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The path of visual attention

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Abstract

Visual cuing is one paradigm often used to study object- and space-based visual selective attention. A primary finding is that shifts of attention within an object can be accomplished faster than equidistant shifts between objects. The present study used a visual cuing paradigm to examine how an object's size (i.e., internal distance) and shape, influences object- and space-based visual selective attention. The first two experiments manipulated object size and compared attentional shift performance with objects where the within-object distance between cued and uncued target locations was either equal to the between-object distance (1:1 ratio condition) or three times the between-object distance (3:1 ratio condition). Within-object shifts took longer for the larger objects, but an advantage over between-object shifts was still evident. Influences associated with the shapes of the larger objects suggested by the results of the first two experiments were tested and rejected in Experiment 3. Overall, the results indicate that within-object shifts of attention become slower as the within-object distance increases, but nevertheless are still accomplished faster than between-object shifts.
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1. Introduction

Considerable research indicates visual attention operates on both space-based and object-based information (Abrams & Law, 2000; Duncan, 1984; Egly, Driver, & Rafal, 1994; Egly, Driver, Rafal, & Starrveveld, 1994; Iani, Nicoletti, Rubichi, & Umilta, 2001; Lamy & Egeth, 2002). Evidence for space-based attention comes from visual cuing studies, showing that it takes more time to shift attention between a cue and a target as the distance between them increases (Shulman, Remington, & McLean, 1979; Tsal, 1983). Since shifting attention over space takes time, responses are faster to a target appearing at a cued (i.e., a valid cue) compared to an uncued location (i.e., an invalid cue) because in the latter case attention must shift from the cued location to the target location.

Visual cuing studies have also provided evidence for object-based selection (Egly, Driver, et al., 1994; Egly, Driver, Rafal, et al., 1994; Iani et al., 2001; Lamy and Egeth, 2002; Lamy and Tsal, 2000; Moore et al., 1998; Vecera, 1994). For example, Egly, Driver, et al.'s (1994) objects were bar stimuli like those in Fig. 1. On valid trials the target appeared at the location of the cue. On invalid trials it appeared at a nearby location. On half the invalid trials the target appeared at the opposite end of the bar requiring a shift of attention within the object, on the other half the target appeared in a nearby bar requiring a shift of attention between objects (see Fig. 1 for examples). The stimuli were configured so the cue-to-target distance was the same for both types of invalid trials. A purely space-based account predicts that targets should be detected equally fast because whether attention shifts within or between objects, the physical distance between the cue and the targets is the same. However, as they and many others have found, targets are responded to faster when they appear in the same object as the cue rather than in an adjacent object. This advantage for within-object shifts of attention (or disadvantage for between-object shifts)

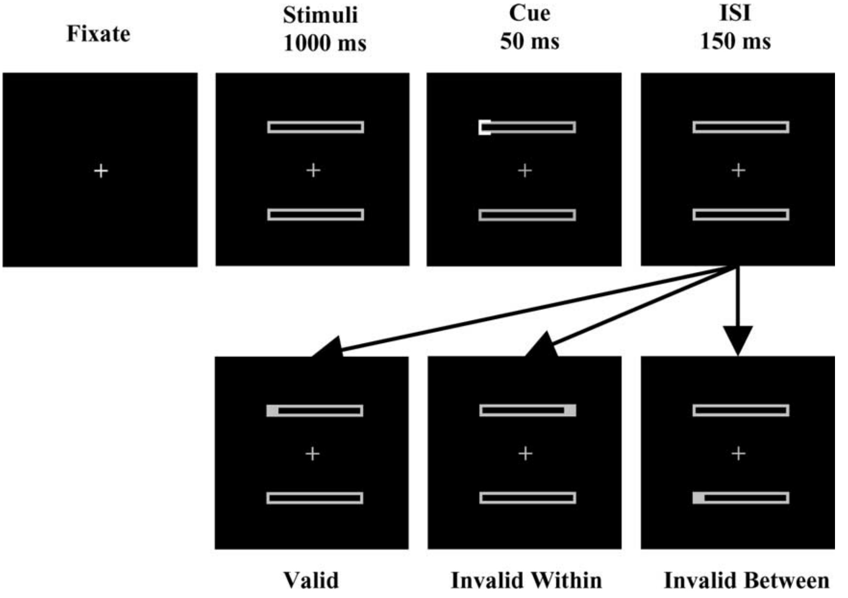

Fig. 1. An example of bar stimuli used in Experiments 1 and 2, and an example of the sequence of events that occurred on each trial for all stimuli in all experiments.

is a consistent finding in the literature and has been used as evidence of object-based contributions in visual selective attention.

2. Experiment 1

The present study examined how an object's size and shape influences the object advantage. Object-based biases have been shown to occur over large distances in divided attention paradigms, even when the target elements are closer together but on two different objects (Lavie & Driver, 1996). The present experiments used a cuing paradigm to test whether an object advantage would be present for objects with internal distances greater than the distance between objects (see Fig. 2). For example, the within-object distance for the bracket stimuli in Fig. 2 (i.e., from one end of a bracket to the other end following the

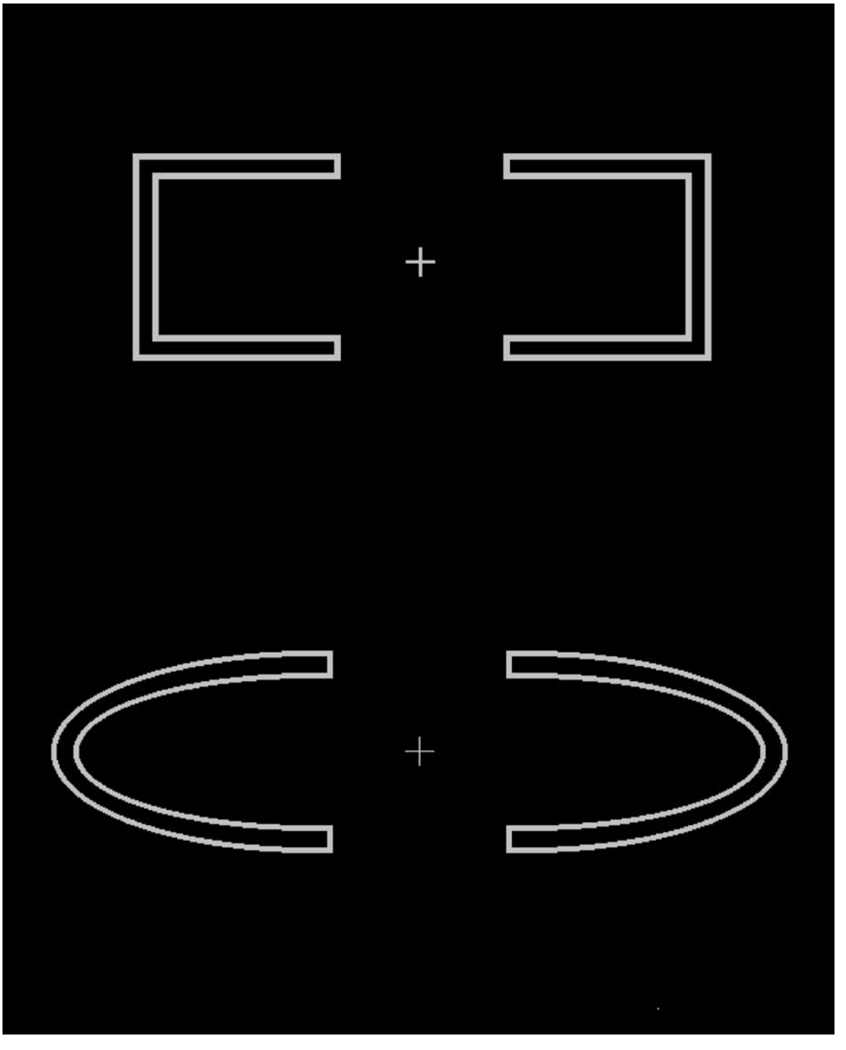

Fig. 2. Examples of bracket and arc stimuli where the within-object to between-object distance ratios were 3:1.

bracket contours) is three times the between-object distance (i.e., the distance between the end of a bracket and the end of the bracket opposite it). Will attention follow the object's shape or will it take the shorter route across a spatial gap? One way we tested this was to compare performance using the bar and the bracket stimuli. With the bar stimuli, the within- and between-object distances are equated and thus an object advantage would be expected. If tracing the object's contours is in some way obligatory (Avrahami, 1999; Jolicoeur, Ullman, & Mackay, 1991), then the object advantage should be reduced or eliminated for the brackets because of their greater within- compared to between-object distances. However, if attention takes the shortest possible route from cue to target, then RTs for within- and between-object shifts should be similar for bracket and bar stimuli because the physical distance between cues and targets are identical for both objects.

3. Method

3.1. Participants

Forty (20 females) undergraduates of the University of Georgia participated in two sessions for Introductory Psychology course credit. All participants had normal or corrected to normal vision, were classified as right-handed according to the Annett Handedness Scale, and reported no history of attention deficit disorder.

3.2. Stimuli and apparatus

Stimuli presentation and data collection were carried out using commercially available software (SuperLab Pro™) running on a PC computer with a VGA monitor. Responses were collected from a response box that interfaced with the computer. Participants sat in a darkened room, 60 cm from the monitor using a chin-rest.

All stimuli were white on a black background. The fixation cross was $0.76° \times 0.76°$ in size. Each bar was centered 2.39° from fixation and subtended $5.33° \times 0.57°$. Each of the three sides of the brackets also subtended $5.33° \times 0.57°$. From fixation, the distance of the open ends of the brackets was equal to the distance of the end points of the bars. The width of the lines constructing the objects subtended 0.19°. Targets consisted of a solid square (0.57° on each side) filling one end of an object. Cues were also 0.19° in width and consisted of an outline of three sides of the target area. All stimuli were presented in both horizontal (shown) and vertical orientations.

3.3. Procedure

Participants ran in the bar and bracket conditions on separate days with the order of conditions counterbalanced across participants. Following a brief introduction to each condition, participants completed 10 practice trials before starting the experiment. Trials were presented in eight blocks of 80 trials and were randomized within each block for a total of 640 trials. There was a 5-min break after the fourth block and 30 s breaks after the second and sixth blocks.

Of the 80 trials in each block, 48 were valid trials in which the cue and target appeared in the same location, 16 were invalid trials in which the cue and target did not appear in the same location, and 16 were catch trials in which no target appeared. The invalid trials consisted of eight invalid within-object trials in which the cue and target were in different locations but within the same object and eight invalid between-object trials in which the cue and target appeared in different objects.

The sequence of events for a trial is depicted in Fig. 1. Each trial began with a white fixation cross at the center screen that remained visible throughout the trial. Participants initiated a trial with a key press. A stimulus appeared for 1000 ms, followed by the cue appearing at the end of one of the objects for 50 ms. After 150 ms the target appeared for 1500 ms or until the participant responded. On catch trials no target appeared. At the end of each trial the screen went blank for 500 ms followed by the fixation cross indicating the next trial. Reaction times were measured from the onset of the target until a response was made. Participants received a warning screen if their reaction time was less than 150 ms or if they made a false alarm on a catch trial.

4. Results

RTs less than 150 ms and greater than 1000 ms (2.4%) were trimmed from all analyses. Mean false alarm rate on catch trials was 4.1%. Mean RTs were calculated for each participant for valid and invalid trials for each stimulus and were submitted to a 2 (stimulus: bar vs. bracket) × 2 (cue: valid vs. invalid) repeated measures ANOVA. Both main effects of stimulus (bars: 378 ± 12 ms, brackets: 391 ± 14 ms) $F(1,39) = 4.26$, $p < .05$ and cue (valid: 359 ± 10 ms, invalid: 411 ± 15 ms) $F(1,39) = 56.42$, $p < .001$ as well as their interaction $F(1,39) = 9.79$, $p < .003$ were significant (see Fig. 3). The interaction indicates responses were slower to the brackets, particularly for invalid trials.

To examine the object- and space-based contributions, the costs for shifting attention on invalid trials within objects (within-object cost = invalid within-object RT minus valid RT) and between objects (between-object cost = invalid between-object RT minus valid RT) were calculated for each stimulus in this experiment and subsequent experiments. A 2 (stimulus: bar vs. bracket) × 2 (shift condition: within-object vs. between-object) ANOVA of these costs revealed significant main effects of stimulus $F(1,39) = 10.59$, $p < .003$ and shift condition $F(1,39) = 43.12$, $p < .001$ and a significant interaction

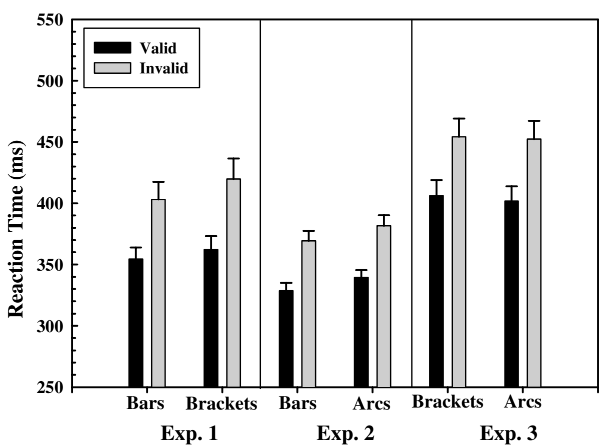

Fig. 3. Mean valid and invalid reaction times for each stimulus condition tested in Experiments 1–3.

$F(1, 39) = 12.94$, $p < .0015$ (see Fig. 4). Post hoc pairwise comparisons (Newman Keuls, all $p < .05$) indicated a significant object advantage for both bars (26 ms) and brackets (11 ms). The reduction in the object advantage for the brackets was due to the 17 ms greater cost of within-object shifts of 52 ms for the brackets compared to the 35 ms for bars. In comparison, there was no difference between costs for between-object shifts (brackets: 63 ms, bars: 62 ms).

5. Discussion

Using bar stimuli, Vecera (1994) found the object-advantage reduced when the between-object distance was less than the within-object distance, but this was due to faster responses in the between-object condition due to the shorter distance attention that had to shift between objects. In our experiment the between-object distance was held constant and the within-object distance was varied. Finding within-object shifts took longer for the brackets compared to the bars, consistent with the idea of attention following the object's contours, moving or radiating through it (Abrams & Law, 2000). This interpretation must be tempered with the realization that responses in the between-object conditions still required disengaging attention from the cued object to shift to the other. However, this aspect was constant for both bracket and bar stimuli so the greater within-object costs may reasonably be attributed to the greater within-object distance.

6. Experiment 2

In addition to the greater within-object distance for the brackets relative to the bars, the shape of the brackets may have also contributed to the results. From a part-based perspective, the brackets could be described as containing five figural parts, three sides and two corners. Using a different type of task, Jolicoeur and Ingleton (1991) and Jolicoeur et al. (1991) have shown curve tracing time increases with increases in distance and curvature. Hence, the abrupt changes in direction (i.e., from zero curvature to a very high

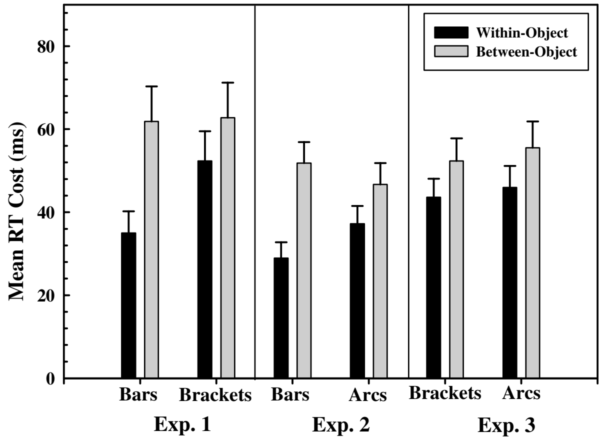

Fig. 4. Mean RT costs for within-object and between-object shifts of attention for each stimulus condition tested in Experiments 1–3.

curvature) along the contours of the brackets, in addition to their longer distance, may have contributed to the longer response times for the brackets in Experiment 1. To examine this issue the second experiment used arc stimuli that also had an internal distance three times that of the bars. Similar to the brackets, the greater internal distance should produce a reduction in the object advantage compared to the bars. However, the arcs could be described as simpler than the brackets from a part-based description (e.g., a single curve with gradual changes of curvature) as well as from the perspective of the Gestalt organizational principles of good continuation. If these figural attributes facilitate shifts of attention, then the increase in within-object costs over the bars may be less for the arcs compared to the brackets.

6.1. Participants

Forty (20 females) undergraduates of the University of Georgia participated in two sessions for Introductory Psychology course credit. All participants had normal or corrected to normal vision, were classified as right-handed according to the Annett Handedness Scale, and reported no history of attention deficit disorder.

6.2. Stimuli, apparatus, and procedure

Other than the arc stimuli that shared the dimensions of the brackets (i.e., a 3:1 within-object to between-object distance ratio), everything concerning the stimuli, apparatus, and procedure were the same as Experiment 1.

7. Results and discussion

RTs less than 150 ms and greater than 1000 ms (1.5%) were trimmed from all analyses. Mean false alarm rate was 4.8%. A 2 (stimulus: bar vs. arc) $\times$ 2 (cue: valid vs. invalid) repeated measures ANOVA on the mean RTs showed a significant main effect of stimulus (bars: 349 ± 7 ms, arcs: 360 ± 7 ms) $F(1,39) = 3.96$, $p < .05$ and cue (valid: 334 ± 6 ms, invalid: 375 ± 8 ms) $F(1,39) = 96.99$, $p < .001$ but no interaction $F(1,39) = 0.36$, $p > .55$ (see Fig. 3).

To examine the object- and space-based contributions, the costs for shifting attention within and between objects were calculated. A 2 (stimulus: bar vs. arc) $\times$ 2 (shift condition: within-object vs. between-object) ANOVA of these costs revealed a significant main effect of shift condition $F(1,39) = 51.93$, $p < .001$ and a significant interaction $F(1,39) = 11.78$, $p < .001$ (see Fig. 4). Post hoc pairwise comparisons (Newman Keuls) indicated a significant object advantage for both bars (23 ms) and arcs (10 ms). As in Experiment 1, the between-object costs for the bars (52 ms) and arcs (47 ms) were not significantly different. Moreover, it again appears that the reduction of the object advantage for the arcs is due to an 8 ms greater cost of within-object shifts of 37 ms for the arcs compared to the 29 ms for bars.

However, two comparisons are noteworthy. First, the 52 ms within-object cost for brackets (Experiment 1) is larger than the 37 ms within-object cost for arcs (Experiment 2). And secondly, the 17 ms difference between costs for within-object shifts in brackets compared to bars (Experiment 1) was greater than the corresponding 8 ms difference between costs for within-object shifts in arcs compared to bars (Experiment 2). On both counts, it appears that the within-object advantage was weaker for the brackets

(Experiment 1) than for the arcs (Experiment 2). This stronger within-object advantage for arcs as compared to brackets is consistent with our hypothesis that figural factors such as good continuation and good curve might facilitate shifts of attention within objects. If attention moves within objects by radiating through them (Abrams & Law, 2000) and guided by their contours (Avrahami, 1999), then the smaller and more gradual changes of curvature in the arcs as compared to brackets should facilitate attentional shifts (Jolicoeur & Ingleton, 1991; Jolicoeur et al., 1991) and thereby yield lower costs within the arcs compared to the brackets. However, this interpretation of the results of Experiments 1 and 2 is complicated by the fact that overall RT differences were also evident between the two experiments. A statistical comparison of mean RTs for the bars (1:1 ratio) conditions from Experiments 1 and 2 was made using a 2 (experiment) $\times$ 2 (cue: valid vs. invalid) ANOVA with a experiment between-subjects variable. A similar analysis was made of the mean RTs of the brackets and the arcs (3:1 ratio) conditions from Experiments 1 and 2. The RTs in the 1:1 (bars) $F(1,78) = 4.76$, $p < .03$ and 3:1 (brackets and arcs) conditions $F(1,78) = 3.94$, $p < .05$ were significantly longer in Experiment 1 than Experiment 2. While these differences may simply be due to sampling (i.e., different groups of observers), the interpretations of the results of the first two experiments may be called into question if costs and cost differences interact with overall RTs.

8. Experiment 3

The present experiment was designed to test this possibility by comparing the brackets and arcs conditions directly in a within-subject design. This allowed us to test the reliability of the main finding of increased costs for within-object shifts for objects with longer internal distances as well as eliminating possible alternative accounts for the differences between Experiments 1 and 2 in terms of their attentional shift costs. Between-object costs were again predicted to be greater than within-object costs, but due to the 3:1 ratios of the within- to between-object distance for the brackets and arcs, the object advantage was expected to be reduced compared to the 20+ ms object advantage found with the bar stimuli. Moreover, if for reasons outlined above the within-object shifts of attention are more efficient for the arcs than the brackets, then within-object costs should be larger for brackets than for arcs and the cost differences between within-object and between-object shifts should likewise be larger for brackets than for arcs.

9. Method

9.1. Participants

Forty (20 females) undergraduates of the University of Georgia participated in two sessions for Introductory Psychology course credit. All participants had normal or corrected to normal vision, were classified as right-handed according to the Annett Handedness Scale, and reported no history of attention deficit disorder.

9.2. Stimuli, apparatus, and procedure

Other than randomly receiving the bracket or arc stimuli first, everything concerning the stimuli, apparatus, and procedure were the same as the first two experiments.

10. Results

RTs less than 150 ms and greater than 1000 ms (4%) were trimmed from all analyses. Mean false alarm rate was 3.8%. A 2 (stimulus: bracket vs. arc) × 2 (cue: valid vs. invalid) repeated measures ANOVA on the mean RTs, shown in Fig. 3, only yielded a significant main effect of cue (valid: 404 ± 13 ms, invalid: 453 ± 15 ms) $F(1, 39) = 104.81$, $p < .001$.

To examine the object- and space-based contributions, the costs for shifting attention within and between objects, shown in Fig. 4, were also analyzed. A 2 (stimulus) × 2 (shift condition: within-object vs. between-object) ANOVA of these costs revealed a significant main effect of shift condition, only $F(1, 39) = 16.28$, $p < .001$ indicating within-object shifts were faster (45 ms) than between-object shifts (54 ms). The differences in cost for within- versus between-object shifts was comparable to that found in the first two experiments, replicating the influence of a greater internal distance on within-object shifts. The lack of significant interaction $F(1, 39) = 0.06$, $p > .81$ between the stimulus and cost factors also indicates that the differences in RTs between the first two experiments was due to associated observer differences, rather than due to figural differences between the brackets and arcs.

11. General discussion

Researchers continue to explore the complex interaction of perception and visual selective attention (Avrahami, 1999; Lamy & Egeth, 2002; Robertson & Kim, 1999; Watson & Kramer, 1999). The present study examined the interaction between object- and space-based attention by assessing how the shape and internal size of objects influenced shifts of attention within and between them. While shifts of attention within objects was always found to be faster than between objects, the advantage for shifts within objects was attenuated for bracket and arc stimuli with an internal distance three times greater than the distance between them. This indicates an interaction between shifts of attention and configural aspects of the stimuli associated with shape and size (i.e., perceived distance). The results support both space-based and object-based views of visual selective attention. Consistent with an object-based account, attention shifts were faster within objects than between them, when the within- and between-object distances were equated (i.e., the bars stimuli). However, consistent with a space-based account, increasing the within-object distance led to increases in the time it took for attention to shift from one end of the object to the other (i.e., it took more time for attention to shift farther in space), thus reducing the object advantage.

The present results provide convergent evidence using different shaped stimuli consistent with other cuing studies that have manipulated the between-object distance (Vecera, 1994) and the perceived size (i.e., perceived internal distance) of the objects (Robertson & Kim, 1999). Vecera used bar stimuli like those used here but moved the bars closer together so the between-object distance was half the within-object distance. Although reduced in magnitude, an object advantage was still found. In this case, costs for within-object shifts remained constant while costs for between-object shifts decreased due to the shorter distance attention had to shift between the objects. Our results mirror Vecera's in that our costs for between-object shifts remained constant while our costs for within-object shifts increased with a greater within-object distance. In a related study, Robertson and Kim (1999) used linear perspective depth cues to manipulate the perceived length of their objects (i.e., lines) and the perceived distance between them even though the physical (i.e., retinal) distance was the same within and between objects. The depth cues made one object appear longer and the distance between the objects appear greater than the distance within either object. An overall advantage was found for shifts within objects compared to between them. Most relevant to the present study, the cost for shifting attention within objects was greater for the object perceived to be longer. The increased cost for within-object shifts for our larger stimuli in which both the perceived and physical distance within them was greater is consistent with this and supports the notion of attention being distributed over perceived space.

An interesting and important difference between our bracket and arc stimuli with a 3:1 within-to-between distance ratio compared to our bar stimuli and to similar stimuli used by others with a 1:1 ratio (e.g., Lamy & Egeth, 2002; Robertson & Kim, 1999) is the direction the contours making up the stimuli are pointing. Our bracket and arc results suggest within-object shifts of attention are in some way obligated to follow an object's contours. An alternate account might be that attention takes the shortest route between the cue and the target for the brackets and arcs, traveling directly from one end to the other. Although this distance is identical to that for a between-object shift, an object advantage would still be expected because attention would still be shifting from one object to another. However, a shortest route account would not predict a reduction in the object advantage relative to the bar stimuli as was found because the cue-to-target distance attention would be shifting would then be identical for within-object shifts with the bar, bracket, and arc stimuli. The present results highlight how an object's shape may influence the spread of attention within it. Future cuing studies examining other shapes may help elucidate the nature of attentional shifts within objects.

References

Abrams, R. A., & Law, M. B. (2000). Object-based visual attention with endogenous orienting. *Perception and Psychophysics, 62*, 818–833.

Avrahami, J. (1999). Objects of attention, objects of perception. *Perception and Psychophysics, 61*, 1604–1612.

Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology: General, 113*, 501–517.

Egly, R., Driver, J., & Rafal, R. D. (1994). Shifting attention between objects and locations: Evidence from normal and parietal lesion subjects. *Journal of Experimental Psychology: General, 123*, 161–177.

Egly, R., Driver, J., Rafal, R. D., & Starrveveld, Y. (1994). Covert orienting in the split brain reveals hemispheric specialization for object-based attention. *Psychological Science, 5*, 380–383.

Iani, C., Nicoletti, R., Rubichi, S., & Umilta, C. (2001). Shifting attention between objects. *Cognitive Brain Research, 11*, 157–164.

Jolicoeur, P., & Ingleton, M. (1991). Size invariance in curve tracing. *Memory and Cognition, 19*, 21–36.

Jolicoeur, P., Ullman, S., & Mackay, M. (1991). Visual curve tracing properties. *Journal of Experimental Psychology: Human Perception and Performance, 17*, 997–1022.

Lamy, D., & Egeth, H. (2002). Object-based selection: The role of attentional shifts. *Perception and Psychophysics, 64*, 52–66.

Lamy, D., & Tsal, Y. (2000). Object features, object locations and object-files: Which does selective attention activate and when? *Journal of Experimental Psychology: Human Perception and Performance, 26*, 1387–1400.

Lavie, N., & Driver, J. (1996). On the spatial extent of attention in object-based visual attention. *Perception and Psychophysics, 58*, 1238–1251.

Moore, C. M., Yantis, S., & Vaughn, B. (1998). Object-based visual selection: Evidence from perceptual completion. *Psychological Science, 9*, 104–110.

Robertson, L. C., & Kim, M. (1999). Effects of perceived space on spatial attention. *Psychological Science, 10*, 76–79.

Shulman, G. L., Remington, R. W., & McLean, J. P. (1979). Moving attention through visual space. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 522–526.

Tsal, Y. (1983). Movements of attention across the visual field. *Journal of Experimental Psychology: Human Perception and Performance, 9*, 523–530.

Vecera, S. P. (1994). Grouped locations and object-based attention: Comment on Egly, Driver, & Rafal (1994). *Journal of Experimental Psychology: General, 123*, 316–320.

Watson, S. E., & Kramer, A. F. (1999). Object-based visual selective attention and perceptual organization. *Perception and Psychophysics, 61*, 31–49.