claim that visual symmetry around the vertical can be detected effortlessly in parallel. Introspection also seems consistent with this hypothesis (cf. Pascal, op. cit.). On the other hand, the difficulty of detecting repetition is consistent with serial processing of repetition. However, in all cases the evidence for parallel symmetry detection and serial repetition detection is either indirect or incomplete.

A final aspect of symmetry perception that has received much prior attention is the orientation of the axis of reflection. A number of studies have reported that observers are less sensitive to horizontal than to vertical symmetry. The first such demonstration was by Goldmeier (1937), who produced patterns that were symmetrical about both a vertical and a horizontal axis. She then introduced violations of one or other symmetry and asked subjects to indicate which of the resulting figures most closely resembled the original doubly symmetrical stimulus. Subjects generally chose the stimulus with a violation of horizontal symmetry in preference to that with a violation of vertical symmetry. Goldmeier took this as an indication that subjects find symmetry about the vertical more salient than symmetry about the horizontal. More recent studies have shown that vertical symmetry is most rapidly detected (e.g. Barlow & Reeves, 1979; Corballis & Roldan 1974; Julesz, 1971; Palmer & Hemenway, 1978; Rock & Leaman, 1963). It is unknown whether this difference arises because horizontal symmetry must be detected by processes that are qualitatively different from those used to detect vertical symmetry (e.g. serial rather than parallel).

The present study examines how judgements of symmetry and repetition are affected by differences in visual complexity, varying the number of discontinuities that have to be compared along the contours of a single shape. Our method represents an extension of the standard visual search technique (which examines whether a particular visual process is parallel by manipulating set-size) to the case of shape coding for a single shape (so that "set-size" now corresponds to the number of discontinuities on each side of the shape).

Donnelly, Humphreys, and Riddoch (1991) pioneered this use of the visual search method for the study of shape coding within single objects. Their subjects had to detect whether the separated apices of a polygon all pointed outwards (in which case the dashed polygon as a whole had *pragnanz* resulting from closure and continuation), or whether one apex pointed inwards, disrupting the form of the dashed polygon. Subjects' reaction times were independent of the number of apices in this task. These data suggest that the overall form of a polygon can be computed in parallel and provide support for the notion that aspects of form such as symmetry might be encoded in parallel within a single object. In a further experiment, Donnelly et al. (1991, Experiment 4) found that although shape descriptions could be derived in parallel within a single object, accessing these for different objects appeared to be a serial process. Thus, our question of parallel symmetry coding within an object should be distinguished from the question of parallel symmetry coding across objects.

The purpose of our first experiment was to test directly whether symmetry detection can be parallel within a single outline shape. We presented our subjects with single elongated block-shapes that had randomly jagged or "stepped" edges. Subjects had to decide whether these shapes were symmetrical about their axis of elongation. We varied the number of random deviations (which took the form of steps) along the edges that had to be compared. If symmetry detection relies on a serial, part-by-part comparison of the two edges, decision time should increase with the number of steps—i.e. with the visual "complexity" of the shapes. On the other hand, if symmetry detection proceeds in parallel within individual shapes, there should be no effect of the number of steps (within the limits of factors such as acuity).

In addition, we compared the detection of symmetry about the vertical versus horizontal, to see whether the common advantage with vertical axes of reflection arises from a qualitative difference in parallel verses serial coding. On an unpredictable half of all trials, the shapes were presented at a 90° orientation rather than upright, so that any symmetry was now about their horizontal axis of elongation rather than about the vertical. If symmetry detection about the vertical proceeds in parallel, whereas the detection of symmetry about the horizontal relies on a more serial point-by-point comparison, we should find substantially larger effects of the number of points along each side on judgements of horizontal symmetry as compared with vertical symmetry.

Our second experiment uses a similar logic to investigate the process of repetition detection. Subjects were again presented with single shapes of varying complexity and now asked to judge whether their contours were repeated. If judgements of repetition require point-by-point comparisons, we would expect reaction times and error rates to increase sharply with increasing visual complexity. As the stimuli used in Experiment 2 are analogous to those used in Experiment 1, direct comparisons between the processes of symmetry and repetition judgement can be made.

# EXPERIMENT 1

## Method

### *Subjects*

The 15 subjects—9 female and 6 male—were psychology undergraduates with normal or corrected acuity by self-report. Subjects received either course credit or were paid £3.50 ($5) for their participation.

### *Apparatus and Materials*

The experiment was conducted on an Optimal 286 microcomputer or Viglen III/33 386-compatible with colour VGA graphics in both cases. Display onsets and offsets were provided by altering the colour lookup table to ensure that they occurred within a single frame.

Example displays are shown in Figure 1. They were presented in bright red on a black background. Viewing distance was 70 cm. The shapes were elongated and approximately rectangular, with jagged "stepped" edges along their elongated axis and completely straight edges along their short axis. Vertically elongated shapes (e.g. Figures 1a and 1b) were 5.5° in height and had lateral contours on

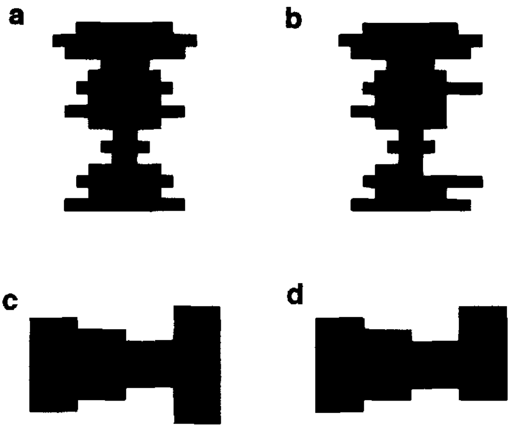


FIG. 1. Example stimuli from Experiment 1. These were shown in red on a black background. (a) A vertical symmetrical shape, with 16 steps on each elongated side; (b) a vertical asymmetrical shape (25% of the steps mismatch), with 16 steps on each elongated side; (c) a horizontal symmetrical shape, with 4 steps on each elongated side, (d) a horizontal asymmetrical shape (again, 25% of the steps mismatch), with 4 steps on each elongated side.

average 1.5° (varying randomly between 0.5° and 2.6° in 0.03° units) to the left or right of the central vertical meridian of the display. The horizontally elongated shapes (e.g. Figures 1c and 1d) had the same dimensions, but they were rotated through 90°. A new shape was generated by the same pseudorandom algorithm on every trial. The asymmetrical shapes (e.g. Figures 1b and 1d) were constructed exactly like the symmetrical shapes (e.g. Figures 1a and 1c), but 25% of the "steps" on one edge were altered to a new random value. The new value for these mismatching steps was at least 0.5° different (in distance from the centre) from the value on the other side.

The task was to respond by pressing one of two buttons (the "Z" key or the "/" key on the standard extended keyboard) with one or other index finger as rapidly as possible, depending on whether the jagged contours in the display were symmetrical or asymmetrical. The mapping of particular hands to symmetrical and asymmetrical responses was counterbalanced across subjects.

### Design

The design was within-subject with three independent variables. The first was whether the shape was vertically or horizontally elongated (henceforth, vertical versus horizontal shapes). The second factor was whether displays were symmetrical or asymmetrical, and the third was the number of pseudorandom steps along the elongated sides of each shapes (4, 8, or 16 on each side). These three factors were crossed to yield 12 equiprobable and randomly intermingled conditions.

### *Procedure*

Subjects were shown a diagram of typical displays, analogous to Figure 1, and told that they must judge whether each presented shape was perfectly symmetrical or not, responding as quickly and accurately as possible by pressing the appropriate key. The sequence of events on any one trial was then explained to them. A fixation cross was presented for 500 ms, followed by a shape centred at fixation until the subject responded, when the screen was made blank. An incorrect response produced a loud beep, whereas no feedback was given on correct trials. Following an intertrial interval of 800 msec, this sequence was repeated to produce the next trial. Reaction times (RTs) were recorded in msec.

Subjects were given 8 blocks of 150 trials. Within each block, the conditions were interleaved in a different pseudorandom sequence for each subject. At the end of each block, the subject's mean RT for correct responses was displayed on the monitor, together with the mean error rate and a message that requested that they be more accurate in the next block if the error rate had exceeded 15%, or that they respond more quickly if the error rate had been below 5%. Subjects rested for as long as they wished between blocks, pressing the space-bar to continue.

## Treatment of Results

The first block of 150 trials was discarded as practice, as were the first 2 trials of each block. Thus, 1036 trials were available for each subject. All these trials contributed to the accuracy analyses. However, the data were trimmed for RT analysis by removing incorrect responses as well as trials immediately following an error because of the variability they typically introduce (Rabbitt, 1966). Trials on which the reaction time exceeded 3000 msec or was less than 200 msec were also discarded. The combination of these upper and lower RT criteria excluded 2.0% of the recorded data (2.1% for Experiment 2). For both experiments in this paper, all further analyses were carried out using SYSTAT (Wilkinson, 1990).

## Results

The means of subjects' median RTs, together with their associated mean error rates, are shown in Figure 2a (i.e. left panels) for the vertical shapes and in Figure 2b (i.e. right panels) for the horizontal shapes. A three-way within-subjects analysis of variance (ANOVA) on the RT data showed a significant effect of orientation, $F(1, 14) = 39.4$, $p < 0.001$ (with faster responses for vertical shapes), of symmetry, $F(1, 14) = 18.5$, $p < 0.001$ (with faster responses for symmetrical shapes), and of the number of steps, $F(2, 28) = 26.1$, $p < 0.001$ (with slower responses when there were more steps). The Orientation $\times$ Number of Steps interaction was also significant, $F(2, 28) = 12.4$, $p < 0.001$ (with a greater effect of steps for horizontal shapes). No other interactions approached significance.

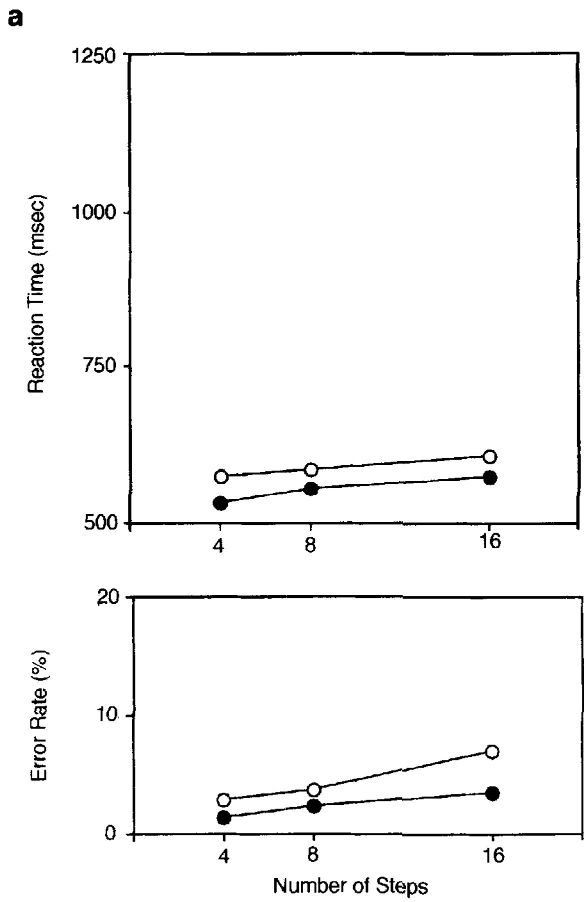


FIG. 2. Means of subjects' median RTs (above) and error rates (below) for the different display types in Experiment 1. (a) Results for vertical shapes; (b) results for horizontal shapes. Data for symmetrical stimuli are shown as filled symbols, those for asymmetrical stimuli are shown as open symbols. The extensive scale is to allow a direct comparison with the results of Experiment 2, which are plotted against the same scale as in Figure 4.

A similar three-way ANOVA on the error data showed the same pattern of results. There was a significant effect of orientation, $F(1, 14) = 28.0, p < 0.001$ (with greater accuracy for vertical shapes), of symmetry, $F(1, 14) = 3.9, p < 0.001$ (with greater accuracy for symmetrical shapes), and of the number of steps, $F(2, 28) = 25.8, p < 0.001$ (with more errors when there were more steps). The Orientation × Number of Steps interaction was also significant, $F(2, 28) = 5.9$, $p < 0.001$ (with a greater effect of steps for horizontal shapes). No other interactions approached significance.

In both RT and accuracy measures the effect of the number of steps was highly linear. Linear regression of RT against the number of steps for vertical

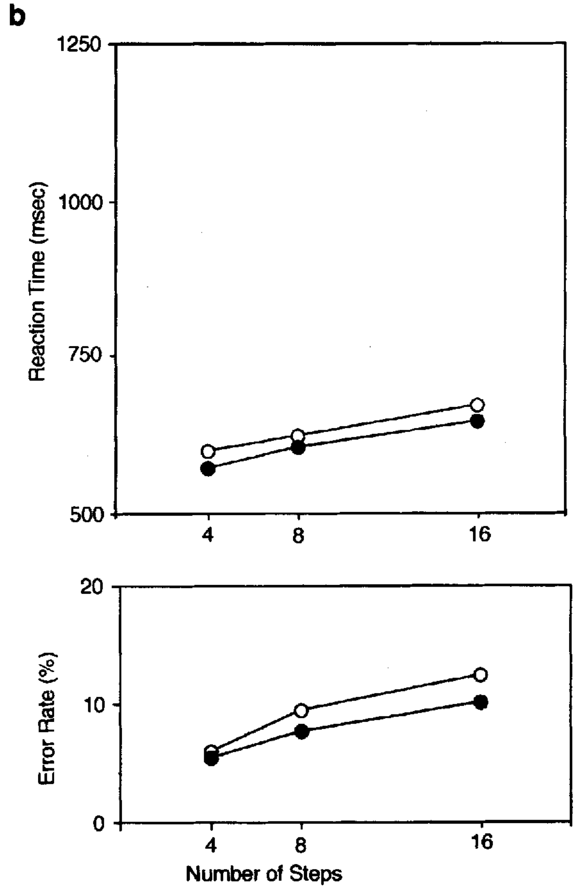


FIG. 2. Continued.

shapes gave a slope of 3.2 msec/step ($R^2$ = 0.94) for symmetrical responses and 2.5 msec/step ($R^2$ = 0.99) for asymmetrical responses. The corresponding slopes for horizontal shapes were 5.7 msec/step ($R^2$ = 1.0) for symmetrical responses and 5.8 msec/step ($R^2$ = 0.98) for asymmetrical responses. All these slopes are within the range normally taken to indicate parallel rather than serial processing of items in the visual search literature. In this case, the parallel processing we infer applies to steps rather than items.

The analogous linear regressions of error-rates against the number of steps for vertical shapes gave 0.17% errors/step ($R^2$ = 0.98) for symmetrical responses and 0.35% errors/step ($R^2$ = 0.98) for asymmetrical responses. The corresponding slopes for horizontal shapes were 0.36% errors/step ($R^2$ = 0.97) for symmetrical responses and 0.49% errors/step ($R^2$ = 0.94) for asymmetrical responses.

## Discussion

These results provide clear evidence for parallel processing of the discontinuities along the contours of a single visual shape that determine whether or not it is symmetrical. Although there were reliable effects of the number of such discontinuities on symmetry judgements, these effects were all relatively small (2–6 msec/step), falling within the range normally taken to indicate parallel rather than serial processing (e.g. Duncan & Humphreys, 1989; Treisman & Gormican, 1988). If a serial and self-terminating step-by-step comparison were involved, asymmetrical responses should be fastest, as these could be initiated as soon as a mismatch is detected, whereas more steps need to be compared before a shape can be accurately categorized as perfectly symmetrical. In fact, the opposite was found, consistent with parallel processing.

Judgements for horizontal symmetry were slower and less accurate than those for vertical symmetry, confirming previous reports (e.g. Barlow & Reeves, 1979; Baylis & Driver, in press; Corballis & Roldan, 1974; Julesz, 1971; Mach, 1885; Rock & Leaman, 1963). A new finding was that the effect of the number of discontinuities to be compared was larger for judgements of horizontal symmetry than those for vertical symmetry. However, despite this significant increase, the costs from additional discontinuities remained relatively small even for the horizontal shapes (around 6 msec/step, as compared with 2–3 msec/step for vertical shapes). It appears, therefore, that horizontal as well as vertical symmetry may be detected by parallel processing, at least under the present conditions where horizontally elongated shapes could be anticipated on a random 50% of trials.

Nevertheless, horizontal symmetry is clearly detected less readily than vertical symmetry, even when it is equally frequent. One possible explanation for the observed difference follows Broadbent (1985), who illustrated the well-known point that parallel processes can produce larger "set-size" effects as they become more noisy. On this interpretation, detection of symmetry about the horizontal would be just as parallel as for symmetry about the vertical, but greater noise in the process (perhaps due to poorer localization of a contour's component parts) would lead to a somewhat larger effect of the number of steps.

The critical result from this study is that very small costs were incurred when additional discontinuities (varied by the number of steps along the shape's edge) had to be compared in the determination of symmetry, with these costs falling in the range conventionally taken to indicate parallel processing. However, several factors were confounded with the number of discontinuities along a shape, in addition to the intended change in visual "complexity". For example, the spatial-frequency composition of shapes with many steps differed consistently from those with fewer steps. Some such aspect of our stimuli may have artifactually benefited shapes with more steps, leading to an underestimation of the costs produced when more discontinuities have to be compared. For instance, the steps were larger along the elongated axis of the shape when they were less frequent, and smaller steps might be judged more efficiently for some unknown reason. Alternatively, it might be argued that because a constant proportion of the presented steps were mismatching in asymmetrical shapes, judgements would inevitably become easier with additional steps simply because there were necessarily more mismatches.

The threat posed by these suggestions is that a true cost of comparing additional discontinuities may have been masked by some artifactual advantage for shapes with additional steps. Fortunately, any such possibility is discounted by our second experiment. In this follow-up study, the task was the same as in Experiment 1, but subjects now judged whether the two elongated sides of each shape were *repetitions* of each other—that is, when the two sides were related, they were now identical contours across a translation, as contrasted with the previous symmetrical shapes where the two sides were identical across a translation plus a reflection.

The paradox originally noted by Mach (1885) that symmetry (translation plus reflection) is more salient than repetition (pure translation) has since been confirmed many times in different tasks. Using random block patterns, Fitts et al. (1956) found that subjects could find the pattern that matched a sample more rapidly in the case of symmetrical than in that of repeated patterns (although the repeated patterns typically comprised two distinct objects and the symmetrical patterns only one). Using sparse dot-patterns, Corballis and Roldan (1974) found that when distinguishing symmetrical from repeated patterns, symmetrical judgements were made faster. Using sparse textures, Bruce and Morgan (1975) found a latency advantage for symmetrical over repeated patterns when distinguishing regularity from irregularity (provided violations of symmetry were in peripheral vision). Using even simpler textures (random $6 \times 6$ grids), Chipman (1977) found that symmetrical patterns were rated as less complex than repeated patterns. Finally, Baylis and Driver (in press) found that judgements of symmetry for the curved edges of a single nonsense object were more rapid than analogous judgements of repetition.

Thus, there is a wide range of evidence for an advantage of symmetry over repetition. This might be taken to suggest that whereas symmetry may be detected in parallel (as confirmed in Experiment 1), repetition detection may require a process of serial comparison. However, this has never been formally tested. By examining any effect of the number of discontinuities on repetition judgements, we can determine whether the greater salience of symmetry arises because, unlike symmetry, the detection of repetition within a shape requires a serial step-by-step comparison.

Note that any of the possible artifacts discussed above (in terms of spatial frequency, etc.), which might have spuriously benefited shapes with more discontinuities in Experiment 1, should apply equally to the new task of judging repetition, just as for the previous task of symmetry detection. Thus, if substantial serial effects from the number of steps are now found for repetition judgements, the potential artifacts can be discounted as explanations of our symmetry results.

# EXPERIMENT 2

## Method

Unless otherwise stated, the method followed that of Experiment 1. Subjects now judged whether or not the two elongated, jagged sides of each shape were exact repetitions of each other.

### *Subjects*

The 15 new subjects—8 female and 7 male—were again undergraduates with normal or corrected acuity by self-report. They were rewarded for participation as in Experiment 1.

### *Apparatus and Materials*

Example displays are shown in Figure 3. The task was to respond by pressing one of two buttons (the "Z" key or the "/" key on the standard extended keyboard) with one or other index finger as rapidly as possible, depending on whether the jagged contours in the display were perfect repetitions of each other (e.g. Figures 3a and 3c) or not (e.g. Figures 3b and 3d). Repeated shapes were generated just as for symmetrical shapes in Experiment 1, but the two jagged contours were now identical rather than reflected. Unrepeated contours were generated analogously to the asymmetrical shapes from Experiment 1—that is, 25% of the steps mismatched randomly, whereas the remainder were repetitions of each other, as defined above. Half the shapes were vertically elongated, half horizontally elongated. Within these categories, half had repeated jagged edges and half had unrepeated ones. The mapping of particular hands to repeated and unrepeated responses was counterbalanced across subjects. The procedure was as before in Experiment 1, with the exception of the change in task and corresponding changes in the instructions.

## Results and Discussion

The means of subjects' median RTs, together with their associated mean error rates, are shown in Figure 4a (i.e. left panels) for the vertical shapes and in Figure 4b (i.e. right panels) for the horizontal shapes. A three-way within-subject ANOVA on the RT data showed no effect of orientation, $F(1, 14) = 4.0$, n.s., no effect of repetition, $F(1, 14) = 1.2$, n.s.), but a highly significant effect of the number of steps, $F(2, 28) = 34.2$, $p < 0.001$, with additional steps causing substantial slower responses. The Orientation × Repetition interaction was

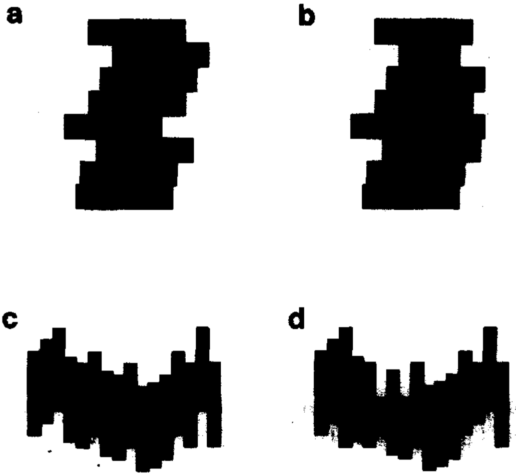


FIG. 3. Example stimuli from Experiment 2. These were shown in red on a black background. (a) A vertical repeated shape (i.e. with identical elongated contours), with 8 steps on each elongated side; (b) a vertical unrepeated shape (25% of the steps mismatch), with 8 steps on each elongated side; (c) a horizontal repeated shape, with 16 steps on each elongated side; (d) a horizontal unrepeated shape (again, 25% of the steps mismatch), with 16 steps on each elongated side.

significant, $F(2, 28) = 6.2, p < 0.05$, with slower responses to repeated displays only for the vertical shapes. No other interactions approached significance.

An analogous three-way ANOVA on the error data showed a similar pattern of results. There was no effect of orientation, $F(1, 14) = 2.6$, n.s., no effect of repetition, $F(1, 14) < 1$, but a highly significant effect of the number of steps, $F(2, 28) = 17.9, p < 0.001$. The Orientation × Number of Steps interaction was significant, $F(2, 28) = 5.2, p < 0.02$, with a greater effect of number of steps for the horizontal displays. No other interactions approached significance.

## Comparisons between Experiments 1 and 2

The most striking difference from the results of Experiment 1 is that the effect from the number of steps was dramatically larger for the present repetition judgements (compare Figures 2 and 4). Four-way mixed-design ANOVAs were carried out to analyse the difference between experiments more closely. The between-subjects factor was experiment, and the three within-subjects factors were orientation, relatedness (i.e. symmetric versus asymmetric shapes in Experiment 1, and repeated versus unrepeated shapes in Experiment 2), and the number of steps. The four-way ANOVA on the RT data showed an effect of experiment, $F(1, 28) = 22.3, p < 0.001$, with repetition-judgements in Experiment 2 slower than symmetry judgements in Experiment 1. Experiment did not interact with orientation, $F(1, 28) < 1$, but it did interact with relatedness, $F(1, 28) = 4.4, p < 0.05$, and with the number of steps, $F(1, 28) = 25.6, p <$

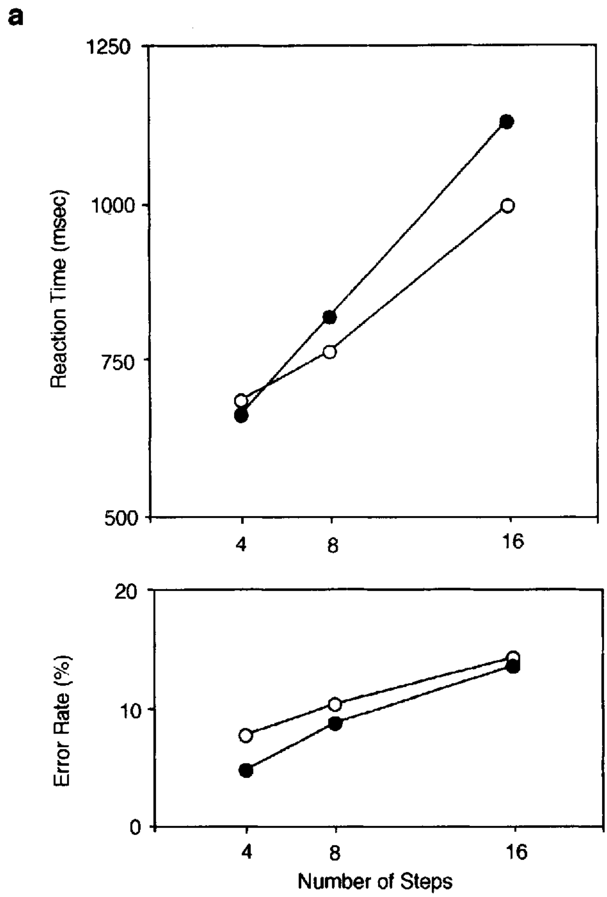


FIG. 4 Means of subjects' median RTs (above) and error rates (below) for the different display types in Experiment 2. (a) Results for vertical shapes; (b) results for horizontal shapes. Data for repeated stimuli are shown as filled symbols, those for unrepeated stimuli are shown as open symbols. The scale is the same as for the results of Experiment 1 shown in Figure 2.

0.001, with substantially greater costs from additional steps in the repetition judgements of Experiment 2.

The three-way Experiment × Orientation × Relatedness interaction was significant, $F(2, 56) = 7.2$, $p < 0.02$. This presumably arose because responses were slower for related contours only with the vertical shapes of Experiment 2 (where the related contours were repeated rather than symmetrical). We have no clear explanation for this aspect of the results at present. The advantage for detecting violations of repetition versus detecting repetition itself is consistent with a self-terminating serial search for violations (as such search would be exhaustive only in repeated displays). However, it is unclear why this result

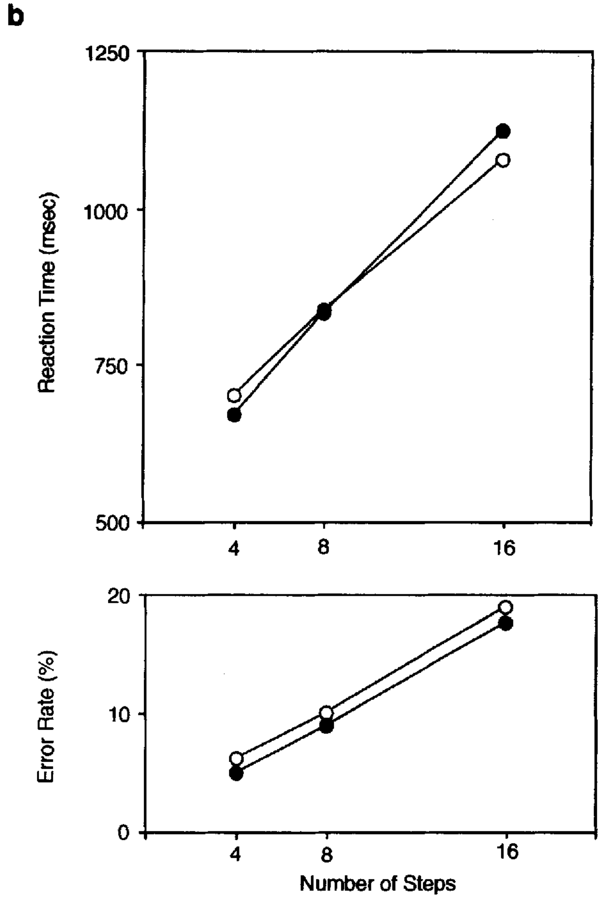


FIG. 4 Continued.

should only reach significance for the vertical stimuli, and not for the horizontal. No other three-way or higher-order interactions were significant.

A similar four-way mixed-design ANOVA on the error data showed broadly similar results. There was a significant effect of experiment, $F(1, 28) = 6.0$, $p < 0.05$, with judgements of repetition in Experiment 2 less accurate than symmetry judgements in Experiment 1. Experiment interacted with orientation, $F(1, 28) = 10.7$, $p < 0.01$, with horizontal shapes differing from vertical only in Experiment 1, and with number of steps, $F(1, 28) = 3.8$, $p < 0.05$, due to a greater cost for additional steps in Experiment 2. There were no higher-order interactions.

For both RT and accuracy measures, the substantial effects from the number of steps in Experiment 2 were highly linear. Linear regression of mean RT against the number of steps for vertical shapes gave a slope of 38.7 msec/step

($R^2 = 1.0$) for repeated responses and 26.1 msec/step ($R^2 = 0.99$) for unrepeated responses. The corresponding slopes for horizontal shapes were 37.2 msec/step ($R^2 = 1.0$) for repeated responses and 30.7 msec/step ($R^2 = 1.0$) for unrepeated responses. All these slopes are within the range normally taken to indicate serial processing in the visual search literature and contrast dramatically with the shallow slopes observed in Experiment 1. This contrast is evident in the interactions between number of steps and experiment in the omnibus ANOVAs above.

The analogous regressions of error-rates against the number of steps for vertical shapes gave 0.70% errors/step ($R^2 = 0.98$) for repeated responses and 0.52% errors/step ($R^2 = 0.99$) for unrepeated responses. The corresponding slopes for horizontal shapes were 1.04% errors/step ($R^2 = 1.0$) for repeated responses and 1.04% errors/step ($R^2 = 1.0$) for unrepeated responses.

As noted above, the large scale of these effects from the number of steps contrasts dramatically with the small effects seen in Experiment 1 and seems consistent with serial processing of individual steps (or opposing pairs of steps) during the present repetition judgements. Of course, the scale of the "set-size" slope is only one criterion for serial processing in the visual search literature. An additional criterion is that 1:2 ratios for target-present versus target-absent slopes are usually taken to indicate a self-terminating serial search (e.g. Broadbent, 1985; Treisman & Gelade, 1980; Treisman & Gormican, 1988). This latter criterion rests on several assumptions. Items are held to be processed individually and veridically in strict succession, and responses are held to be only initiated with confidence. With these assumptions, only half the presented items should need to be examined on average before a target is found when present, whereupon a target-present response can be initiated. By contrast, all the items (i.e. twice as many) must be examined before a target-absent response can be confidently initiated, hence producing the observed 1:2 ratios for target-present versus target-absent slopes in the set-size function.

We can extend this conventional reasoning to the present repetition-judgement task. Recall that either all the steps were repeated, or only 75% were repeated. Let us assume for the purpose of argument that, just as in standard accounts of serial visual search, items (in this case, the steps on each side of the shape at a particular point) are examined individually and veridically in strict succession, and that only confident judgements are made. If the repetition judgement is based upon serial self-terminating comparisons of corresponding steps along the two sides, a repeated response can only be confidently initiated when *all* corresponding steps have been examined in the case where there are four steps on each side of the shape (as the fourth pair to be examined might be mismatching). When there are eight steps on each side, at least seven corresponding steps have to be examined (because the final two steps might be deviant, but the last step cannot be deviant alone, given that 25% mismatch). When there are sixteen steps on each side, at least thirteen steps must be examined (as four steps are deviant for unrepeated shapes in this condition). Note that this estimate of the steps that must be examined as their total number increases is conservative, because it assumes that subjects realize that no less than 25% of the steps must be deviant on unrepeated trials. If we relaxed this assumption, the increase in the number of steps that must be examined on repeated trials would be even sharper, corresponding to the number of steps presented.

In the case of correct responses to unrepeated shapes, the number of steps that need be examined increases much less sharply with the number of presented steps. To determine that a shape is unrepeated should require, on average, 2.5 steps to be examined at a set-size of 4, 3.0 at a set-size of 8, and 3.4 at a set-size of 16[1]. Hence, by analogy with standard accounts of serial visual search (and assuming that a response is initiated when a mismatching step is found, with search continuing exhaustively on repeated trials because no deviance is detected), a ratio of 10.6:1 should be found in the slopes of RT against the

[1]The mean number of steps that must be examined before the first mismatching step is found can be calculated by considering all possible locations where deviant steps can occur. In the case of an unrepeated shape with four steps, this is straightforward. The deviant step is equally likely to be the first, second, third, or fourth step that is examined. Thus, the mean number of steps that must be examined in order to find this deviation step is:

$$\frac{\sum_{i=1}^{4} (i)}{\sum_{i=1}^{4} (1)} = 2.5$$

In the case of an unrepeated shape with eight steps, two of which are deviant, a noiseless self-terminating process should need to detect only one mismatching step before initiating a response. The two deviant steps are each equally likely to be the first, second, third, and so on through the eighth step that is examined. The mean number of steps that must be checked before the first deviant is encountered can be calculated by considering all of the equiprobable combinations of locations for the two deviant steps. For example, if the first deviant step is the one initially examined, the second deviant step is equally likely to be the second, third, and so on through the eighth step in the search (although a self-terminating search would not need to proceed as far as the second mismatching step, of course). Thus, there are seven ways in which the first deviant step could be the first step checked. Similarly, if the first deviant step to be encountered were the second step that was checked, the other deviant step is equally likely to be at the third, fourth, fifth, and so on through the eighth step in the search. Here, there are only six ways in which the first deviant step could be found at the second step that is examined. A similar logic produces the five ways in which the first deviant step could be found as the third step that is examined, and so forth until we reach the single way in which the first deviant step could be the seventh step checked. The mean number of steps that must be examined before search can self-terminate for unrepeated shapes with eight steps is therefore given by:

$$\frac{\sum_{i=1}^{7} [i \cdot (8-i)]}{\sum_{i=1}^{7} (8-i)} = 3.0$$

A similar but more complex reasoning allows us to calculate the mean number of steps to be examined in the case of unrepeated shapes with sixteen steps, of which four are deviant. This is given by:

$$\frac{\sum_{i=1}^{13} [i \cdot (16-i) \cdot (15-i) \cdot (14-i)]}{\sum_{i=1}^{13} [(16-i) \cdot (15-i) \cdot (14-i)]} = 3.4$$

number of steps for repeated versus unrepeated.[2] Clearly, our data are totally inconsistent with such a serial self-terminating model.

In fact, the observed slopes against the number of steps did not differ significantly for the two classes of response. The ANOVAs on Experiment 2 reported above found no interaction between response and the number of steps. Furthermore, comparison of the slopes of RT against the number of steps when computed for individual subjects found no difference between slopes for the two responses with vertical shapes, $T(14) = 2.0$, n.s., or horizontal shapes, $T(14) = 1.2$, n.s. Similarly, comparison of the error slopes found no difference between the two responses for vertical shapes, $T(14) = 0.9$, n.s., or for horizontal shapes, $T(14) = 0.0$, n.s.

The indistinguishable slopes we observe for repeated and unrepeated responses are inconsistent with a serial self-terminating search. They are consistent with an exhaustive serial search, with a serial search that terminates according to some complex rule (e.g. when the number of mismatching steps examined exceeds the number of matching steps examined[3]), or with an exceptionally noisy parallel process (Broadbent, 1985). All subjects in Experiment 2 reported during debriefing that they had had to examine individual steps successively, supporting the possibility of serial search. No subjects in Experiment 1 reported this in response to the same question.

[2]The slope for the regression of the numbers of steps to be examined (i.e. 4, 7, 13) against the presented number of steps for repeated shapes is 0.75. The corresponding slope for unrepeated shapes (where 2.5, 3.0, and 3.4 steps must be examined) is 0.071. The ratio of these two slopes is 10.6:1.

[3]The number of steps to be checked on unrepeated trials until a given weight of evidence is accumulated (or all steps have been checked) can be determined by an iterative method. The number of steps that need to be examined in order to exceed a given criterion can be calculated for every combination of locations of the deviant steps, and the mean of these numbers can be computed. Under the criterion that search only self-terminates when more evidence is found for the shape being unrepeated than repeated, an average of 3.25, 6.07, and 11.53 steps should need to be examined when the shape has 4, 8, and 16 steps on each side, respectively. What are the implications of these figures for the observed slope ratios for repeated versus unrepeated responses? The rate of increase in these theoretical averages for the number of items that must be searched on unrepeated trials can be compared to that for the theoretical numbers produced by the exhaustive search required on repeated trials (i.e. 3, 7, and 13—see main text for derivation of these). Such a comparison reveals that these theoretical values should yield an observed ratio of 1.09:1 for the slopes of repeated versus unrepeated RTs against the number of steps. The theoretical slope-ratio can be similarly calculated using other, more lax, criteria for an unrepeated response. For example, if search terminates whenever there is more than half as much evidence for non-repetition as for repetition, the slope ratio should be 1.78:1 for repeated and unrepeated responses. As the criterion for unrepeated responses is relaxed, an asymptotic value of 10.56:1 is approached for the slope-ratio (at the point where *any* evidence for non-repetition causes self-termination). The present study found slope ratios for RTs of 1.48:1 (vertical shapes) and 1.12:1 (horizontal shapes). When compared by T-tests against these theoretical ratios, the intersubject means of RT slopes calculated for individual subjects yield a ratio that differs significantly ($p < 0.05$) only from ratios greater than or equal to 1.78:1. This ratio corresponds to a criterion of self-termination only when at least half as much evidence for non-repetition has been accumulated as for repetition. Thus, on the present model, subjects' criterion must have been more stringent than this.

Whatever the precise details of their interpretation, the substantial effects from the number of steps for the repetition-judgements in Experiment 2 contrast dramatically and qualitatively with the minor effects found for symmetry-judgements in Experiment 1. This contrast allows us to rule out any account of the results from Experiment 1 in terms of artifactual benefits for shapes with additional steps. Recall our discussion of the problem that various factors could have obscured a true cost from additional steps in Experiment 1. Any such factors should apply equally to Experiments 1 and 2. As substantial costs from additional discontinuities were found in the present study, such factors can now be discounted as an explanation for the parallel results in Experiment 1.

## GENERAL DISCUSSION

The basic results from these experiments are both simple and clear-cut. Symmetry judgements about the vertical and horizontal for single two-dimensional shapes were scarcely affected by the number of discontinuities along the edges that had to be compared. The small costs incurred by additional discontinuities (2–6msec/step) fall within the range conventionally taken to indicate parallel processing and may therefore be attributed to factors such as reduced acuity for the smaller steps. By contrast, judgements of repetition about the vertical or horizontal were substantially affected by the number of discontinuities that had to be compared (with costs of 30–40 msec/step). These effects fall within the range conventionally taken to indicate serial processing.

These results confirm and extend previous observations that symmetry is detected more readily than is repetition (Baylis & Driver, in press; Bruce & Morgan, 1975; Corballis & Roldan, 1974; Julesz, 1971). Our findings go further, revealing that processing differs qualitatively for symmetry and repetition, rather than just quantitatively. In agreement with previous conjectures (e.g. Pascal, 1950), symmetry within a shape can be detected in parallel, at least when the potential axes of symmetry are restricted to two known possibilities. However, under the very same conditions, detection of repetition within a shape apparently requires serial processing.

We propose that the source of this qualitative difference is that only symmetry judgements can be based on shape descriptions derived when edges are given figure-ground assignment. This proposal follows the arguments of Baylis and Driver (in press), who recently adapted Hoffman and Richards' (1984) general-purpose theory of shape perception to explain the ease of symmetry judgements. Specifically, they suggested that symmetry perception emerges naturally from shape description, rather than as the result of some specialized mechanism for its detection.

Hoffman and Richards (1984) originally proposed that shapes are coded by decomposition into parts according to a computationally simple method that reflects a fundamental law of nature. The generic intersection of two rigid bodies produces concave cusps at almost all points of intersection. If these cusps are smoothed, they become negative minima of the principal curvature of the surface. Thus minima of curvature generally result from the intersection of two bodies, and segmentation at these points can yield the parts from which an object was generated (see also Biederman, 1987). This minima rule results in convexities being coded as parts, with concavities as the divisions between them. This scheme is illustrated in Figure 5 for pseudorandom shapes, where the major boundaries between parts on the minima rule are given by arrows. Preliminary evidence that the mimima rule for part decomposition applies to human shape perception was provided by Braunstein, Hoffman, and Saidpour (1989). More conclusive data have since been obtained by Baylis and Driver (in press) and Driver and Baylis (in press).

Baylis and Driver (in press) noted that symmetry may be so salient in displays like those in Figures 1a or 5a precisely because the two sides of the shape receive exactly the same decomposition into component parts by the minima rule during routine shape perception. That is, every convexity or concavity on one side of the figure has a corresponding convexity or concavity on the other side. Thus, symmetrical shapes are unique in having a perfectly matching part-decomposi-

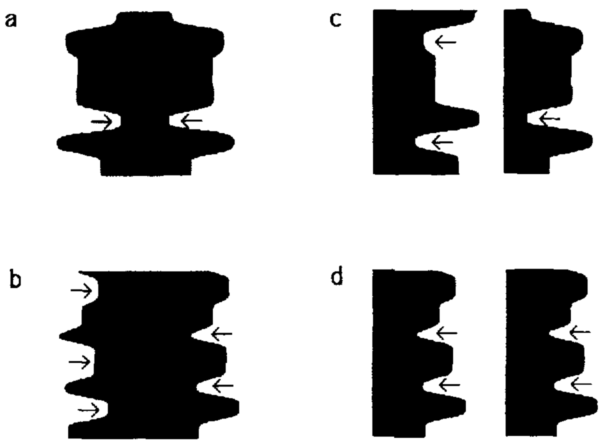


FIG. 5. Example shapes from Driver and Baylis (in press, Experiments 1 and 4). The arrows indicate the major divisions between parts at concave points of minimum curvature on the occluding contour (cf. Hoffman & Richards, 1984). (a) As a consequence of its symmetry, this shape has matching part-decompositions on each side; (b) by contrast, a shape with repeated contours does not have matching part-decompositions on each side, as indicated by the arrows; (c) The curved contours in these two shapes are symmetrical, even though the contours do not receive matching part-decompositions, as indicated by the arrows; (d) The curved contours in these two shapes are repeated yet receive matching part-decompositions. Baylis and Driver (in press) found that symmetry judgements were easier than repetition judgements with the format exemplified by (a) and (c). The reverse was found for the format shown in (c) and (d).

tion for their two sides. This does not apply in the case of repeated rather than symmetrical contours (e.g. Figures 3a or 5b), as every convexity (i.e. part) on one side now has a corresponding concavity (i.e. part-boundary) on the other side, resulting in mismatching part decompositions for the two sides.

Baylis and Driver (in press, Experiments 1 and 4) found support for this account by the following logic. As argued above, symmetrical contours within a single shape will always have matching part-descriptions, and repeated contours will have mismatching part-descriptions (Figures 5a and 5b.) However, consider the case where the critical contours belong to separate shapes, with figure-ground factors manipulated to reverse the assignment of convexity and concavity for just one of them (as in Figures 5c and 5d). Now the reverse applies (as compared with Figures 5a and 5b) in terms of part-decomposition. Symmetrical contours have mismatching part-descriptions in this format (e.g. Figure 5c), whereas repeated contours now have matching part-descriptions (e.g. Figure 5d). Under these conditions, Baylis and Driver (in press, Experiments 1 and 4) found that the Mach phenomenon reverses—that is, repetition now becomes easier to judge than symmetry. This result suggests that the relative salience of symmetry and repetition depends primarily upon whether part-descriptions match.

These ideas can be brought to bear on the present findings. Our results may arise simply because the visual system codes the layout of component parts in parallel for individual shapes. Such a description would inherently code whether a shape was symmetrical, because in this case part-descriptions would match for the two sides. In contrast, such a part-description could not reveal whether a shape's contours are repeated, as the equivalence between repeated contours would be obscured by the part-decompositions being different. Instead, subjects may have to attend effortfully to the details of each repeated contour in order to overcome the differences in part-decomposition introduced in the parallel shape description. In other words, serial coding of repeated contours may be required because these are only equivalent at the level of locally attended edges. On the other hand, parallel coding of symmetry would emerge naturally from the parallel derivation of a global shape description in terms of component parts. Our suggestion that the component parts of a single shape may be derived in parallel accords with previous evidence from shapes that are neither parallel nor repeated (Donnelly et al., 1991).

It remains to be tested whether the parallel part-descriptions revealed by the present symmetry judgements can be encoded in parallel for multiple objects as well as within single shapes. It is possible that attention must be directed to each object in turn in order for these descriptions to be derived (see Baylis, 1994; Baylis & Driver, 1993; Donnelly et al., 1991). Putting such questions to one side for the present, the present account makes one clear prediction for shape comparisons between objects rather than within objects. We found that symmetry perception appears to operate in parallel for single shapes, but repetition is apparently detected by serial checking. However, the reverse may apply when figure–ground assignment is manipulated in the manner shown in Figures 5c and 5d. Here, part-descriptions match for the repeated contours (Figure 5d) but not for the symmetrical contours (Figure 5c). Thus, provided that part-descriptions have been derived for both shapes (possibly requiring attention to each in turn), repetition detection should proceed in parallel for cases such as Figure 5d. Conversely, serial checking may be required for symmetry detection in displays like Figure 5c. We are currently designing experiments to test this prediction.

Whatever the outcome of this future research, our present findings clearly establish that symmetry perception can proceed in parallel within a single shape, whereas the detection of repetition within a shape apparently requires serial checking. These results are consistent with Baylis and Driver's (in press) proposal that shape description by decomposition into parts (in accordance with the minima rule) occurs necessarily as the edges of individual shapes acquire figure–ground assignment.



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