Directing Spatial Attention Within an Object: Altering the Functional Equivalence of Shape Descriptions

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Three experiments extended the demonstrated effects of spatial attention to a new area, the perceptual organization of objects. We manipulated observers' fixation location, their spatial attention location, and their intentions to hold one alternative of a Necker cube that had been altered in one region to favor one of the alternative interpretations (the biased region) and measured reports about the perceived organization of the cube over 30-s trials. Regardless of fixation location, responses showed obligatory effects of the bias only when observers attended to the biased region of the cube and not when they attended to the unbiased region of the cube, even when the biased region lay between fixation and the attended unbiased region. On the basis of these experiments, we argue that spatial attention operates through mechanisms of facilitation and inhibition to determine the functional nature of the structural description of an object.

This article is directed to the question of whether it is possible to pay attention selectively to subregions within an object while ignoring other subregions or whether attention must be directed to an object in its entirety. Kahneman and Henik (1977, 1981) and their colleagues (Kahneman & Treisman, 1984; Treisman, 1988) have argued that when attention is directed to an object, responses to all properties, attributes, and parts of that object are obligatory; that is, attention cannot be focused preferentially on a subregion within a preattentively defined object. On the other hand, based on experiments showing that perceptual organization can depend more on the subregion of an object to which fixation and attention is directed than on unfixed, unattended regions, Peterson and Hochberg (1983, 1989; Hochberg, 1968, 1982; Hochberg & Peterson, 1987) have argued that attention can be directed preferentially within an object.

The tasks and objects upon which the evidence supporting these two hypotheses rests are very different. Kahneman and Henik (1977, 1981) measured memory performance, or Stroop interference. They created "objects" by embedding words within geometric shapes or by grouping strings of alphanumeric characters together according to proximity or similarity of color. These objects and tasks suited their interest in examining whether preattentive processes necessarily limit the minimum area to which spatial attention can be focused, but the use of these objects and tasks may limit the generalizability of their results. For example, although variables like proximity and similarity of color are clearly important for segmentation and grouping (Banks & Prinzmetal, 1976; Beck, 1972, 1982; Pomerantz, 1981; Treisman & Gelade, 1980), it is not apparent which, if any, preattentive processes are involved in identifying objects, such as three-dimensional (3D) cubes or two-dimensional (2D) depictions of 3D cubes (cf. Biederman & Ju, 1988; Spelke, 1988). Moreover, recent evidence points to the error of assuming that gestalt variables always operate before other organizing processes such as shape recognition (Peterson, Harvey, & Weidenbacher, 1990; Spelke, 1988). In addition, the objects used by Kahneman and Henik were objects in which the location but not the identity of the local elements was relevant to the global object structure. As Pomerantz (1981, 1983) has pointed out, objects such as these should be distinguished from objects constructed from local elements with globally relevant identities.

On the other hand, Peterson and Hochberg (1983, 1989; Hochberg & Peterson, 1987) measured reports about the alternating organization of 3D wire-frame Necker cubes or 2D depictions of such cubes in order to examine whether the perceptual organization of an object was necessarily determined by objectwide properties, as implied by gestalt and gestalt-derived simplicity metrics, or whether more piecemeal organization could occur. Peterson and Hochberg's experiments were not designed to separate the effects of spatial attention location from the effects of fixation location, however, so their findings are only suggestive of attentional effects.

In the experiments reported here, we used the same altered Necker cubes objects used by Peterson and Hochberg (1983) to pursue the possibility that the allocation of spatial attention within a multistable object can have functional significance for its perceived depth organization. Multistable objects (and the associated perceptual processes) have been relegated to a special class by theorists who doubt the objects' ability to be representative of other objects (and consequently, of the perceptual processes involved in perceiving other objects; e.g., Gibson, 1959). We do not agree with this distinction and argue that multistable objects and shapes are representative of other objects and shapes for the following reasons. First, ambiguity may be a pervasive property of perceptual processing. For example, recent theories of perceptual organization propose that objects and shapes are identified through a process in which the extracted parts of an object are matched...
Spatial Attention and the Organization of Multistable Figures

The hypothesis that allocating spatial attention to a part or a subregion of an object might influence its perceived organization has typically rested on the constructivist assumption that the first glance at a figure instantiates a hypothesis about the identity of the figure that provides the context for interpreting subsequent glances (Hochberg, 1968; Neisser, 1967; Simon, 1967). An implicit assumption of this view is that some parts of a reversible figure must favor one interpretation whereas other parts must favor the alternative interpretation, although these distinctive parts must be capable of being assimilated into the alternative interpretations (Chastain & Burnham, 1975).

One way to test the constructivist view is by examining whether the eyes come to rest on different object parts just before reversal into the different alternatives for a multistable figure. Such tests have generally been unsatisfactory for a constructivist view. Although eye movements do seem to be coupled with reversals, it is often unclear whether they precede or follow reversal (Ellis & Stark, 1979; Pfeiffer, Eure, & Hamilton, 1956). Moreover, in one experiment in which eye movements clearly occurred more often before than after reversal, the locations to which the eyes moved did not change with the size of the objects, and hence with the location of the would-be distinctive features (Ellis & Stark, 1979). Furthermore, it has been shown that reversals can occur in stabilized images when eye movements cannot bring different parts of the object into foveal vision (Pritchard, 1958).

Tsai and Kolbet (1985) examined whether spatial attention location, rather than fixation location, predicted which organization of multistable figures would be perceived. To do so, they first identified the distinctive features for the two alternative interpretations of the Jastrow duck/rabbit figure by asking one set of observers to decide which side of the figure favored the duck interpretation and which side favored the rabbit interpretation. Tsai and Kolbet next showed brief exposures of the duck/rabbit figure to another set of observers who had been instructed “to try to see the rabbit” or “to try to see the duck.” Immediately after the brief exposure of the duck/rabbit figure, a letter, which observers were required to identify, was exposed briefly in either the left or the right visual field.

Tsai and Kolbet (1985) found that, on trials on which observers tried to see the rabbit, they were faster to name letters flashed in the side of the visual field judged by other observers to contain the distinctive part for the rabbit interpretation. Similarly, on trials on which observers tried to see the duck, they were faster to name letters flashed in the side of the visual field judged by other observers to contain the distinctive part for the duck interpretation. Because Tsai and Kolbet’s subjects never reported about the perceived organization of the duck/rabbit figure, however, we know only that the subjects who were instructed to try to see the duck or the rabbit had the same intuitive ideas about which parts of the figure favored which interpretation as did the subjects who had previously judged the distinctive features; we have no evidence that the allocation of attention influenced which interpretation was seen. Hence, while Tsai and Kolbet’s experiments may provide additional evidence that attentional allocation facilitates the detection of letters (Eriksen & Hoffman, 1972a, 1972b; Posner, Snyder, & Davidson, 1980), they can provide no evidence that attentional allocation is of any consequence for the organization of multistable figures.

Peterson and Hochberg’s experiments (1983, 1989; Hochberg & Peterson, 1987) suggesting that attention can be directed to subregions of multistable figures are not subject to the same criticisms as Tsai and Kolbet’s (1985), because observers in Peterson and Hochberg’s studies reported about perceptual organization. We next describe those studies in some detail because the experiments we report here use the same basic paradigm.

The stimuli used by Peterson and Hochberg were 2D and 3D cubes that were biased toward one interpretation by use of shading and occlusion cues present in only one half of the cube, as shown in Figure 1. Observers were asked to fixate and attend to the internal intersection in either the biased region or the unbiased region of the cube (see Points 1 and 2 in Figure 1) for 30-s trials and to report about alternations in the perceived depth organization of the lines (or wires) in that region. On alternate trials, Peterson and Hochberg manipulated viewers’ intentions by instructing them to “try to hold” a local organization consistent with one of the two depth organizations of the cube. Peterson and Hochberg were testing the predictions of a simplicity metric; accordingly, they used a relatively small object—the two internal intersections were
separated by less than $2^\circ$ of visual angle—to provide a reasonable test of the theory.

Peterson and Hochberg predicted that if the perceived organization was always the simplest organization computed across the entire object, as predicted by the simplicity metric (Boselie & Leeuwenberg, 1986; Buffart, Leeuwenberg, & Restle, 1981; Leeuwenberg, 1971), even when fixation and attention were located in the unbiased region of the cube, then, under both conditions of intention, the bias present in the unfixated, unattended, and biased region should influence the organization perceived in the fixated, attended, and unbiased region of the cube. In that case, observers fixating and attending to the unbiased region would report seeing only (or predominantly) the organization consistent with the bias, which is the question of interest here.

Peterson and Hochberg's experiments supported the latter hypothesis: Even though the bias was effective when observers fixated and attended to the intersection in the biased region (i.e., observers mostly reported seeing the organization consistent with the bias), this had no observable effect on the perceived organization of the cubes when observers fixated and attended to the intersection in the unbiased region (i.e., observers were approximately equally successful at holding both potential interpretations of the cube).

Thus, Peterson and Hochberg succeeded in showing that perceptual organization varied when observers were instructed to fixate and attend to different subregions within an object (see especially Hochberg & Peterson, 1987; Peterson, 1986). Because Peterson and Hochberg did not attempt to separate the effects of fixation location and attention location, however, their results might be due to differences in the perceptibility of the biased region from the two different fixation points rather than to attentional effects. Further complications are raised by the fact that with fixation on the internal intersection in the biased region, the biasing information fell in both visual hemifields, whereas with fixation on the internal intersection in the unbiased region, the biasing information fell entirely in one visual hemifield. Hence, what looks like an ability to preferentially allocate attention within an object may simply reflect an ability to allocate attention preferentially to one hemifield (Hughes & Zimba, 1985).

Accordingly, the question of whether directing attention to a subregion of an object can have functional significance for the object's perceived organization remains unanswered. In the experiments reported here, we examined this question directly by separating fixation location from spatial attention location. Observers were instructed to fixate one of three locations: in the center (center fixation), or to the right or the left of the cube (side fixations), as shown in Figure 2. The cubes were small, thus all regions of the cube were perceptible (the maximum distance from a fixation point to the far edge of a cube was $1.8^\circ$). From each fixation location, observers participated in two conditions of attention: spatial attention centered on the internal intersection in either the biased region or the unbiased region (see Figure 1, Intersections 1 and 2, respectively). In addition, each spatial attention instruction was paired with two intention instructions: Observers were asked to try to hold the organization consistent with the bias or the organization inconsistent with the bias. (The intention instructions were not phrased in these terms; subjects were asked to try to keep either the vertical or the horizontal line in front at the location to which their attention was directed. We use the terms consistent and inconsistent throughout this article to avoid potential confusions that may be caused by the use of cubes biased at each of the two internal intersections toward both orientations.)

Intention instructions were originally used by Peterson and Hochberg (1983) to examine the conditions under which viewers can intentionally influence perceptual organization. In this study, the intention instructions are used to place upper and lower limits on subjects' biases to see either alternative. Accordingly, the intention instructions allow us to examine the conditions under which the unbiased region of the cube can be perceived in the organization inconsistent with the bias, which is the question of interest here.

If directing attention to subregions within an object can have functional significance for the perceived organization of the object, then the results obtained previously by Peterson and Hochberg (1983; Hochberg & Peterson, 1987) ought to be replicated here. Specifically, even when the shading and occlusion cues effectively bias the interpretation perceived when observers direct their spatial attention to the biased region, the unbiased region should remain reversible and open to the observers' intentional influence when they direct their attention there.

If the previous results were attributable to variables that vary with fixation location but not with spatial attention location, then comparison of performance across the different conditions used in these experiments might begin to identify those variables. For example, in the center fixation condition, the biased region falls in one hemifield and the unbiased

Figure 1. One of the partially biased Necker cubes used by Peterson and Hochberg (1983). (At 1, the intersection in the biased region, occlusion and shading specify that the horizontal line is in front of the vertical line. At 2, the intersection in the unbiased region, no information has been added to specify that either line is in front. A minor diagonal bisecting the cube would separate the biased region from the unbiased region.)
region in the other, whereas in the side fixation conditions, both regions fall entirely in one hemifield. Hence, if the unbiased region is more ambiguous in the center fixation condition than in the side fixation conditions, that would imply a role for hemifield-specific attentional strategies. On the other hand, in the center fixation condition, the two intersections are equally close to fixation (and hence, equally perceptible), whereas in the side fixation conditions, the biased and unbiased regions fall at different distances from fixation. Hence, if the unbiased region is less ambiguous in the center fixation condition than in the side fixation conditions, that would imply that the relative perceptibility of the biased and unbiased regions could account for some of the piecemeal perception effects. We can examine perceptibility effects further by comparing whether the unbiased region is more ambiguous in the side fixation condition in which the fixation point lies on the side of the cube far from the bias rather than on the side of the cube near the bias (fixation to the left and right, respectively, for the stimuli shown in Figure 2).

The three experiments reported here show that directing observers' attention to subregions of an object can have functional significance for the perceived organization of the object. In Experiment 1, observers viewed the two cubes shown in the top and bottom rows of Figure 2. The results were difficult to interpret without a baseline, so in Experiment 2, we examined performance with biased cubes in relation to performance with an unbiased cube. In Experiment 3, the results of Experiment 2 were replicated with observers who participated in an eye movement monitoring task in addition to the tasks used in the first two experiments.

Experiment 1

Method

Subjects. Subjects were 12 students at the State University of New York at Stony Brook, who participated in this experiment in order to fulfill a requirement for an introductory psychology course. All subjects had vision that was normal or corrected to normal.

Stimulus and apparatus. The stimuli were line drawings of the cubes shown in Figure 2, which were versions of the cubes used by Peterson and Hochberg (1983). The stimuli were positioned 84 cm from the subjects so that the cubes subtended 1.6° of visual angle and the distance between the biased and unbiased intersections was approximately 1° of visual angle. Figure 2a was biased toward the orientation that faces downward and to the left, and Figure 2b was biased toward the orientation that faces upward and to the right. The biasing was achieved by the use of shading and occlusion cues (see Peterson & Hochberg, 1983, for details regarding the design of these cubes). If the influence of the bias extends to the unbiased region, then the organization of the internal intersection in the unbiased region should be consistent with the organization of the internal intersection in the biased region. The consistent organization of the intersection in the unbiased region would be that the horizontal line is in front of the vertical line in Figure 2a and that the vertical line is in front of the horizontal line in Figure 2b. Reports of the aforementioned organizations will be considered responses consistent with the
bias. Reports of the reversed organization in these regions will be considered responses inconsistent with the bias.

From the right and left fixation points, the distance to the near internal intersection was approximately 0.8° of visual angle, the distance to the far internal intersection was approximately 1.4°, and the distance to the farthest edge of the cube was 1.8°. In pilot studies, observers had judged the entire cube to be perceptible at this size. From the center fixation point, the distance to each of the two internal intersections was approximately 0.5°. The figures shown to the observers contained only the fixation point relevant for the current trial.

Subjects pressed keys to report whether the horizontal or vertical line appeared forward. The frequency, order, and duration of these key presses were recorded by a Rogers A6 Timer/Driver in an Apple IIe computer.

Procedure. Subjects participated in the experiment individually. First, we showed subjects a reversible cube and pointed out to them the two alternative interpretations. We told them that we were examining the degree to which viewers could intentionally influence the way in which attended but unfixated objects were seen.

We manipulated intention through the use of hold instructions (Peterson & Hochberg, 1983). Before each trial, we asked viewers to try to hold either the horizontal or the vertical line in front of the attended intersection. For Figures 2a, b, and c, the instructions to hold the vertical line forward at the biased intersection and the horizontal line forward at the unbiased intersection were instructions to hold the organization consistent with the bias. For Figures 2d, e, and f, the instructions to hold the horizontal line forward at the biased intersection and the vertical line forward at the unbiased intersections were instructions to hold the organization that was consistent with the bias. We instructed viewers not to move their eyes when following these hold instructions but to simply concentrate on holding the instructed organization.

Before each trial, we showed observers the version of Figure 2 they would be viewing throughout the trial. The instructions about the location to which they were to direct their spatial attention were given with reference to the fixation point. For the side fixation conditions, they were told to center their attention on either the "near" or the "far" intersection. For center fixation trials, they were told to center their attention on either the "top" or the "bottom" intersection. We instructed them to keep their attention right around the instructed location.

During each trial, viewers pressed buttons to indicate whether the horizontal or the vertical line appeared forward. We instructed them to remove their fingers from the buttons when the attended intersection appeared flat, when their attention wandered from the instructed intersection, or when their eyes strayed from the fixation point.

Before the experimental trials, observers participated in eight practice trials. On four of these trials, they viewed an unbiased Necker cube (Figure 3c) from a center fixation point. On the other four practice trials, they viewed this unbiased cube from either the left or the right fixation point. (Half of the subjects viewed the cube from the left; the other half viewed the cube from the right.) These sets of four practice trials consisted of one trial with each hold instruction paired with instructions to attend to each of the two intersections.

After subjects completed each of the practice trials, we stressed to them the importance of maintaining fixation on the fixation point, keeping attention right around the location of the instructed intersection, and signaling the occurrence of any reversal (regardless of how brief).

Observers participated in 24 experimental trials lasting 30 s each. For each cube, there was one trial in which subjects attended to each intersection while following each hold instruction from each fixation point. Observers viewed the experimental figures only during the experimental trials. They participated in all four trials with each figure–fixation point combination before viewing the next figure.

Figure order, fixation order, and hold instruction order were counterbalanced within and across subjects.

Data analysis: Intention index. For each 30-s trial, we computed the total duration that viewers reported seeing the instructed line (I) in front and the total duration that they reported seeing the un instructed line (U) in front. The data from each trial were then represented as an intention index (Peterson, 1986),

$$I = (I - U) / (I + U)$$

When there is a substantial amount of time during the 30-s trials during which subjects pressed neither key, the intention index provides a good measure of the relative durations of seeing the two alternative interpretations. We chose to use this measure because we encouraged the observers to report lapses of attention or fixation by removing their fingers from both keys.1

The I can range from +1 to −1 for a single condition of hold instruction and attention to an intersection, reflecting total success (+1) or total failure (−1) at following the intention instructions. We performed an analysis of variance (ANOVA) on the intention indices with four within-subject variables: fixation location (left, center, or right); cube type (facing downward or upward); spatial attention location (intersection in the unbiased region or the biased region); and hold instruction (hold the interpretation consistent with the bias, or hold the interpretation inconsistent with the bias).

Malleability. In addition to the individual I calculated for each intersection for each combination of attention location and hold instruction, we examined the mean I across hold instructions for each attention location as a measure of the effectiveness of the viewer's intentions. If the intersection in the attended region is malleable (i.e., subject to influence from the viewers' intentions), the mean I will be significantly greater than zero. If the intersection is not malleable (i.e., if only one organization is seen regardless of the viewer's intentions or if the cube alternates between two percepts regardless of the viewer's intentions), the mean I for a given intersection will not differ from zero (see Peterson, 1986).

Lapses. We summed the durations that neither response button was pressed during each trial as a measure of lapses in subjects’ following the fixation and attention instructions. Differences in the durations of recorded lapses can provide an index of how difficult it was to maintain fixation or attention in the various conditions.

Results

Intention effects. The ANOVA on the individual Is failed to show any effects of fixation: The main effect of fixation location was not significant, F < 1, nor were any interactions involving fixation location, all ps > .35, thus ruling out both perceptibility and hemifield selectivity as the sole explanations of Peterson and Hochberg’s results.

As can be seen in the top half of Table 1, observers were more successful at holding the interpretation consistent with the bias than the interpretation inconsistent with the bias, $F(1, 11) = 9.11, MS_e = 0.38, p = .012$. However, the difference between the ability to hold the consistent and the inconsistent interpretations was greater when attention was directed to the biased as opposed to the unbiased region, as indicated by an interaction between attention location and hold instruction, $F(1, 11) = 5.0, MS_e = 0.25, p = .047$. Moreover, the consistency effects were stronger in the downward-facing cube than

1 All effects, where applicable, are replicated with total durations.
Table 1

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<td>Consistent</td>
<td>Inconsistent</td>
<td>Consistent</td>
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</tr>
<tr>
<td>Cube type</td>
<td>hold instruction</td>
<td>M</td>
<td>SE</td>
<td>M</td>
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<tr>
<td>Up</td>
<td>0.694</td>
<td>0.074</td>
<td>0.359</td>
<td>0.085</td>
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<tr>
<td>Down</td>
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<td>0.063</td>
<td>0.360</td>
<td>0.127</td>
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<tr>
<td>M</td>
<td>0.714</td>
<td>0.065</td>
<td>0.360</td>
<td>0.164</td>
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Intention index

Lapses (in seconds)

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<tr>
<td>Cube type</td>
<td>hold instruction</td>
<td>M</td>
<td>SE</td>
<td>M</td>
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<tr>
<td>Up</td>
<td>4.591</td>
<td>1.263</td>
<td>7.346</td>
<td>1.180</td>
</tr>
<tr>
<td>Down</td>
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<td>5.773</td>
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</tr>
<tr>
<td>M</td>
<td>4.468</td>
<td>1.028</td>
<td>6.559</td>
<td>1.077</td>
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in the upward-facing cube, as reflected in the ANOVA by an interaction between cube type and hold instruction, $F(1, 11) = 5.19, M S_e = 0.05, p = .044$. Indeed, the Is obtained at the unbiased intersection for hold-consistent and hold-inconsistent trials differed for the downward-facing cube only, $t(11) = 2.74, p < .02$, but not for the upward-facing cube, $t < 1$.

Malleability. Both intersections of the cube were malleable: The mean Is across hold instructions for the intersections in both the biased and unbiased regions were greater than zero for both cubes, all $p s < .01$, indicating that the organization perceived at both intersections of the cube was influenced by the viewer’s intentions. Compared to similar conditions of other experiments (Hochberg & Peterson, 1987; Peterson & Hochberg, 1983), the intersection in the biased region was quite malleable (mean I across hold instructions = 0.50).

Lapses. Lapses are also shown in Table 1. The observers in Experiment 1 indicated lapses in fixation or attention for an average of 5.3 s per trial. The reported more lapses when they tried to hold the inconsistent interpretation, as reflected in the ANOVA by a main effect of hold instruction, $F(1, 11) = 7.67, M S_e = 11.88, p = .018$. This was true for both cubes only when attention was directed to the biased intersection, however; when attention was directed to the unbiased intersection of the upward-facing cube, fewer lapses were recorded on hold-inconsistent trials than on hold-consistent trials. These effects were reflected in the ANOVA by a two-way interaction between spatial attention location and hold instruction, $F(1, 11) = 9.88, M S_e = 6.8, p = .009$, and a three-way interaction among cube type, attended location, and hold instruction, $F(1, 11) = 10.18, M S_e = 6.15, p = .009$.

Discussion

Experiment 1 did not provide a clear answer to the question of whether attention can be restricted to subregions of unfixated objects. Observers attending to both the biased and unbiased intersections were more successful at holding the interpretation consistent with the biased intersection, as would be predicted if attention cannot be preferentially allocated within an object. Other results suggest that the response to the biased region may not have been obligatory, however. For example, differences between hold-consistent and hold-inconsistent trials with attention directed to the intersection in the unbiased region were found in the downward-facing cube but not in the upward-facing cube. Even in the downward-facing cube, the difference between the durations of seeing the consistent and inconsistent interpretations was larger when attention was directed to the intersection in the biased region than in the unbiased region.

None of the effects of fixation location was significant, implying that Peterson and Hochberg’s results are not attributable to the location of the biased and unbiased intersections in relation to the two hemifields, nor to the relative perceptibility of the two intersections from the different fixation points. Moreover, the fact that no effects of fixation were obtained in this experiment suggests that the bias was equally effective when attention was directed to the intersection in the biased region, regardless of whether fixation was located near to or far from the biased intersection. Conversely, when attention was directed to the unbiased region, the biased region was no more effective when it was located between fixation and the attended location than it was when it was located farther from fixation.

Although the absence of fixation effects rules out a strict perceptibility account, the fact that the biased intersection was so malleable (mean I across hold instructions = 0.50) might be attributed to its being less perceptible when unfixated in this experiment than when fixated in previous experiments. That is, the effectiveness of the occlusion and shading information at the biased intersection may have been diminished when it was removed from fixation by at least 0.5° (the distance between fixation and the intersection in the biased region in the center fixation condition). Inasmuch as we do not know what the baseline reversal rate of an unbiased cube is when viewed under the conditions used in Experiment 1,
however, we cannot be sure of the extent of the influence exerted either by the viewers' intentions or by the shading and occlusion in the biased region. Accordingly, we included an unbiased Necker cube as a control cube in Experiment 2 so that we could better measure the effectiveness of the bias when it is unfixated.

The unbiased cube served as a baseline for viewers' a priori preferences as well. For example, the fact that a larger \( I \) was obtained for hold-consistent trials than for hold-inconsistent trials with attention directed to the intersection in the unbiased region of the downward-facing cube (but not the upward-facing cube) might reflect the preference that viewers have for seeing a Necker cube in the downward-facing orientation (e.g., Price, 1967). Alternatively, a larger \( I \) on hold-consistent trials than on hold-inconsistent trials with attention directed to the intersection in the unbiased region might reflect a strategic widening of attention to include the biased intersection on hold-consistent trials. Of course, if the increase in \( I \) on hold-consistent trials with attention directed to the intersection in the unbiased region reflects a nonobligatory strategy adopted by the viewers, similar results would be expected for the upward-facing cube, unless a priori preferences to see the cube in the downward-facing orientation interacted with this strategy. Hence, including an unbiased cube as a baseline condition in Experiment 2 may eliminate the difference between the two cubes observed in Experiment 1.

Experiment 2

Method

Subjects. The subjects were 12 students from the University of Arizona who participated in this experiment as part of a course requirement. All had vision that was normal or corrected to normal.

Stimulus materials, apparatus, and procedure. The stimuli used in Experiment 2 are shown in Figure 3. In addition to the unbiased Necker cube, we used cubes that were biased at the top rather than at the bottom to examine the generality of the effects obtained in Experiment 1.

The viewing distance and stimulus dimensions were the same as those used in Experiment 1. Observers' responses were collected and analyzed on a Compaq 386 microcomputer. The procedure was the same as that used in Experiment 1.

Data analysis: Bias influence index. The responses to the reversible Necker cube served as a baseline against which to examine the responses to the two biased experimental cubes. As in Experiment 1, an intention index, \( I \), was computed for each combination of cube, fixation location, attention location, and hold instruction. Next, we calculated a bias influence index (\( B \)) for each of these conditions by subtracting the \( I \) obtained with the same fixation point and same hold instruction at the analogously distant attention location in the unbiased control Necker cube (\( I_c \)) from the \( I \) obtained for the biased experimental cube (\( I_e \)).

\[
B = I_e - I_c.
\]

Thus, in Experiment 2, we measured the reversibility of the two internal intersections of the biased cube in relation to the reversibility of the two internal intersections of the unbiased cube under similar conditions of fixation, attention, and intention. The \( B \) can range from +2 to -2; a \( B \) of zero indicates that performance with the biased cube did not differ from performance with the unbiased cube. If the \( B \) obtained when viewers attend to the biased intersection is both significantly greater than zero on hold-consistent trials and significantly less than zero on hold-inconsistent trials, then the biasing will be considered effective, even when unfixated.

Given a finding that the bias in the biased region is effective when attention is directed there, we will examine the \( B \) obtained when viewers attend to the intersection in the unbiased region for evidence of influence from the biased region. If responses to the biased region are obligatory even when attention is directed to the unbiased region, then the \( B \) obtained with attention directed there will duplicate those obtained with attention directed to the intersection in the biased region. If the biased region can be ignored and spatial attention can be directed to the unbiased region, then the \( B \) obtained on hold-inconsistent trials, in particular, should not differ from zero; that is, intentions should be as effective on a biased cube as on an unbiased cube.

Because the effects of the bias will be revealed by whether or not the \( B \) index differs from zero in these different conditions, we tested that specific question in a series of planned comparisons.

Lapses. The lapses reported here are the differences between the lapses reported with the biased cube and the unbiased cube (\( L_c - L_e \)) under similar conditions of fixation, attention, and hold instruction.

Results

Bias influence index. As in Experiment 1, the main effect of fixation location was not significant, \( F < 1 \), nor were any interactions involving fixation location. Moreover, no effects of cube type were obtained, \( F < 1 \), nor were there any

![Figure 3. The cubes used in Experiment 2. (Both a and b are the experimental cubes, which are biased at the top; c is the control cube, which remains unbiased. All cubes were presented with each of the three fixation points used in Experiment 1.)](image-url)
interactions involving cube type. Accordingly, the means for the planned comparisons were averaged across fixation location and cube type.

As can be seen in Table 2, the bias present in the biased region was effective: When observers attended to the intersection in the biased region, B was both significantly less than zero when observers tried to hold the inconsistent interpretation (M = -0.12), t(11) = -2.56, p < .05, and significantly greater than zero when observers tried to hold the consistent interpretation (M = 0.12), t(11) = 3.74, p < .005. However, the biased region did not exert an obligatory influence on perceived organization when observers attended to the intersection in the unbiased region: For both cubes, B did not differ from zero when observers tried to hold the inconsistent interpretation (M = -0.06), t(11) = -1.57, p > .10, although B was significantly greater than zero when observers tried to hold the consistent interpretation (M = 0.08), t(11) = 2.99, p < .02.2

Malleability. The B measures performance with a partially biased cube in relation to performance with an unbiased cube. Hence, a B that does not differ from zero should not be taken as evidence that intention was not effective, but only that intention was no more or less effective than it was on an analogous trial with an unbiased cube. For both the experimental and the control cubes, the Bs obtained in all conditions were greater than zero for both hold instructions (range = 0.37 to 0.85, ps < .001).

Lapses. The mean lapse time recorded in this experiment was 1.53 s for the biased experimental cubes (Lb) and 1.37 s for the unbiased control cubes (Lc). As can be seen in Table 2, Lb - Lc was greater when observers tried to hold the inconsistent organization instead of the consistent organization during conditions when attention was directed to the intersection in the biased region only; when attention was directed to the intersection in the unbiased region, Lb - Lc was smaller when observers tried to hold the inconsistent organization instead of the consistent organization. This effect was reflected in the ANOVA by an interaction between attended location and hold instruction, F(1, 11) = 5.80, MSe = 2.24, p = .035.

Discussion

Because of the inclusion of the control cube, Experiment 2 provides strong evidence that directing attention to subregions of an object can have functional significance for the perceived organization of that object. The shading and occlusion effectively biased the perceived organization of both cubes when observers attended to the intersection in the biased region, even when that intersection was removed from fixation by a distance as great as 1.4° of visual angle. Responses to the biased region were not obligatory when observers attended to the intersection in the unbiased region, however: Even though observers were more successful at holding the organization consistent with the bias than they were when attending to the analogous intersection of the unbiased control cube, they were not less successful at holding the organization inconsistent with the bias, as would be expected were the response to the biased region obligatory.

As long as there is no difference between observers’ ability to hold the inconsistent organization of the experimental and control cubes when their attention is directed to the intersection in the unbiased region, any increased success at holding the consistent organization of the experimental cube relative to the control cube might be attributable to a strategy adopted by the viewers. Thus, Experiment 2 shows that the differential allocation of attention within a reversible object can influence the perceived organization of that object. When observers directed their attention to the intersection in the unbiased region of the partially biased experimental cube, they could hold the organization inconsistent with the bias as long as they could under similar conditions of fixation and attention with the unbiased control cube. Thus, with attention allocated away from the biased intersection, the partially biased cube can be functionally equivalent to an unbiased cube.

As in Experiment 1, no fixation effects were obtained in Experiment 2, indicating that the experimental results are attributable to the allocation of spatial attention to a subregion of an object and not to the relative perceptibility of the two intersections or to the allocation of spatial attention to one visual hemifield.

The lapses of attention or fixation reported by the observers in Experiments 1 and 2 did not vary systematically with fixation location, hold instruction, or spatial attention location, suggesting that viewers did not move their eyes or their attention differently in the different conditions. This finding is consistent with other experiments that have failed to find any differences in eye movements under different intention instructions (Peterson, 1984, 1986). Given the importance of the separation of fixation and attention in these experiments, however, we conducted an additional experiment with practiced observers who closely monitored their eye location.

Experiment 3

In Experiment 3, we converted the left and right fixation points into circular fixation regions with a diameter of approximately 0.5° of visual angle and instructed observers to maintain a 0.25° afterimage within the boundaries of the circular fixation region. We used this technique to monitor eye movements because the precision of measurement offered by the small perimeter of the fixation regions was greater than that offered by the recording devices typically used in the spatial attention literature (e.g., electrooculogram recordings, cf. Downing & Pinker, 1985). In addition, viewers’ reports about the location of an afterimage have served as good indicators of eye location in a variety of tasks (Alpern, 1971; Post & Leibowitz, 1982). In Experiment 3, we examined whether the results obtained in Experiment 2 were replicated when an eye movement monitoring task was combined with the tasks used in the previous experiments.

2 In a replication (n = 9), the biased region was again found to exert no influence on the perceived organization of the unbiased region, even on hold-consistent trials.
Method

Subjects. The observers were 3 psychology graduate students at the University of Arizona. Two were unaware of the experimental hypothesis. The third observer was the second author (BG), who was not aware of the specific hypotheses of this study at the time of testing. All observers had vision that was normal or corrected to normal.

Stimuli and apparatus. The bottom-biased, downward-facing cube (Figures 2a and 2c) and the unbiased Necker cube (Figure 3c) were used as stimuli in this experiment. They were viewed from the same distance as the cubes in the previous two experiments.

The solid fixation points used in Experiments 1 and 2 were replaced by black circular outlines, measuring 0.7 cm in diameter, which subtended approximately 0.5° of visual angle. Only two fixation areas were used in this experiment, one to the left of the cube and the other to the right of the cube. The circular frames were drawn so that the arc of the circle nearest the cube was located at the same distance as the cube’s edge, as the fixation points had been in the previous two experiments.

Afterimages were created by using a Vivitar electronic flash attachment that was covered by an opaque black shield except for a small hole (0.2 cm in diameter). The flash attachment was mounted at a distance of 44 cm from the subject, so that the afterimage subtended approximately 0.25°. A 2.5-Hz strobe light was used to create a flickering field, which has been shown to extend the duration that an afterimage is visible (e.g., Hochberg & Hay, 1956). In other respects, the stimuli and apparatus were the same as those used in Experiment 2.

Procedure. Observers participated in the experiment individually in three sessions conducted on 3 different days. When observers entered the lab on the first day, they were told that they would be participating in an experiment about the relation between spatial attention and perceptual organization. To that end, they would be asked to keep their eyes fixed in a certain region and to pay attention to another region and report about what they perceived at the attended region. They were told that they would receive a large amount of practice performing these tasks before the experiment trials.

Observers received practice maintaining the afterimage within the fixation circle first. Afterimages were induced foveally in alternate eyes on successive trials so that the afterimage used for the first trial decayed while the observer participated in the second trial, and so forth. We outlined the circular opening in the black opaque shield covering the flash attachment with fluorescent paint to provide viewers with a visible fixation point prior to flash onset. Viewers signaled when they were fixating, and the experimenter initiated a 10-ms flash. After the flash, the observers closed their eyes briefly while the experimenter removed the flash apparatus and turned on the strobe light illuminating the paper on which the cubes were drawn. Then, the observer fixated the cube monocularly with the eye in which the afterimage had just been generated, observers participated in an average of eight 20-s trials, during which they practiced maintaining the afterimage within the circle. (Trials in Experiment 3 lasted for 20 s rather than 30 s, because pilot work revealed that the afterimage became difficult to observe after approximately 20 s.)

Next, observers practiced attending to each of the intersections of an unbiased cube while maintaining the afterimage within the fixation circle. They participated in an average of eight practice trials, with fixation alternating between the right and left fixation points on each trial.

Next, observers practiced following the hold instructions and using the response buttons to report about perceived organization while maintaining the afterimage in the fixation circle and their attention on the instructed intersection. We instructed observers to remove their fingers from the response keys when the afterimage strayed outside the fixation circle or when their attention strayed from the instructed intersection. Observers participated in 16 of these practice trials in which all three tasks were combined: one trial per hold instruction with each combination of attention location, fixation point, and eye.

Unbiased cubes were used on all practice trials. We questioned observers after each practice trial about their ability to perform each of the three tasks when the tasks were combined, and we reminded them of the importance of faithful monitoring of the locus of both

\[ L_x - L_c \] (in seconds)

<table>
<thead>
<tr>
<th>Cube type</th>
<th>M</th>
<th>SE</th>
<th>M</th>
<th>SE</th>
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<tbody>
<tr>
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<td>0.388</td>
<td>0.726</td>
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<table>
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<td>M</td>
<td>0.083</td>
<td>0.028</td>
<td>-0.064</td>
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Table 2

Bias Influence Index and \( L_x - L_c \) as a Function of Cube, Attended Region, and Hold Instruction in Experiment 2
the afterimage and their attention. The first session ended after these 16 practice trials.

The second session began with four more practice trials with the unbiased cubes: one trial with each hold instruction at each spatial attention location. Observers used their right eye for half of the practice trials and their left eye for the other half. The attended intersection was the near intersection for half the practice trials, and the far intersection for the other half of the practice trials. These practice trials were followed by 16 of the 32 experimental trials.

The third session consisted of four more practice trials followed by the remaining 16 experimental trials. The order of these trials was counterbalanced within subjects.

Results and Discussion

Bias influence index. The results, shown in Table 3, replicate the findings of Experiment 2. We collapsed the data across fixation point because the previous two experiments showed no effects of fixation point, and across right and left eye because we neither expected nor saw any differences in performance with the two eyes.

The biased region effectively influenced perceived organization when attention was allocated there: In all cases, when attention was directed to the intersection in the biased region, B was less than zero on hold-inconsistent trials and greater than zero on hold-consistent trials. However, the biased region did not exert an obligatory influence when observers attended to the intersection in the unbiased region: In no case was B less than zero on hold-inconsistent trials when attention was directed to the intersection in the unbiased region, and in two cases, B was less than zero on hold-consistent trials when attention was directed to the intersection in the unbiased region. (The performance of the observers in Experiment 3 on trials during which they attended to the unbiased intersection fell within the range of the performance of the observers in Experiment 2.)

Lapses. The lapses reported by the observers in Experiment 3 also fell within the range of the lapses reported by the observers in Experiment 2. As can be seen in Table 3, 2 of the 3 observers reported more lapses on hold-inconsistent trials when their attention was directed to the intersection in the biased region, as was found for the observers in Experiment 2. For the third observer (EH), $L_e - L_c$ was close to zero in this condition.

For all observers, $L_e - L_c$ was only slightly greater than zero on hold-inconsistent trials coupled with attention to the unbiased intersection. For one observer (EH), $L_e - L_c$ was greater on hold-consistent trials than on hold-inconsistent trials while she attended to the unbiased intersection. She reported later that it was more difficult to keep attention away from the biased intersection on hold-consistent trials than on hold-inconsistent trials, because she knew she would be more successful at following the hold-consistent instructions if she could attend to the biased intersection.

General Discussion

The three experiments reported here extend the work of Peterson and Hochberg (1983, 1989; Hochberg & Peterson, 1987) by showing that simply directing spatial attention to subregions of multistable objects can have functional significance for the perceived organization of those objects. We have shown that when spatial attention is directed away from those regions of the cube—which, when fixated or attended, clearly specify one depth organization—those regions can lose their effectiveness in determining perceived organization. Thus, responses to all regions or properties of the attended object are clearly not obligatory, at least when the task examined is perceptual organization.

Distinctive Features Hypothesis

Our results should not be taken as supporting the distinctive features hypothesis of reversal, however. In our experiments, subjects were successful at holding both organizations when they directed their attention to an unbiased intersection (i.e., the unbiased intersection of the experimental cubes and both intersections of the control cubes). To retain the distinctive features hypothesis in the presence of these findings, one would have to suppose that different subregions of the unbiased region favor different interpretations for the cube and

<table>
<thead>
<tr>
<th>Attended region</th>
<th>Biased region</th>
<th>Unbiased region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observer</td>
<td>Consistent hold instruction</td>
<td>Inconsistent hold instruction</td>
</tr>
<tr>
<td>Bias influence index</td>
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<td></td>
</tr>
<tr>
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<td>EH</td>
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<table>
<thead>
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<th>$L_e - L_c$ (in seconds)</th>
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<tbody>
<tr>
<td>JB</td>
</tr>
<tr>
<td>EH</td>
</tr>
<tr>
<td>BG</td>
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</tbody>
</table>
that viewers followed the different hold instructions by attending to those different subregions. Clearly, in light of our evidence, the distinctive features hypothesis is forced to predict smaller sized distinctive features, thereby becoming increasingly ad hoc and increasingly difficult to support experimentally.

Moreover, we do not accept the constructivist assumptions of the distinctive features hypothesis of reversal, namely that the potential interpretations for each of the parts of an object are ordered and that the parts of the figure are analyzed serially. Recent theory and research in shape recognition suggest that the number of components used to represent shapes is finite (e.g., see Biederman, 1987). If so, then each representational component occurs in thousands of shape representations and must, therefore, support large numbers of interpretations. Yet, shape recognition occurs too rapidly to be accounted for by a perceptual mechanism that cycles through large numbers of interpretations for a single part. It is more likely that a stimulus shape is first expressed as a description of the shape’s components in their relative locations (i.e., a structural description) and is then matched in parallel against multiple memory representations (cf. McClelland & Rumelhart, 1981, 1986). In what follows, we present a theory of how the allocation of attention within an object might influence this process. The theory specifies how spatial attention might interact with distinctive features (like the bias) if there are any, but it also allows for reversal without distinctive features.

The Functional Equivalence Theory of Spatial Attention in Object Perception

We propose that, when attention is directed to a part of an object, the processing of the stimulus information in the location to which spatial attention is directed is facilitated and the processing of the stimulus information in unattended locations is attenuated. The idea that the allocation of attention in space results in facilitation is not new (cf. Eriksen & Hoffman, 1972a, 1972b; Posner et al., 1980), nor is the proposal that attentional effects include inhibition as well as facilitation (see Maylor & Hockey, 1985; Neill & Westberry, 1987; Posner & Cohen, 1984). The type of inhibition we propose is different from the inhibition proposed by these investigators, however. It is neither an inhibition of competing responses nor an inhibition specific to a previously attended location. Instead, the type of inhibition we propose takes the form of attenuating the processing of information in the unattended region (Johnston & Dark, 1986; Treisman, 1960). Like LaBerge and Brown (1989), we argue that the allocation of attention entails both active facilitation and active inhibition, both of which are effected through a filter that operates on the location information in the display, regardless of the content of that location.

Our results demand interpretation in terms of the attenuation of processing of information in the unattended regions, because the effectiveness of the biased region was found to vary with attentional locus even when fixation was held constant (and hence, the perceptibility of the biased and unbiased regions of the cubes remained constant). The response to the biased region was obligatory only when spatial attention was directed to that region of the cube. When observers directed their attention to the unbiased region of the cube, the response to the biased region was no longer obligatory. This finding indicates that for the purposes of perceptual organization, the importance of information outside the attentional focus is diminished.

The joint facilitation of the processing of attended regions of a shape and attenuation of the processing of unattended regions of a shape results in an interpretation for the object that depends more on the attended than on the unattended regions. We describe the way this occurs using our experimental cubes as examples. When attention is directed to the biased region of a partially biased cube, the processing of the occlusion and shading details there is facilitated. This depth information is then strongly depicted in the structural description of the stimulus so that the best-matching object representation will be the one that faces in the direction specified by the bias. On the other hand, when attention is restricted to the unbiased region, the combined facilitation of the processing of the unbiased region and attenuation of the processing of the biased region can result in a structural description that is functionally equivalent to that of an unbiased cube, in that the set of potentially matching object representations is equivalent to that accessed by an unbiased cube. The ambiguity can be resolved in the service of the intention instructions through the top-down activation of one of the memory representations that potentially fits an unbiased cube (Peterson et al., 1990). Thus, to be successful at holding the inconsistent interpretation of partially biased Necker cubes, observers need simply restrict their spatial attention to the unbiased region and prime the memory representation corresponding to the inconsistent interpretation. This strategy will assure that the best-fitting representation will be the one inconsistent with the bias. Our results suggest that observers using this strategy while viewing partially biased Necker cubes will organize those cubes in the interpretation inconsistent with the bias at least as often as observers viewing unbiased Necker cubes.

These experiments extend the demonstrated effects of spatial attention to a new area—the perceptual organization of objects. Although other research has demonstrated that both semantic and nonsemantic processing (measured by semantic priming and identity priming, respectively) outside the attentional spotlight is attenuated (Francolinii & Egeth, 1980; Johnston & Dark, 1986; Kahneman & Henik, 1981), none of these previous experiments has demonstrated that the allocation of spatial attention within a bounded, spatially continuous object can influence the perceived organization fitted to that object.

Our experiments should not be taken as evidence that perceptual organizing processes cannot limit the size of the attentional focus. Pomerantz (1981; Pomerantz & Garner, 1973; Pomerantz, Pristach, & Carson, 1989) has argued that spatial attention cannot be directed to subregions of preattentively identified shape primitives. In much of his work, Pomerantz has identified potential perceptual primitives by failures of selective attention in speeded classification tasks. His basic approach consists of constructing potential primitive configurations from combinations of curved or straight bits.
of contour and then examining whether observers’ reaction times in a speeded classification task suggest that they must attend to the entire configuration or that they can ignore parts of the configuration. Faster reaction times are expected if observers succeed in selectively attending to part of the configuration because that strategy yields a smaller response set. Those configurations that behave like indivisible units are identified as perceptual primitives. According to Pomerantz’s logic, our cubes cannot be primitive configurations, because observers can attend selectively to subregions of the cubes. (Note, however, that we manipulated spatial attention directly, whereas Pomerantz and his colleagues inferred whether or not selective attention was possible from reaction times. It is not clear what differences were caused by this difference in technique.)

Other investigators have used other methods to partition configurations into components, and those other methods may identify different primitives than those identified in speeded classification tasks. For example, Biederman (1985, 1987) has recently proposed a theory of shape recognition in which the primitive volumetric components of an object are identified through a preattentive partitioning process that locates the minima of curvature from inside the object (Hoffman & Richards, 1985). Our cubes cannot be divided into subunits using this partitioning process because their contours exhibit maxima, but not minima, of curvature (and indeed, cubes fit Biederman’s, 1985, 1987, description of one of his volumetric components). If cubes are identified as primitive components, then our results suggest that attention can be distributed preferentially within a preattentively defined primitive shape recognition component. The problem of partitioning a cube into subunits cannot be solved within Biederman’s theory by simply extending the partitioning rule to include maxima of curvature, because in that case the cubes (and indeed, many such 3D objects) would be constructed from planar, rather than volumetric, components. Clearly, the relation between the primitives identified in classification tasks and in perceptual organization or shape recognition tasks must be mapped out before perceptual primitives can be identified with any certainty.

"Objects" Of Spatial Attention and Organization

The question of how small the focus of attention can be within an object remains. The finding that the partially biased cubes could be functionally equivalent to unbiased cubes when spatial attention was directed to the unbiased region was obtained in conditions in which the biased and unbiased regions were separated by a least 1° of visual angle. Eriksen and Hoffman (1972b) had proposed 1° as the minimum diameter of the attentional spotlight. Kahneman and Henik (1981) had argued that the minimum diameter could not be attained when preattentively defined objects larger than 1° occupied the region of space to which attention was directed. Our objects were larger than 1° and we found that spatial attention could be allocated to subregions within those objects. Inasmuch as we did not vary the distance between the biased and unbiased intersections in the cube, we can provide no further evidence regarding the minimum size of the attentional focus within the objects such as ours, however.

A related issue for future research concerns which types of object properties can be rendered ineffective by the attenuation or inhibition of unattended regions. The experiments reported here show that the depth cues in the biased region can be attenuated when spatial attention is allocated elsewhere. Depth assignment is integral to the perceptual organization of these cubes. Future research must determine which object properties (implicated in which processes) are susceptible to attenuation effects and which are not.

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