Object and spatial representations in the corner enhancement effect

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Cole, Gellatly, and Blurton (2001) have shown that targets presented adjacent to geometric corners are detected more efficiently than targets presented adjacent to straight edges. In six experiments, we examined how this *corner enhancement effect* is modulated by corner-of-object representations (i.e., corners that define an object's shape) and local *base-level* corners that occur as a result of, for instance, overlapping the straight edges of two objects. The results show that the corner phenomenon is greater for corners of object representations than for corners that do not define an object's shape. We also examined whether the corner effect persists within the contour boundaries of an object, as well as on the outside. The results showed that a spatial gradient of attention accompanies the corner effect outside the contour boundaries of an object but that processing within an object is uniform, with no corner effect occurring. We discuss these findings in relation to space-based and object-based theories of attention.

One issue that has dominated visual attention work for the past 2 decades concerns the perceptual units that the visual system uses to deploy resources across a visual scene. Originally, it was suggested that attention is allocated to unsegmented regions of space, with the common metaphor being an attentional *spotlight* (e.g., Broadbent, 1982). According to this *space-based* view of attention, a spotlight is said to traverse the visual field, selecting any stimuli that fall within its "illuminated" boundary for further processing. Although variations on the spotlight theme exist, such as *gradient theory* (Downing & Pinker, 1985; Hughes & Zimba, 1985; LaBerge & Brown, 1989) and the *zoom lens* model (Eriksen & St. James, 1986; Eriksen & Yeh, 1985), all these models implicate spatial location as the basis of selection. Other theories (Driver & Baylis, 1989; Duncan, 1984; Neisser, 1967), however, propose that attention is directed to objects and perceptual groups that have been parsed preattentively on the basis of Gestalt principles of perceptual organization. In some sense, these *object-based* theories view the selection of a spatial location as epiphenomenal, since objects necessarily occupy a region of space; however, the "real" basis of attention is seen as the object representation.

Although the debate has become polarized, whereby attentional allocation is seen as being either object-based or space-based, attention is likely to operate on both object

and spatial representations. Indeed, a growing number of studies have demonstrated that selection can occur for both objects and space (e.g., Vecera, 1994). This point was emphasized by Duncan (1984) in an article commonly viewed as containing the original argument for object-based attention. Furthermore, Scholl (2001) has commented that the distinction between the processing of objects and spatial locations is somewhat blurred and that the two need not be mutually exclusive. For example, Scholl states that the shape of LaBerge and Brown's (1989) spatial spotlight may deform around an object (see also Vecera & Farah, 1994). The principal aim of the present research was to assess how a relatively new visual phenomenon, reported by Cole, Gellatly, and Blurton (2001), relates to space-based and object-based theories of attention. Specifically, we examined whether the distribution of attention following the onset of a new object can concur with both object-based and space-based views of attention.

Cole et al. (2001) showed that a stimulus presented in a region of space adjacent to a corner of a new object receives a processing advantage, as compared with a stimulus presented adjacent to one of the object's straight edges. For example, reaction time (RT) to detect a target presented next to a corner was relatively reduced, as compared with RT to detect a target presented next to a straight edge. We dubbed this phenomenon the *corner enhance-*

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ment effect (or simply, the corner effect). In a series of nine experiments, evidence was presented showing this effect to be a higher order phenomenon whereby attentional enhancement occurs at locations adjacent to corner regions. Nonattentional sensory explanations, such as low-level luminance and chrominance masking, were investigated and eliminated, as well as an account based on corner target response bias. We also demonstrated that the effect is the result of new onset, since the effect ceased to occur 500 msec after the appearance of the object. In addition to being demonstrated with RT measurement, the corner effect has been demonstrated using a temporal discrimination task. Miyauchi, Hikosaka, and Shimojo (1992) and Stelmach and Herdman (1991) have shown that the locus of attention can be indexed via the judgment of relative temporal order (see also Shore, Spence, & Klein, 2001). For instance, two simultaneously presented signals will appear to onset asynchronously if the location of one of the signals is attended, a phenomenon Titchener (1908) referred to as the *prior-entry effect*. Cole et al. manipulated this paradigm so that two targets were presented simultaneously, one next to a corner of a new object and the other next to a straight edge. Participants were asked to judge which of the two appeared to onset first. The results showed that corner targets were perceived to occur first significantly more often than chance would allow. The corner enhancement finding supports the notion that a nonuniform spatial spotlight surrounds any recently onset object. As Scholl (2001) hypothesized, the spotlight can indeed distort. This concurs with many other accounts of how new objects distort their surrounding visual space (Miyauchi et al., 1992; Ruda, 1998; Steinman, Steinman, & Lehmkuhle, 1995; Suzuki & Cavanagh, 1997, 1998; Tsai & Shalev, 1996). In the present article, we report six experiments assessing how the corner effect relates to space-based and object-based theories of attention. We show, for instance, that although the distribution of attention surrounding an object is more consistent with space-based views of attention, the distribution within the contour boundaries of an object is more consistent with object-based accounts.

GENERAL METHOD

All the experiments reported here employed slight variations on a basic trial procedure. This procedure was the same as that in the RT experiments reported by Cole et al. (2001). Figure 1 demonstrates the basic paradigm. Each trial began with the onset of a small dot located at the center of the display, and the participant was instructed to maintain fixation on this point throughout each trial. A *priming figure* then appeared before the presentation of a target (a small dot) 100 msec later, adjacent to the figure.¹ On half the trials, a target would appear next to one of the priming figure's corners, and on the other half, next to a straight edge. The participants were asked to respond as quickly as they could to the onset of the target by pressing the space bar on a standard keyboard with one preferred finger. The only exception to this was Experiment 3B, in which the participants were asked to determine which of two possible targets had appeared. When the participant responded, the next trial was initiated with the presentation of the fixation point 1,000 msec later. Between 1,500 and 3,000 msec after this, the priming figure would again appear. On 20% of all the trials (except in Experiment 3B), no target was

Figure 1. The basic corner effect demonstrated by Cole, Geladly, and Blurton (2001). This example shows a square as the priming figure and a target appearing adjacent to one of the figure's corners. The fixation point is located inside the square. Note that Cole et al. used solid figures, rather than the line boxes shown here.

presented, in order to ensure that the participants were responding only to the target, rather than to the onset of the priming figure.

All the present experiments employed the same principle for stimulus positioning. Relative to fixation—that is, irrespective of the priming figure—a target could appear at one of eight possible locations in the display, each being positioned on the edge of a virtual circle whose radius extended 1.9° from fixation. On 50% of the trials on which any one of these targets was presented, the priming figure would be positioned so that one of its corners would be located adjacent to the target. On the other half, the figure would be positioned so that one of its straight edges was positioned next to the target (see Figure 2). This procedure ensured that any differences in the time to detect each target could be attributed to the position of the target relative to the priming figure, rather than, for example, to retinal effects. In total, the priming figure would appear at one of eight possible locations relative to fixation (except in Experiments 4A and 4B). Two of these locations are shown in Figure 2; the other six locations were generated by changing the orientation of the figure so that the figure was rotated through 90°, 180°, and 270°, centered at the fixation point.

The participants were undergraduate psychology students from the University of Keele who reported normal or corrected-to-normal visual acuity. Each was positioned with his or her head located approximately 80 cm from the monitor and was asked to minimize head and body movement. All stimulus displays reported here were presented by a Pentium PC running at 60 Hz linked to a standard color monitor. The experiments were carried out in a dimly lit room.

EXPERIMENT 1

The purpose of Experiment 1 was to demonstrate the basic corner enhancement effect when the priming object was an outline box, rather than the solid figure employed by Cole et al. (2001). In previous research in which the effects of objects on visual processing have been investigated, objects have been defined in such a way (e.g., Egly, Driver, & Rafal, 1994). Given the newness of the phenomenon, we also felt it important to demonstrate the replicability of the effect. Therefore, Experiment 1 tested the prediction that the corner phenomenon would be observed—that is, that

Figure 2. Stimulus locations. Relative to the fixation point (located inside the two triangles), two of the eight possible target locations are shown, as well as two of the eight possible priming figure locations. The other six target and priming figure locations can be generated by rotating the figure (i.e., changing its orientation) through 90°, 180°, and 270°, centered at the fixation point. If the left-hand target is presented together with the left-hand triangle, this target becomes a straight edge target. If, by contrast, this same target is presented with the right-hand triangle, the target now becomes a corner target. This principle was used for all the experiments reported here.

corner-located targets would be subject to a reduction in RT, as compared with straight edge targets.

Method

Participants. There were 12 participants.

Stimuli. The priming figure was an isosceles line triangle measuring 3.0° of visual angle in height and 4.7° along the longest side. The three lines forming the triangle were 1 pixel in thickness—that is, 0.04°. The two equal angles measured 53° of geometric angle, and the third 74°. The triangle lines consisted of pink pixels presented against a uniform green background. The color coordinates of these, measured in $L^*u^*v^*$ color space (using a Cambridge Research Systems ColorCal chromameter), were 0.287 (u^*) and 0.278 (v^*) for the triangle lines, and 0.358 (u^*) and 0.518 (v^*) for the background. The target was a small square made up of green pixels (0.388 [u^*] and 0.518 [v^*]) and measured 0.18° along each side. The targets were displaced from the triangle by 0.1° of visual angle. The luminance of the triangle and the background was recorded at 39.6 and 40.5 cd/m², respectively. The triangle and background may therefore be said to have had low luminance contrast but high chromatic contrast. The targets measured 43.8 cd/m².

Design and Procedure. The experiment was a single-factor within-participants design. The critical manipulation was the position of the target relative to the priming triangle—that is, next to either a corner or a straight edge. There were 192 experimental trials: 96 corner trials and 96 straight edge trials. These were divided equally between the eight possible target locations (relative to fixation). A further 48 catch trials were also included on which no target was presented. The participants were shown demonstration trials before undertaking a practice session of 32 trials. After half the experimental trials were completed, the participants were offered a break by the program. All trial types were presented randomly.

Results and Discussion

In all the experiments reported here, outliers were automatically excluded from condition means. All responses more than two standard deviations above and below the mean for a single participant were excluded from analysis. This resulted in the removal of approximately 5.5% of responses in Experiment 1. The participants responded on 3.4% of the catch trials. All other RTs were automatically

categorized according to whether the target appeared adjacent to a corner or a straight edge. This then formed the basis of the analysis. Mean RTs for corner and straight edge targets were 604 and 695 msec, respectively. This difference proved to be significant [$t(11) = 4.54$, $p < .001$]. The results of this experiment have, therefore, replicated the findings previously reported by Cole et al. (2001). Targets presented in a region of space adjacent to a corner of an onsetting object accrued enhanced processing, as compared with targets presented next to a straight edge. Hence, the corner effect is observed when the priming object is an outline shape, rather than a solid object, such as those used in previous experiments.

EXPERIMENT 2

The visual world comprises an abundance of corner stimuli. Some are corners that define an object's shape, but some are local *base-level* representations of contour geometry that are not associated with the corners of objects (i.e., non-object-defining corners)—for instance, where the straight edges of more than one object overlap. The aim of Experiment 2 was to assess the degree to which corner facilitation occurs at regions of space adjacent to non-object-defining corners, relative to areas of space adjacent to corners of *object* representations—that is, corners that define an object's shape. If the magnitude of the effect is greatest at the corners of objects, one can argue that the corner effect is based primarily on an object representation. As Abrams and Law (2000) stated, attention will be shown to be *object aware*. In order to assess this, Experiment 2 replicated the baseline *standard* corner/straight-edge condition in Experiment 1 with a condition in which the targets appeared next to either a corner of an object or a base-level corner created by the occlusion of one object by a second object (see Figure 3).

Method

Participants. There were 12 participants.

Stimuli. All the attributes of the stimuli in the standard condition were identical to those in Experiment 1. In the *occluding figure* condition, the triangle used for the standard condition was presented together with a rectangular box (see Figure 3). The color and luminance of the rectangle's lines were the same as those for the triangle. The rectangle measured 3.5° in length and 1.9° in height. As with the standard baseline condition, stimulus locations in the occluding figure condition were generated by rotating the figure shown in Figure 3 about the fixation point.

Design and Procedure. The design and procedure were identical to those in Experiment 1, with the exception that a 2 × 2 within-participants factorial design was employed. The first factor was target location (corners vs. straights), and the second factor was priming stimulus (standard vs. occluding figure). In addition, the participants were told that on half the trials, a square would appear together with the triangle.

Results and Discussion

Outliers were omitted, resulting in the removal of 5.9% of the data. The participants responded on 3.6% of the catch trials. Figure 4 shows the mean RTs for targets presented at corners and straight edges for both the standard

Figure 3. The stimuli used in the occluding figure condition in Experiment 2. Both possible target locations are shown. Even though the target located at the overlap of both figures is adjacent to a local *base-level* corner, we refer to these as *straight edge targets*, because this position is next to the straight edges of two objects.

and the occluding figure conditions. Mean participant RTs were entered into a 2×2 within-participants ANOVA with target location (corner vs. straight edge) and priming stimulus (standard vs. occluding figure) as factors and levels. The main effect of target location was significant [$F(1,11) = 6.5, p < .05$], as well as the main effect of priming stimulus [$F(1,11) = 6.8, p < .05$]. The interaction between target location and priming stimulus was not significant [$F(1,11) < 1$]. The main effect of target location demonstrates that over the whole experiment, corner targets were subject to a reduction in RT, as compared with straight edge targets. Although not important with respect to the critical analysis, the second main effect shows that the targets accrued shorter RTs in the standard condition than in the occluding figure condition. The occurrence of a second figure on half the trials appears to have had a distracting influence on target processing. The critical analysis, however, concerns the presence of a corner effect in the occluding figure condition. Recall that “straight edge” targets in this condition were actually positioned next to a base-level corner as a consequence of the positioning of two figures. Hence, even though the targets were located in an area of space adjacent to a physical corner, these did not receive the usual facilitation. This would suggest that the distortion of space giving rise to the corner effect is greatest for areas adjacent to the corners of *objects*. This is consistent with the notion that the distortion of visual space created by the onset of an object is based on an object representation.

However, there could be other possible explanations. For instance, targets located at the overlap of the two straight edges in the occluding figure condition occurred inside the meeting of two contours. Such targets may have failed to accrue an RT benefit because they were masked by virtue of this position. The possibility of masking also arose in Experiments 4A and 4B. We

therefore addressed this alternative and ruled it out as an explanation in Experiment 5. A further related possibility is that targets presented adjacent to an “L” type stimulus (i.e., a corner) accrue priority of processing, relative to targets presented adjacent to a “T” type stimulus, as occurred at the overlapping edges of the occluded and occluding figures. This would constitute an explanation based on a local *base-level* representation, rather than on a higher object-defining representation. We will discuss this and related issues further in the General Discussion section.

EXPERIMENT 3A

The results of Experiment 2 suggest that facilitated processing is greatest for stimuli presented adjacent to corners that define an object’s shape. The aim of Experiment 3A was to assess whether the corner effect is based exclusively on an object representation or can occur also for base-level corner representations. In addition to presenting targets adjacent to corners that defined an object’s shape, we presented targets that could appear adjacent to corners that were “cut” into the straight sides of an object but did not form object-defining (i.e., triangle) corners (see Figure 5). If, as Experiment 2 suggests, the corner effect occurs exclusively for corners that define an object’s shape, rather than for corners per se, these base-level corners inserted along the straight edges of the priming object should not be associated with such facilitation. Alternatively, if base-level corners can also accrue attention, targets occurring at these locations will also receive facilitation. Hence, the present experiment compared RT for targets presented in the standard triangle condition (employed in Experiments 1 and 2) against RTs in a condition in which the triangle had gaps inserted along its three sides.

Figure 4. Results from Experiment 2, showing reaction times for corner and straight edge targets for both stimulus figure conditions.

Method

Participants. There were 20 participants.

Stimuli. The triangle in the standard condition was as previously described. In the *inserted-gaps* condition, the triangle was identical in all respects, except that it had three small sections cut out along its three straight edges. Each of these sections measured 0.42° in length and 0.38° in height.

Design and Procedure. The design and procedure were identical to those in Experiment 2, with the exception that the standard condition was compared with the inserted-gaps condition.

Results and Discussion

Outliers accounted for 6.2% of the data and were omitted from analysis. The participants responded on 5.1% of the catch trials. RTs for corner and straight edge targets for both the standard and the inserted-gaps conditions are shown in Figure 6. Mean participant RTs were entered into a 2×2 within-participants ANOVA with target location and triangle type as the two factors. The main effect of target location proved to be significant [$F(1,19) = 13.3, p < .01$], whereas the main effect of triangle type did not [$F(1,19) < 1$]. The interaction between target location and triangle type was also significant [$F(1,19) = 4.4, p < .05$]. The corner facilitation effect was significantly reduced when the straight edge targets were located adjacent to a base-level corner. This suggests that such corners do indeed accrue attention. In other words, the facilitatory effect observed at a corner is not solely dependent on the corner's being a corner that defines an object's shape.

Given this, an important question is whether the significant interaction reflects an *absence* of a corner effect with the inserted-gaps figure or a *reduction*. Clearly, total abolition of the effect, as opposed to a mere reduction, would show that the targets located at the local base-level corners accrued the same amount of attentional resources as did the corners defining the object as a triangle. This would refute any notion that the corner effect is based on an object representation. In order to assess this, we entered each participant's mean RT for targets appearing adjacent to the corners and straight edges in the inserted-

Figure 5. The inserted-gaps stimuli used in Experiments 3A and 3B. The gaps cut into the straight edges of the triangle create local base-level corners, as opposed to the corners that define the figure as a triangle.

Figure 6. Results from Experiment 3A, showing reaction times for corner and straight edge targets for both stimulus figure conditions.

gaps condition into a paired samples t test. The difference did not reach conventional statistical significance [$t(19) = 1.4, p < .1$]. At best, there was only a small corner effect. The primary aim of Experiment 3B was to further assess this effect.

EXPERIMENT 3B

Experiment 3A clearly shows that base-level corners accrue attentional facilitation, as well as corners of object representations. Experiment 3B set out to assess whether object corners accrue *greater* attentional facilitation, relative to base-level corners. In order to increase power, we replicated the inserted-gaps condition in Experiment 3A, but omitting the standard condition. A second aim of Experiment 3B was to assess the corner effect by using a task different from those in all the other experiments reported here. Rather than deciding whether a dot had appeared or not (i.e., target-present or catch trial), the participants were asked to decide which of two possible targets occurred. A relatively large or a slightly smaller target appeared at either a corner or a straight edge. This enabled us to investigate whether the corner advantage observed in Experiment 3A (or indeed, in any of the experiments reported here) was due to the participants' lowering their criterion for responding to targets on corner target trials. Both Shaw (1984) and Yantis (1998) have suggested the possibility that some attentional facilitation effects can, in part, be explained by participants' responding to certain targets on the basis of less stimulus information—that is, lowering their response criterion. This hypothesis could be tested by having participants perform a two-alternative forced choice discrimination task and analyzing their error rates for the different conditions being assessed. If the participants were, indeed, lowering their criterion for responding on corner target trials, one should expect more discrimination errors to

be made on such trials. Hence, the present experiment allowed us to assess this.

Method

All aspects of the experiment were the same as those described for the inserted-gaps condition in Experiment 3A, with the following exceptions. One of two possible targets could appear, either a small or a large square measuring 0.18° or 0.36° , respectively, along each side. The participants were asked to decide as quickly as possible which of the targets appeared by pressing one of two buttons. Half responded with their right hand to a large target and with their left hand to a small target, and half had the reverse response assignment. In addition, no catch trials were presented. Fourteen participants took part in the experiment.

Results and Discussion

Outliers accounted for 3.4% of the data and were removed from the analysis. Mean RTs were 610 msec for corner targets and 666 msec for straight edge targets. The difference of 56 msec proved to be significant [$t(13) = 5.4, p < .001$]. These data clearly show that object corners accrued an attentional advantage, relative to the base-level corners positioned on the straight edges. Although Experiment 3A showed a reduced corner effect when the object has base-level corners cut into its straight edges, crucially, Experiment 3B demonstrates that corners of object representations accrue *greater* attention than do base-level corners. In addition, the results from Experiment 3B revealed that the participants made response errors on 5.2% of the corner target trials and 5.1% of the straight edge target trials. This difference was not significant [$t(13) < 1$]. This suggests that the participants did not lower their criterion for responding to targets appearing adjacent to object corners. One remaining issue is why the corner effect occurred in the present experiment but failed to do so in the inserted-gaps condition in Experiment 3A. One possibility is that the discrimination task employed in the present experiment was simply more sensitive to the corner effect, as compared with the target detection task previously used. Different experimental tasks may vary in their susceptibility to Type II error. Overall, the results from Experiments 3A and 3B reveal that although the corner effect occurs primarily for corners of object representations, the effect is also modulated by local base-level corners.

EXPERIMENT 4A

One of the basic tenets of object-based theories of visual attention is that if one part of an object is attended or processed, all parts of that object should be attended (Duncan, 1984; see also Vecera, Behrmann, & McGoldrick, 2000). This idea of how visual attention mechanisms operate explains some of the findings that support object-based theories. Attention may be said to “grow” along an object once one part of that object has been attended. This could, for example, explain the effect reported by Egly et al. (1994), whereby attention is more efficiently directed within the contour boundaries of one object than across an equal spatial separation to another object. The findings of Kramer and Jacobson (1991) might also be

explained by this effect. They demonstrated that the interference created by a distracting item on the processing of a target was increased if both the distractor and the target were grouped together to form a single object. Similar results have been reported by Baylis and Driver (1992), Driver and Baylis (1989), and Harms and Bundesen (1983; but see also Berry & Klein, 1993; Kramer, Tham, & Yeh, 1991). The purpose of Experiment 4A was to investigate how attention might be distributed within the boundaries of a single object. This issue was addressed by assessing whether the corner finding would still be observed when the targets presented to index the effect appeared on, or inside, the object, as well as outside its contour boundaries. All the previous experiments reported by Cole et al. (2001) located targets in a region of space immediately adjacent to the object. Thus, these studies reveal differences in the processing of the space only outside or surrounding the object. These differences may not hold inside the object, given the argument described above. In Experiment 4A, therefore, we investigated the corner effect using targets that were presented either on the outside of the priming triangle or on the inside (referred to as the *inside-object* condition). It is worth noting that attention should initially be located inside the contours of the inducing figure, by virtue of the figure’s appearing with the fixation point occurring inside the object. We predicted that if attention spreads uniformly within the boundaries of an object, the corner effect should be abolished in the inside-object condition. By contrast, the distortion of visual space on the outside of the object should again be observed. Furthermore, we investigated this using eight probe locations, four inside the inducing triangle and four outside. In effect, this allowed us to assess the corner effect on the inside and outside of the inducing triangle when the targets appeared either immediately adjacent to the edges of the triangle or displaced by a distance of 1.15° (see Figure 7).

Method

Participants. Twelve observers took part in the experiment.

Stimuli. All stimulus attributes were identical to those in Experiment 1, with the exception that the triangle could appear at 1 of 32 different locations relative to fixation, so that it generated the eight different target positions (relative to the triangle), shown in Figure 7. As with all the other experiments reported here, relative to fixation (i.e., irrespective of the priming figure), the target could appear at one of possible locations (see the General Method section and Figure 2).

Design and Procedure. The experiment was a $2 \times 2 \times 2$ fully repeated measures design. The first factor was whether the targets were located inside or outside the inducing triangle; the second factor was whether the targets were immediately adjacent to the edge of the triangle or displaced at a distance of 1.15° , and the third was whether the targets were located next to the corners or the straight edges. For both the outside-object and the inside-object conditions, a target would occur 16 times in each of the four possible target locations. Thus, a total of 128 experimental trials were presented, plus 32 catch trials. All trial types were presented randomly in one block. Unlike for all the other experiments reported here, Experiment 4A was run, and the data initially analyzed, by an experimenter who had no knowledge of the corner facilitation work and was naive as to the aims of the research.

Results and Discussion

Outliers were removed, resulting in the exclusion of 4.2% of all the responses. Figures 8A and 8B present mean RTs for all eight target locations. These were entered into a $2 \times 2 \times 2$ within-participants ANOVA. The main effect of inside/outside was significant [$F(1,11) = 12.5$, $p < .01$], as were the main effects of distance [$F(1,11) = 14.7$, $p < .01$] and corners versus straight edge targets [$F(1,11) = 5.9$, $p < .05$]. Significant interactions were found between the factors of inside/outside and distance [$F(1,11) = 15.5$, $p < .01$] and between inside/outside and corners/straight-edges [$F(1,11) = 6.7$, $p < .05$]. The distance–corner/straight-edge interaction was not, however, significant [$F(1,11) < 1$], nor was the three-way interaction [$F(1,11) < 1$].

Given the rationale for the present experiment, the most pertinent result is the interaction between inside/outside and corners/straight-edges. These data show that although a corner advantage (105 msec) occurred for the outside of the priming triangle, this effect was effectively absent for the inside (6 msec). In fact, additional analyses comparing all possible pairwise comparisons of all four inside-object target locations showed that there were no significant differences between any of these positions.² The second effect of note is the inside/outside–distance interaction. This shows that although no differences in attentional distribution occurred inside the object, a gradient of attention occurred on the outside; RTs were longer for targets presented displaced from the priming object than for those presented immediately adjacent to its contour. These overall findings therefore suggest that it is the *regions of space* adjacent to corners outside the contour boundaries of objects that receive facilitated processing. That is, although attention was distributed uniformly *within* the priming object, a deformation of the spotlight surrounding the triangle occurred, with corner regions producing the usual facilitation. Thus, the overall findings show that the processing of stimuli presented within the figure are consistent with object-based attention (i.e., uniformity of processing within contour boundaries) and that the processing of stimuli presented outside the figure

Figure 7. Target locations used in Experiment 4A.

Figure 8. (A) Results from Experiment 4A, showing reaction times (RTs) for corner and straight edge targets appearing on the outside of the priming triangle. (B) Results from Experiment 4A, showing RTs for corner and straight edge targets appearing on the inside of the priming triangle.

are consistent with space-based principles of processing (i.e., a spatial gradient). As Scholl (2001) stated, one way in which space-based and object-based attention may interact is if the spatial spotlight is shown to deform around an object.

EXPERIMENT 4B

The findings from Experiment 4A show that although the attributes within an object are processed uniformly (Duncan, 1984), a deformation of attentional space exists surrounding the object. The aim of Experiment 4B was to assess this effect when a square was used as the inducing figure, as opposed to a triangle, and additionally, when more probe locations were used. This would also allow us to assess the replicability of the effect observed in Experiment 4A.

Method

Participants. There were eighteen participants.

Stimuli. All the stimulus attributes were identical to those in Experiment 4A, with the exception that a square was used as the inducing figure, as opposed to a triangle. The square measured 5.4° along each side and could appear in 48 different locations relative to fixation, so that it generated the 12 different positions of the target relative to the square, as is shown in Figure 9.

Design and Procedure. The experiment was a $2 \times 3 \times 2$ fully repeated measures design. The first factor was whether the targets were located inside or outside the inducing square; the second was whether the targets could appear immediately adjacent to the edge of the square, located at a distance of 0.4° , or located at a distance of 0.7° , and the third factor was whether the targets were located next to the corners or the straight edges. For both the outside-object and inside-object conditions, a target would occur 16 times in each of the six possible target locations. Thus, a total of 192 experimental trials were presented, plus 48 catch trials. All trial types were presented randomly in one block.

Results and Discussion

Outliers resulted in the removal of 5.9% of the responses. The participants responded on 4.3% of the catch trials. Figure 10A presents the mean RT for each outside location. These were entered into a $2 \times 3 \times 2$ within-participants ANOVA. The main effect of inside/outside did not reach conventional statistical significance [$F(1,17) = 3.0, p < .1$]; neither the main effect of distance [$F(2,34) = 2.5, p < .1$] nor the main effect of corners versus straight edges [$F(1,17) = 2.6, p < .12$] was significant. However, the interaction between inside/outside and distance was significant [$F(2,34) = 3.7, p < .05$], as was the interaction between inside/outside and corners/straight-edges [$F(1,17) = 5.8, p < .05$]. Finally, the distance–corner/straight-edge interaction was not significant [$F(2,34) = 2.3, p < .12$]; nor was the three-way interaction significant [$F(2,34) < 1$].

The pattern of data observed here is very similar to that reported for the previous experiment. Interestingly, *all* the significant effects observed in Experiment 4A narrowly failed to reach conventional statistical significance in Experiment 4B, with two exceptions. Both the interaction between inside/outside and corners/straight-edges and the interaction between inside/outside and distance were significant. As we suggested in Experiment 4A, these are the important analyses. These data again show that although a corner effect occurred on the outside of the priming figure, no such effect was observed for targets presented inside the figure. Attention was uniformly distributed inside the contours defining the object. Furthermore, a gradient of attention was observed for outside-object targets, with RTs being progressively longer for targets located further from the object's contour. This is consistent with early models of how attention is redistributed following the onset of a cue. For instance, following Eriksen and St. James (1986), Castiello and Umiltà (1990) showed that a gradual decrease in processing efficiency occurs surrounding the location of a cue.

In addition, the same multiple *t* test analysis was performed on all combinations of the inside-object mean RTs (see note 2). Again, no differences were found between any of the target positions. Overall, the important

Figure 9. Target locations used in Experiment 4B.

findings from Experiment 4B closely replicate those from Experiment 4A. All parts of the priming figure were processed uniformly within the contour boundaries of the object. A deformation of the visual space surrounding the figure also occurred, with corner regions accruing an attentional facilitation. Furthermore, a gradient of attentional processing was observed as a function of spatial separation from the outline contour of the figure. These data also demonstrate the replicability of the effect.

EXPERIMENT 5

The aim of Experiment 5 was to assess the possibility that the targets located inside the meeting of two contours in Experiments 2, 4A, and 4B failed to accrue an RT benefit, relative to other targets, because they were masked by virtue of this position. We therefore investigated whether targets that were located at these potentially masked positions but on the *outside* of an object would accrue the corner benefit (see Figure 11). If masking did, indeed, result in longer RTs for these targets in Experiments 2, 4A, and 4B, we would expect no corner effect to occur. By contrast, if their position in between the meeting of two contours did not disadvantage them, we should observe a corner advantage, due to their location at a corner on the outside of a priming object.

Method

Participants. There were eighteen participants.

Stimuli. All the stimulus attributes were identical to those in Experiment 1, with the exception that an L-shaped figure was used as the inducing figure. The two long sections of the figure measured 6.8° in length and were 1.8° wide.

Design and Procedure. The design and procedure were the same as those described for Experiment 1, with the exception that there

Figure 10. (A) Results from Experiment 4B, showing reaction times (RTs) for corner and straight edge targets appearing on the outside of the priming square. (B) Results from Experiment 4B, showing RTs for corner and straight edge targets appearing on the inside of the priming square.

were 32 corner targets and 32 straight edge targets. Furthermore, there were 16 catch trials.

Results and Discussion

Outliers resulted in the removal of approximately 5.0% of the responses. The participants responded on 12% of the catch trials. RTs for corner and straight edge targets were 492 and 520 msec, respectively. This difference proved to be significant [$t(17) = 2.13, p < .05$]. These results therefore show that the targets located between two contours in Experiments 2, 4A, and 4B were not disadvantaged due to their position. Because, in the present experiment, such targets were located at a corner on the outside of the priming figure, these targets accrued corner facilitation. It is worth noting that the magnitude of the corner effect (28 msec) was much smaller than that in the other experiments reported here. The smaller corner advantage may be due to

overall reduced RTs, as compared with our other experiments; shorter RTs usually leave less room for an effect to occur. One might say that a masking effect could have contributed to the corner phenomenon. Crucially, however, masking cannot explain the existence of the effect.

EXPERIMENT 6

The aim of Experiment 6 was to investigate whether the deformation of visual space surrounding the triangle would be influenced by the onset of a second object appearing next to it. This would allow us to assess whether the spatial deformation surrounding an onset can be manipulated to “behave” according to an object-based principle. As was described in Experiment 4A, Kramer and Jacobson (1991) showed that the interference created by a distracting item on the processing of a target was increased if both were grouped to form a single object. Following this rationale, we asked whether the deformation of visual space giving rise to the corner effect would be reduced if corner and straight edge regions were grouped together as part of one object. The standard procedure used in Experiment 1 was compared with an *adjacent-object* condition in which a second figure appeared next to the triangle (see Figure 12).

Method

Participants. There were 12 participants.

Stimuli. The triangle in the adjacent-object condition was identical to that in the standard condition, with the exception that a rectangular box appeared adjacent to the triangle. This measured 3.3° in length and 0.35° in height.

Design and Procedure. The design and procedure were identical to those in Experiment 2.

Results and Discussion

The exclusion of outliers resulted in the removal of approximately 5.2% of all the responses. The participants

Figure 11. The stimulus figure used in Experiment 5.

responded on 2% of the catch trials. Figure 13 shows that corner-located targets were subject to an RT advantage in the standard condition but were not in the adjacent-object condition. Mean participant RTs were entered into a 2×2 within-participants ANOVA with status of the adjacent object (present or absent) and position of target relative to object (corner or straight edge) as the two factors. A significant main effect of target position was observed [$F(1,11) = 8.3, p < .02$], whereas the effect of adjacent object being present or absent was not significant [$F(1,11) = 1.9, p < .2$]. The critical analysis, however, concerned the interaction between the two factors. This proved to be significant [$F(1,11) = 14.67, p < .01$]. A simple comparison of corner- versus straight-edge-located targets for the adjacent-object condition revealed that no difference in RT existed [$t(11) < 1$]. Thus, the usual corner effect was observed in the standard condition, but this effect was eliminated in the adjacent-object condition. The results of Experiment 6 have, therefore, shown that a straight edge region that normally confers a relative processing disadvantage no longer does so if this region is perceptually grouped with a facilitated corner region. This concurs with the finding that enhanced processing is observed for two items that are positioned on a single object (Baylis & Driver, 1993; Duncan, 1984; Kramer & Jacobson, 1991).

GENERAL DISCUSSION

Cole et al. (2001) showed that a stimulus located in a region of space adjacent to a geometric corner is detected more efficiently than is a stimulus located in a region of space adjacent to a straight edge. In the present series of experiments, we have examined how this corner enhancement effect is modulated by corners of object representations—that is, corners that define an object's shape—as compared with local base-level corners. We also assessed whether the corner effect persists within the contour boundaries of an object or occurs only for the region of space beyond these boundaries.

In Experiment 1, we replicated the basic finding reported by Cole et al. (2001), demonstrating that targets

Figure 12. Adjacent-object stimulus figure in Experiment 6.

Figure 13. Results from Experiment 6, showing reaction times for corner and straight edge targets in standard and adjacent-object conditions.

presented adjacently to a corner of a new object are subject to reduced RT, as compared with targets presented next to one of the object's straight edges. Experiment 2 assessed whether this facilitation is directed toward regions of space next to corners that define an object's shape or to regions of space next to any type of corner created in the visual scene. Two figures were presented in such a way that a corner was created by the overlapping of two straight edges. The results showed that this non-object-defining corner did not result in a processing enhancement of a target positioned at this location. Experiment 3A showed that such corners can, in fact, accrue attentional facilitation. Importantly, however, Experiment 3B demonstrated that *greater* facilitation occurs for corners of object representations than for base-level corners. *Local* corners created alongside the straight edges of the priming figure did not accrue the same efficiency of processing. Experiments 4A and 4B showed that only corner targets presented on the outside of the priming object are subject to reduced RT. No such reduction was observed for corner targets located on the inside of the object. Experiment 5 was a control experiment designed to assess the possibility that the targets located inside the meeting of two contours in Experiments 2, 4A, and 4B were subject to masking, possibly explaining the relatively long RTs for such targets. The results, however, showed this not to be the case. Targets located inside the meeting of two contours but on the *outside* of the priming object accrued the corner benefit. Our final experiment (Experiment 6) assessed how the onset of a second object presented adjacent to the priming triangle would affect the distribution of spatial attention surrounding the figure. The results showed that the processing disadvantage normally observed for straight edge targets was eliminated when these targets were grouped together with a facilitated corner area on the basis of uniform connectedness. Thus, the spotlight surrounding

the figure was influenced by the simultaneous onset of a second object.

One of the central aims of the present work was to examine how the corner effect relates to space-based and object-based theories of attention and, specifically, how the effect might reveal something about how these two modes of selection interact. A growing number of studies have begun to show an interaction between the two. For example, Vecera (1994) replicated Egly et al.'s (1994) *within-object/between-object* experiment with the addition of a further manipulation. As well as the basic procedure, Vecera included a second condition in which the two priming rectangles were positioned closer together. The results showed that the facilitated processing of targets on invalid trials within an object, relative to between objects, was reduced when the two rectangles were in closer spatial proximity. That is, an *object-based* effect was influenced by a spatial manipulation. Similarly, Kramer and Jacobson's (1991) response competition study showed not only that efficiency of target processing was reduced when targets were grouped with distractors, but also that the strength of this reduction was affected by spatial factors. When targets and distractors were grouped as one object, but with increased spatial proximity, the interference was reduced.

The present series of six experiments shows that the spotlight of attention surrounding a new object is not of a uniform fixed shape but can be distorted according to properties of the object's contours; greater attention is allocated to regions of space adjacent to the corners than to those adjacent to the straight edges. Scholl (2001) has stated that distortion of the spatial spotlight on the basis of object shape would constitute an example of how object-based attention and space-based attention are not mutually exclusive. In addition, a spatial *gradient* of attention (Downing & Pinker, 1985; Hughes & Zimba, 1985; LaBerge & Brown, 1989) was observed, whereby processing of targets was relatively more inefficient as the proximity between the figure and the target increased. This distortion of the spotlight and the spatial gradient effect is clearly consistent with space-based theories of attention. Furthermore, this distortion is also consistent with the notion that attention was allocated on the basis of an object representation, since corner facilitation is greatest at corners that define an object as a particular shape. This concurs with Abrams and Law's (2000) view that the gradient of attention is *object aware*. Moreover, the distortion was observed only in the area surrounding the object; no such corner effect occurred within the contour boundaries of the object, where processing was uniform. This is consistent with one of the basic findings concerned with object-based attention. That is, attention appears to "grow" within the boundaries of an object (e.g., Egly et al., 1994). Overall, therefore, the deployment of attention following the onset of a new object is consistent with both space-based and object-based notions of attention.

Although the corner effect is greatest at corners that define an object as a particular shape, it is clear that corner facilitation is not associated solely with *object* corners. Experiment 3A showed that non-object-defining corners

also accrue facilitation. Indeed, effects of base-level corner processing could potentially explain the facilitation for object-defining corners. It is not yet entirely clear how the basic corner effect is modulated by the different types of base-level corners that can occur, such as the corners that exist in "L" and "T" type stimuli. Thus, for instance, in Experiment 2, the base-level corner generated by the overlapping of two straight edges created a "T" form, whereas the object corner was in the form of an "L." Targets adjacent to these two types of stimuli may be differentially processed at the local level, regardless of how they form part of a global object.

The issue of how the basic corner effect is modulated by the different types of base-level corner is also pertinent to Experiment 3A, in which corners were located along the straight edges of the priming triangle. Whereas these corners were right angles (90°), the competing object-defining corners were acute angles (53°). Although Cole et al. (2001) did not find any effect of angle on the corner effect, the means for the present Experiment 4B show that the magnitude of the effect was much smaller for the corner of a square (90°), relative to the acute corner of a triangle (53°). This also suggests the possibility that the acute corner acts like an arrow guiding attention to the corner target, similar to the effects reported by Friesen, Ristic, and Kingstone (2002). It is also unknown how, if at all, the basic corner effect is differentially affected by proximal regions of concavity and convexity. For example, corner targets located inside the priming figure are positioned in a region of concavity, whereas corner targets located outside the figure are in an area of convexity. Similarly, outside corner targets are opposite a region of concavity, whereas straight edge targets are neither in a region of concavity nor in one of convexity. Clearly, any concavity/convexity confound could have contributed to some of the effects reported here.

The present findings also help us to understand the nature of the basic corner effect. Experiments 4A and 4B provide further evidence that the corner phenomenon is an attentional effect and is not due to a corner bias being operated by the participant. Cole et al. (2001) investigated the possibility that participants were adopting a top-down strategy in which they simply searched the corner areas for a target first. Even though targets appeared at corner and straight edge locations on an equal number of occasions, adopting this strategy may have paid off for the participants, because the corners of objects and, hence, the priming figure covered a smaller spatial area, as compared with the straight edges. In other words, the spatial uncertainty of corner targets is considerably less than that for straight edge targets. Cole et al. attempted to reduce any corner bias by presenting corner targets on only 20% of the trials. Even though straight edge targets appeared with greater frequency, the corner effect was still observed. This finding is supported by the results of the present Experiments 4A and 4B. If any top-down corner bias was being operated by the participants, one would assume that this would occur also for targets presented at corner locations inside the triangle. However, no corner effect was observed with such targets.

Cole et al. (2001) also postulated how the corner effect might aid our understanding of object/shape perception. At the most general level, outlines and contours define the basic shapes of figures. Hebb (1949) stated that lines are of particular importance for the perception of shape and suggested that they constitute perceptual elements in a hierarchy of feature primitives. Such primitives are seen as building blocks on which later shape perception is based. One might, therefore, also expect corners to play a more important role in shape perception than do straight edges. Indeed, this is central to Attneave's (1954) notion of *visual redundancy*. Stimulus input is considered redundant if portions of this information are highly predictable, as one finds in a straight edge, or what Attneave referred to as "a contour of homogeneous direction" (Attneave, 1954, p. 184). By contrast, abrupt changes in angle—that is, corners—are said to possess relatively greater *information*. Hence, the corners of the figures used in the present experiments may have been processed more efficiently because they were subject to less redundancy. Similarly, Hoffman and Singh (1997) argued that different parts of objects have different salience and that the salience of a part is partly dependent on the degree to which it protrudes, relative to the rest of the object. Importantly, this can provide the basis for the computation of figure/ground segregation.

An effect related to the corner phenomenon, and relevant for shape processing in general, has been reported by Jolicœur and his colleagues (Jolicœur & Ingleton, 1991; Jolicœur, Ullman, & Mackay, 1986, 1991). They were interested in how the spatial relationships between different elements in the visual array are specified. Jolicœur and colleagues argued that this specification is performed via an operation they referred to as *visual curve tracing*. With this procedure, the visual system is said to rapidly trace the contour of a shape and, as a result, integrates information from its different parts. Jolicœur et al. (1991) argued that curve-tracing operations are sensitive to a number of contour properties, one of which is high curvature. Hence, corner facilitation and curve tracing might involve shared mechanisms that assist shape perception through the representation of corners and high curvature. The results of Experiment 4A do, however, make the contribution of contour and corner to this process less clear, because no facilitation effect was observed at the inside of corners. Clearly, in order to adequately assess the role of contour, one would need to present probes on the contours themselves.

The finding that targets were subject to reduced RT when presented inside the contour boundaries of our priming figures, as compared with when presented outside, is likely to be related to the so-called *figure superiority effect*. This is the finding that the detection and discrimination of stimuli presented in figural regions is facilitated, relative to stimuli presented against the ground. For instance, Wong and Weisstein (1982) presented observers with Rubin face–vase reversible figures and required them to determine the orientation of a short line segment that was shown for 20 msec. When the line occurred in a region perceived as figure, accuracy was three times greater than when the line occurred in a region perceived

as ground. Moreover, Wong and Weisstein (1983) showed that stimuli of high spatial frequency are detected more effectively when presented in figural regions. Similarly, Van Selst and Jolicœur (1995) observed an effect whereby a *same–different* judgment concerning two targets was facilitated when both were presented inside the contours of a shape, relative to when presented outside. Sanocki and Sellers (2001) have also found a facilitatory effect for targets that fall within the boundary of a priming object. The present data therefore concur with past findings and support Wong and Weisstein's (1983) suggestion that different visual processes mediate the analysis of figure and ground.

AUTHOR NOTE

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NOTES

1. Contrary to the stimuli used by Cole et al. (2001), in the present series of experiments, we employed a line figure as the priming object, rather than the solid figure previously reported. This allowed the targets presented on the inside of the object in Experiments 4A and 4B to be defined in the same way as all the other targets—that is, same luminance, chrominance, and contrast. Furthermore, all the present experiments (except Experiment 4B) used a triangle as the prime figure, as opposed to a square.

2. Clearly, one would not normally perform multiple *t* tests on all possible combinations of all the conditions in an experiment, since this would lead to the real possibility of committing a Type I error. However, our rationale and hypothesis for Experiment 4A predicted *no* RT differences between all the target positions inside the priming object. Given such circumstances, it is therefore appropriate to use the most powerful test possible and, thus, guard against Type II error.

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