

The role of closure in defining the “objects” of object-based attention

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Many recent studies have concluded that the underlying units of visual attention are often discrete objects whose boundaries constrain the allocation of attention. However, relatively few studies have explored the particular stimulus cues that determine what counts as an “object” of attention. We explore this issue in the context of the *two-rectangles* stimuli previously used by many investigators. We first show, using both spatial-cuing and divided-attention paradigms, that same-object advantages occur even when the ends of the two rectangles are not drawn. This is consistent with previous reports that have emphasized the importance of individual contours in guiding attention, and our study shows that such effects can occur in displays that also contain grouping cues. In our divided-attention experiment, however, this contour-driven same-object advantage was significantly weaker than that obtained with the standard stimulus, with the added cue of closure—demonstrating that contour-based processes are not the whole story. These results confirm and extend the observation that same-object advantages can be observed even without full-fledged objects. At the same time, however, these studies show that boundary closure—one of the most important cues to objecthood per se—can directly influence attention. We conclude that object-based attention is not an all-or-nothing phenomenon; object-based effects can be independently strengthened or weakened by multiple cues to objecthood.

Visual attention is fundamentally a process of selection: It helps us deal with a potentially overwhelming amount of incoming information by selecting only some information for further processing. A considerable amount of research in the past few decades has been devoted to determining the nature of this selection process, and in particular to exploring the nature of the underlying units of selection. Most traditional theories of attention either assumed or explicitly argued that attentional selection was a spatial operation; attention was characterized as a spotlight or zoom lens that focused processing resources on whatever visual information fell within the attended spatial region (for a review, see Cave & Bichot, 1999). Such spatial models inherently ignored the actual structure of the attended information: The process of selection was based not on the information itself, but rather on an extrinsic filter (the “spotlight”) through which the information was gated. More recent models of attention, in contrast, have stressed the complex interplay between attention and the actual structure of the attended information. For example, many studies of object-based attention have demonstrated that the underlying units of attention are often discrete

visual objects: Rather than spreading uniformly through a spatially defined region, attention flows more readily through individual objects and/or is constrained by their boundaries (for a review, see Scholl, 2001).

Although many studies of object-based attention have contrasted objects and locations, relatively few studies have explored in detail what can count as an object of attention in the first place. Objects are sometimes contrasted with other high-level classes of entities, such as groups (e.g., Driver, Davis, Russell, Turatto, & Freeman, 2001), parts (e.g., Vecera, Behrmann, & Filapek, 2001; Vecera, Behrmann, & McGoldrick, 2000), and nonsolid substances (e.g., vanMarle & Scholl, 2003). For the most part, however, the stimuli used in studies of object-based attention are defined only intuitively, with little attention paid to the individual image cues from which objects are formed (for a few recent exceptions, see Avrahami, 1999; Barenholz & Feldman, 2003; Marrara & Moore, 2003; Reppa & Leek, 2003; Scholl, Pylyshyn, & Feldman, 2001; Watson & Kramer, 1999). Here, we explore the importance of a particular cue, closure, using what is perhaps the best known and most often studied type of stimulus in research on object-based attention: the *two-rectangles* display, originally studied by Egly, Driver, and Rafal (1994) and since used in various forms by many other researchers (e.g., Abrams & Law, 2000; Avrahami, 1999; Goldsmith & Yeari, 2003; He, Fan, Zhou, & Chen, 2004; Lamy & Egeth, 2002; Lamy & Tsal, 2000; Marrara & Moore, 2003; McCarley, Kramer, & Peterson, 2002; Moore, Yantis, & Vaughan, 1998; Pratt & Sekuler, 2001; Shomstein & Yantis, 2004; Vecera, 1994).

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Same-Object Advantages in the Two-Rectangles

Stimulus: Contours Versus Closure

Subjects in the original two-rectangles experiment (Egly et al., 1994) were shown displays such as that depicted in Figure 1A and had to make a speeded detection response to a target (a small square) that could appear at either end of either rectangle. Before the target's appearance, an exogenous cue appeared at one end of one of the rectangles (for example, at C, for *cue*, in Figure 1A). The cue's location accurately predicted the target's location on 62.5% of the trials. On another 20.8% of the trials, the cue and target appeared in different locations: The target appeared either at the opposite end of the cued rectangle (S, for *same object* in Figure 1A) or at the equidistant end of the uncued rectangle (D, for *different object* in Figure 1A). The remaining 16.7% of trials were catch trials on which no target appeared. As in many cuing studies, the subjects responded faster when the target was validly cued. The most interesting result, however, was that same-object responses were faster than different-object responses on invalidly cued trials. Since the same-object and different-object locations were spatially equidistant from the cue, this indicates an object-based effect, which has since been termed a *same-object advantage*: Attention automatically spreads within an object (in this case the cued rectangle), speeding performance even for uncued regions of that object. (Alternatively, this effect could reflect a cost for switching objects relative to baseline, rather than an advantage; we address this issue below. Both explanations involve a type of selective attention in which certain locations within currently attended objects are prioritized relative to other locations in different objects; see Shomstein & Yantis, 2002.)

What are the image cues that drive this object-based effect? The two rectangles certainly constitute distinct objects on an intuitive level, but several independent image cues may contribute to such intuitions. First, the parallel lines themselves may speed the spread of attention within an object (or constrain the disengagement of attention), and parallelism is known to be an efficient cue to grouping and figure-ground segregation. Second, these parallel

lines are grouped into two closed contours, and (as will be discussed later) this type of closure also influences visual grouping (see the General Discussion). Third, even without closure, the parallel lines may group into pairs by virtue of their relative proximity. Which of these cues modulates the same-object advantage? In this article, we focus exclusively on the role of closure—often appealed to as one of the most important cues to “objecthood”—while holding parallelism and proximity constant.

One recent study suggests that closure may not in fact be required for same-object advantages (Avrahami, 1999). This study employed a regular grid of parallel lines (Figure 1B) and found a similar same-“object” advantage: The lines defined an overall grain in the display and subjects responded faster to invalidly cued targets when the cue and target were oriented along this grain in comparison with when they crossed the grain. This result, combined with a failure in some cases to observe a same-object advantage when “ribbons” (which enjoyed closure but lacked an overall grain) were used, led Avrahami to conclude that the putative object-based effect in the two-rectangles stimulus is a result primarily of efficient line-tracing operations (speeded by the straight parallel lines) rather than an effect of “objecthood” per se. Similarly, Marrara and Moore (2003) found an object-based effect when using rectangles defined only by widely spaced dots, which formed perceptual groups but lacked closure.

The Present Study

Under their strongest interpretation, Avrahami’s (1999) results suggest that cues to “objecthood” per se may play no role in guiding attention; rather, these results are consistent with the view that all such effects are driven only by contour-based line-tracing operations (perhaps along with other, more primitive visual features). This view may seem deflationary, especially for theories that have attempted to relate object-based attention to other processes (e.g., in infants) that do seem to depend on full-fledged objects (see, e.g., Carey & Xu, 2001; Scholl & Leslie, 1999). Thus, in this article we attempt to assess the generality of Avrahami’s results in two ways.

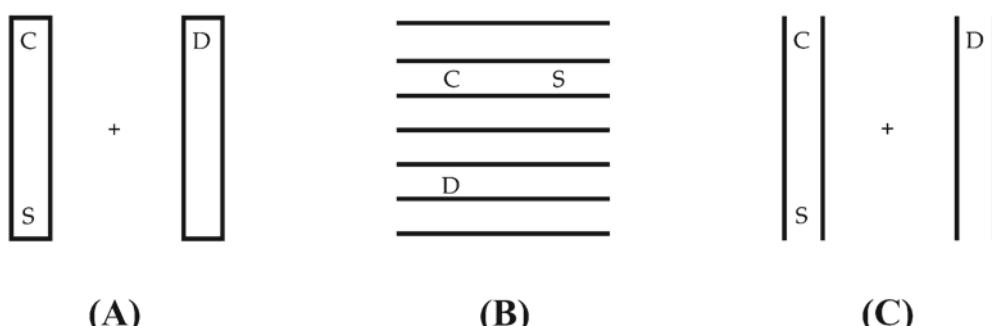


Figure 1. (A) Example of the “two-rectangles” display introduced by Egly et al. (1994). (B) Example of the line-tracing stimulus used by Avrahami (1999). (C) Example of our adaptation of Egly et al.’s display, wherein the lines are still grouped by proximity but lack closure. In each case, “C” indicates a possible cued location, “S” indicates the corresponding same-object target location, and “D” indicates the corresponding different-object target location. Proportions are not drawn to scale. See text for details.

First, we explore whether contour-driven processes can operate at all in the displays used by Egly et al. (1994) in their now classic study. It is possible that Avrahami's (1999) results have no direct implications for the interpretation of Egly et al.'s experiments, since Avrahami's display (Figure 1B) differs from the standard two-rectangles stimulus (Figure 1A) in multiple important ways. Note, for example, that even without closure the lines in Egly et al.'s study were already grouped into pairs by proximity. Avrahami's display, in contrast, was composed of a larger set of evenly spaced parallel lines that seem to remove all cues to "objecthood," leaving only a uniform global pattern. This complete purging of all structure (and all "objects") from the display may have facilitated the type of line-tracing process suggested by Avrahami. Line-tracing operations, in other words, may not require uniform lines but still may be particularly favored for uniform patterns that lack structure. Still, such processes may or may not operate in stimuli of the sort used by Egly et al. when only the closure cue is eliminated simply by removal of the ends of the rectangles, yielding a structured display whose lines are still organized into groups by proximity (see Figure 1C). Thus, a first operationalized goal of our study is to determine whether an "object"-based effect is observed with stimuli such as those in Figure 1C. We would expect an effect with such a stimulus if line tracing operates robustly even in Egly et al.'s stimuli, but perhaps not if uniform patterns are especially conducive to line tracing.¹

A second reason for directly exploring whether closure matters in such displays is that contour-based line tracing—even if it does operate in stimuli such as those presented in Figure 1C—may not be the whole story. In particular, line-tracing effects may operate in Egly et al.'s (1994) two-rectangles display (Figure 1A) but may contribute only partially to the observed effects. In this sense, Avrahami's (1999) experiment may have uncovered an important new component of the effects observed by Egly et al., but these results need not conflict: Attention may be influenced by both line-tracing operations and the more elaborated parsing of scenes into visual objects. Thus, a second operationalized goal of this study, beyond looking for effects in stimuli such as those of Figure 1C, is to determine whether the magnitude of the observed effects is larger in Figure 1A than in Figure 1C. In this way, we are testing for the presence and magnitude of same-object advantages in displays similar to those used by Egly et al. when only one cue (closure) is present or absent and others are held constant.

We explore both of these questions in two experiments, first using the same spatial-cuing paradigm employed by Egly et al. (1994) and then using a divided-attention method.

EXPERIMENT 1

Spatial Cuing

We first explored these issues using the spatial-cuing paradigm, as depicted in Figure 2. Each trial began with the appearance of the two primary "objects"—each of

which was either a rectangle (as in Figure 1A) or a pair of grouped line segments (as in Figure 1C)—followed shortly by the brief appearance of a salient cue at one end of one of the objects. (Our cues always involved a pair of brightened line segments, as depicted in Figure 2. These cues cleaved as closely as possible to those used by Egly et al., 1994; the only difference was that we never brightened the end segment of the rectangle, so that the cues in all of our stimuli were identical.) Shortly after the cue offset, the probe (a small square) appeared, and the observers made a speeded response to indicate their detection of the probe. The cue was equally likely to appear in any of four possible locations. On 65% of the trials, the cue was valid and accurately predicted the location of the probe. On 25% of the trials, the cue was invalid and the probe appeared either at the other end of the same object (12.5% of trials) or at the spatially equidistant end of the other object (12.5% of trials) in relation to the probe. The remaining 10% of the trials were catch trials, in which no probe appeared.

The two primary questions addressed in this study are thus (1) whether or not in displays without closure (as in Figure 1C) probes will be detected faster on same-object invalid trials than on different-object invalid trials and (2) whether or not the magnitude of any such effect will be just as large as that obtained with closed rectangles.

Method

Subjects. Forty-three Yale University undergraduates participated in a 45-min session for a small monetary payment or to fulfill an introductory psychology course requirement.

Materials. The displays were presented on a Macintosh iMac computer using custom software written using the VisionShell graphics libraries (Comtois, 2003). The subjects sat without head restraint approximately 46 cm from the monitor, the viewable extent of which subtended $36.9^\circ \times 28.1^\circ$. (All extents are reported in terms of this approximate viewing distance.)

All stimuli were drawn as black outlines (with a stroke of 0.2°) on a white background. Each initial display included a fixation point in the center of the display, drawn as a cross subtending 0.1° . Each display contained two "objects": either two rectangles or two groups of two parallel lines (identical to the rectangles except that the short ends were not drawn). The two objects (each subtending $1.7^\circ \times 11.4^\circ$) spanned the fixation point either vertically or horizontally, and each was centered 4.8° from the center of the display. Cues consisted of luminance increments of the ends of the parallel lines, such that a pair of segments (each 1.9° in length) changed from black to a midlevel gray. The cues were drawn in the same manner regardless of whether they were drawn on groups of parallel lines or on closed rectangles; in no case was the short end of a rectangle involved in the luminance increment. The probe consisted of a black square subtending 1.9° , placed to "fill in" the end of an object in trials in which it was present.

Procedure. A single trial proceeded as follows (see Figure 2). The subjects initiated the trial by pressing a key, which blanked the screen. After 500 msec, the two objects appeared and remained on the screen until the end of the trial. One thousand milliseconds after the objects' onset, the cue appeared for 100 msec. Two hundred milliseconds after the cue's offset, the probe appeared (except on catch trials), after which the objects and probe remained until the subject responded or the trial timed out (after 2,000 msec). The subjects were instructed simply to press a designated key on the keyboard as quickly as possible when they detected the probe, and to withhold a response when no probe appeared.

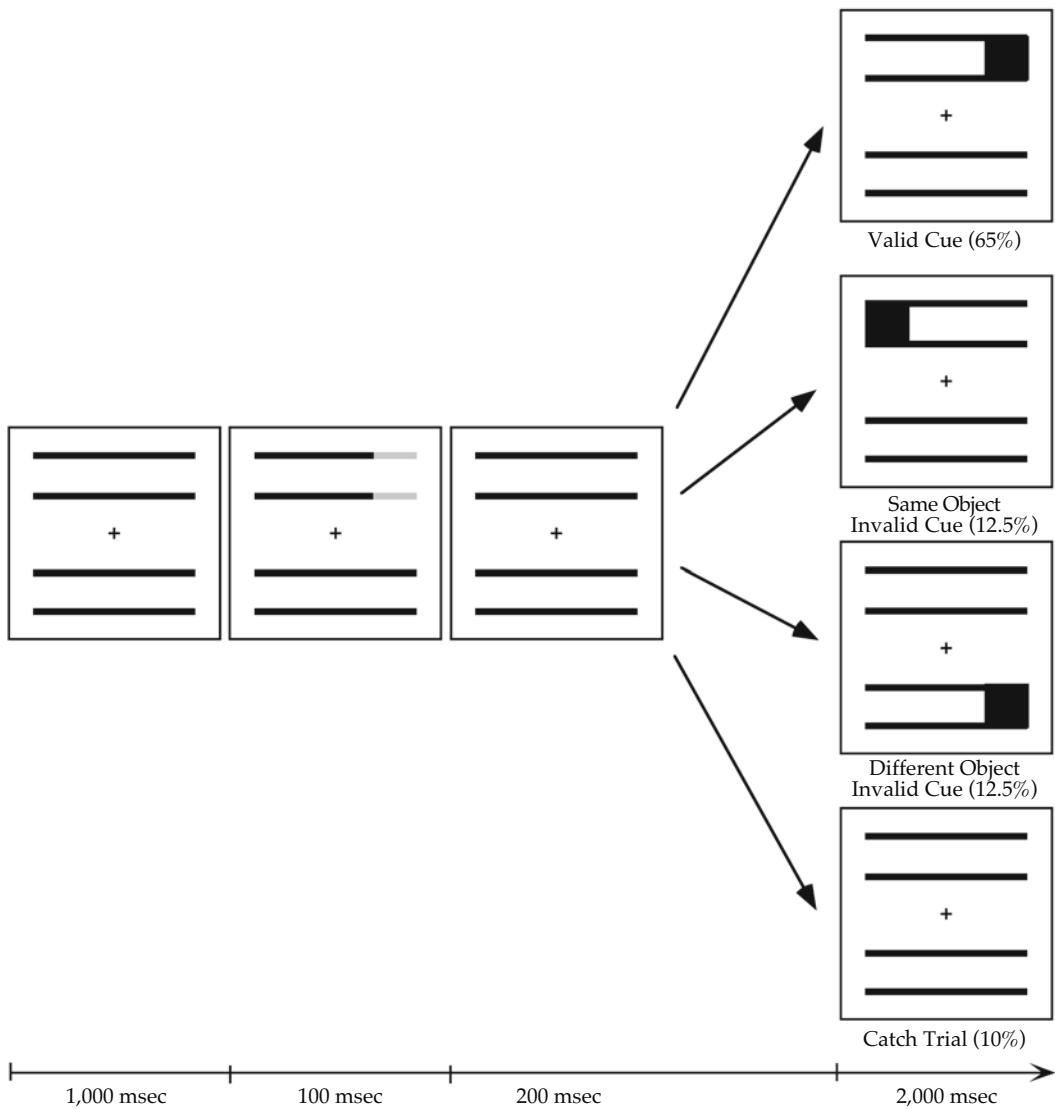


Figure 2. The sequence of events in the spatial-cuing paradigm used in Experiment 1. The unclosed stimuli are presented here, although closed rectangles were used in half of the displays. See text for details.

Design. Trials with rectangles and with groups of parallel lines were presented in separate blocks (the order of which was counterbalanced across observers), each containing 400 trials. Within each block, the location of the cue and the orientation of the objects were fully randomized and counterbalanced. Ten percent of the trials in each block were catch trials, in which no probe appeared; 65% were valid-cue trials, in which the probe appeared at the cued location; 12.5% were same-object invalid-cue trials, in which the probe appeared on the opposite end of the object on which the cue had appeared; and 12.5% were different-object invalid-cue trials, in which the probe appeared on the equidistant end of the object on which the cue had not appeared. Every 80 trials, a message appeared informing the subjects that they could take a break before continuing. Before beginning the experiment, each subject completed several practice trials (involving both types of objects), the results of which were not recorded.

Results

Each observer's accuracy and response latency (measured from the onset of the probe) were recorded for each

trial. Overall, errors were made on relatively few trials (with false alarms on 14.1% of catch trials and misses on 0.7% of probed trials) and are not included in the analyses presented below. As we expected, there was an overall cue validity effect: Responses on validly cued trials were faster than responses on invalidly cued trials [271.28 vs. 285.02 msec, respectively; $t(42) = 5.44, p < .01$]. In addition, there was an unexpected main effect of stimulus type for the invalidly cued trials: Responses to closed rectangles were slower than responses to grouped line segments, perhaps due to their greater complexity [281.16 vs. 267.33 msec, respectively; $t(42) = 2.41, p = .02$]. Of primary interest were the response times (RTs) on the different types of invalidly cued trials, presented in Figure 3. Responses were reliably faster when the cue and probe appeared within the same object in comparison with when they spanned both objects. This was true for both

rectangles [277.57 msec vs. 284.76 msec; $t(42) = 2.33, p = .03$] and groups of parallel lines [264.52 msec vs. 270.14 msec; $t(42) = 2.08, p = .04$], but the magnitudes of these same-object advantages did not differ [7.18 msec vs. 5.61 msec; $t(42) = 0.61, p = .4$.]²

Discussion

This experiment yielded same-object advantages for all of the tested stimuli regardless of whether the groups of lines were closed into rectangles or not. This suggests, first of all, that contour-based line-tracing operations of the sort proposed by Avrahami (1999) can operate even in nonuniform displays, and thus that they probably did play an important role in the two-rectangle results of Egly et al. (1994). This result is also consistent with the effect obtained by Marrara and Moore (2003), wherein the unclosed "rectangles" were defined simply by dots arrayed around their perimeters. Moreover, because the magnitude of the same-object advantage of unclosed groups of lines in the present study was just as great as the magnitude of that of closed rectangles, these results are consistent with the strong interpretation that Egly et al.'s results reflect only line tracing. In this view, important cues to "objecthood," such as closure, may in fact not influence attention at all.

EXPERIMENT 2 Divided Attention

In our second experiment, we attempted to replicate the results of Experiment 1 using a different dependent measure (accuracy rather than RT) in a different paradigm (involving divided attention rather than cuing). We con-

ducted this experiment for two primary reasons. First, and most generally, we wanted to obtain converging evidence for our spatial-cuing results from a different paradigm, to help ensure that these results reflect the operation of visual attention per se rather than some quirks that might be specific to cuing manipulations. Second, a subsidiary goal of this study was to directly compare the sensitivity of these two paradigms. Early pilot results suggested that some popular incarnations of divided-attention measures replicate results from standard spatial-cuing measures, but with fewer observers and greater reliability. (Of course, because these two paradigms involve different task manipulations and different dependent measures, the force of this contrast is meant only as a methodological heuristic for comparing two of the most popular methods as they have actually been used in the literature—rather than as a statement about the relative power of these two paradigms in principle.)

We are confident of the positive result of Experiment 1: the significant same-object advantage obtained without closure. At the same time, however, we remain hesitant to accept the null result of Experiment 1—that is, that adding closure with rectangles does not increase the magnitude of the same-object advantage. As with all null results, this could reflect either the true absence of such an effect or merely a lack of sensitivity in the paradigm. Given some hints that divided attention may sometimes be a more sensitive measure of object-based effects than spatial cuing, we predicted that we might find larger same-object advantages with closure than without closure.

Our use of the divided-attention paradigm was inspired by early studies of object-based attention (e.g., Duncan,

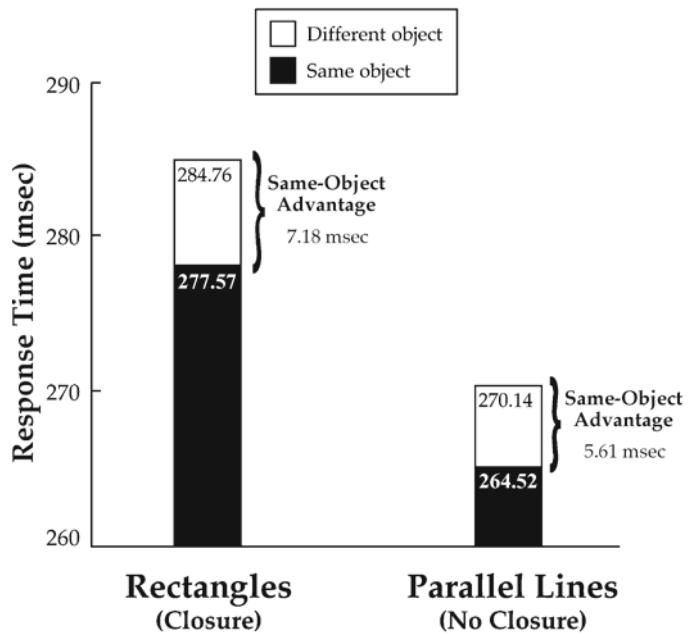


Figure 3. Subjects' response times in Experiment 1 (spatial cuing) by display type.

1984), and paradigms similar to the one used here have since been used in several other studies (e.g., Barenholtz & Feldman, 2003; Behrmann, Zemel, & Mozer, 1998; Ben-Shahar, Scholl, & Zucker, 2003, 2005; Kramer, Weber, & Watson, 1997; Lavie & Driver, 1996; Vecera & Farah, 1994). In this experiment, subjects simply had to compare two simultaneously presented probes. The two objects initially appeared in the display, again as either two rectangles or two groups of two parallel lines. A pair of probe items then appeared in the display, after which the entire display was replaced by a pattern mask. The subjects simply reported on each trial whether the two probes were identical or not.

The probes used in this study were constructed to be as similar as possible to the stimuli used by Egly et al. (1994), but were adapted for use with both closed rectangles and unclosed pairs of line segments (see Figure 4). Each display contained two probes, and each probe consisted of either a pair of line segments (identical to the cue used in Experiment 1) or a single one of these line segments. The subject's task was always to judge whether or not the two probes in each display were identical—that is, whether or not they had the same number of segments.

These probe stimuli introduce two difficulties. First, although the centers of the probes in each pair are equidistant in the same- and different-object cases, the *nearest* points of the probes are occasionally closer in the same-object conditions than in certain different-object conditions (e.g., the lower right example in Figure 4). Second, the probes are always grouped by good continuation in the same-object condition but not in the different-object condition (especially because two one-segment probes in same-object trials were always collinear). Nevertheless, we opted to use these probe stimuli for three reasons: First, a primary goal in designing these probes was

to cleave as closely as possible to the stimuli used by Egly et al. (1994) and in our own Experiment 1, so as to test as strictly as possible whether closure plays a role in the two-rectangles paradigm as used by many other investigators. Second, other recent evidence suggests that good continuation in such cues alone does *not* drive object-based effects (Marrara & Moore, 2003). Third, and most important, our primary goal in this experiment was to explore the comparison between rectangles and grouped unclosed line segments, and the two difficulties mentioned above do not affect these comparisons.

Again, the two primary questions addressed in this study are (1) whether, in displays without closure (as in Figure 1C), probes are compared more accurately on same-object invalid trials than on different-object invalid trials, and (2) whether the magnitude of any such effect will be just as large as that obtained with closed rectangles.

Method

This experiment was identical to Experiment 1, except as noted.

Subjects. Twenty Yale University undergraduates participated in a 45-min session for a small monetary payment.

Materials. The objects were displayed exactly as in Experiment 1.

Probes consisted of luminance increments of the ends of the parallel lines, such that a segment or pair of segments changed from black to a midlevel gray. Probes were drawn in the same manner regardless of whether they were drawn on groups of lines or closed rectangles; in no case was the short end of a rectangle involved in the luminance increment. Each probe involved either a single brightened line segment (1.9° long) at the end of one of the lines or a pair of identical brightened line segments at the end of one group of lines (spanning the extra segment that provided the closure in the rectangles). When two single-segment probes appeared on a same-object trial, the two brightened segments were always collinear.

Procedure and Design. The two objects initially appeared in the display for 1,000 msec. The probes then appeared for 300 msec, after which a pattern mask appeared until the subject responded.

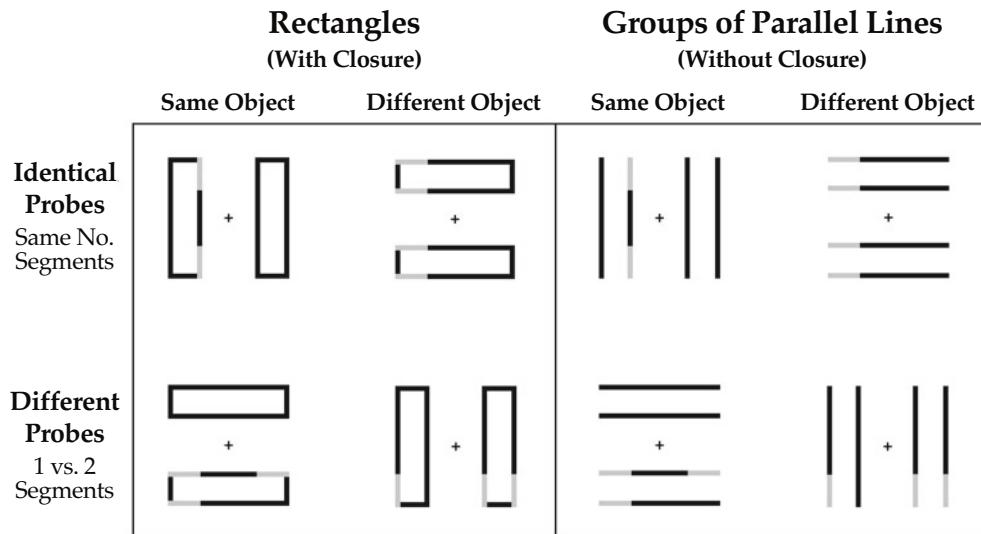


Figure 4. Depictions of the probe stimuli employed in Experiment 2 (not to scale). Each probe consisted of either one or two brightened line segments, and the subjects reported whether or not the two probes in each trial had the same number of brightened segments. The orientation of the objects was fully counterbalanced across each other variable. See text for details.

The subjects were instructed to press one of two keys, depending on whether or not the two probes were identical. The subject's keypress on each trial erased the screen for 500 msec, after which the next trial began. Trials with rectangles and with groups of parallel lines were presented in separate blocks, each containing 304 trials. Two factors were manipulated within each block.

Object manipulation. Half of the trials were same-object trials, wherein both probes appeared on one of the two objects chosen at random. The other half of the trials were different-object trials, wherein the two probes occurred on neighboring ends of different objects.

Probe identity. The two probes on each trial were equally likely to contain the same number of brightened line segments (either both single line segments, or both pairs of line segments, the choice being random) or different numbers of segments (one single line segment, and one pair of line segments). (Display orientation was also varied as in Experiment 1; the two objects on each trial were equally likely to be oriented horizontally or vertically.)

The order of the two blocks was counterbalanced across subjects. Within each block, trials were presented in a randomized order (different for each subject). Before the experiment, each subject completed several practice trials (involving both types of objects) using a longer probe duration (3,000 msec), followed by several practice trials using the normal (300-msec) probe duration.

Results

Response accuracy was recorded on each trial and is summarized in Figure 5. Responses were more accurate for same-object trials than for different-object trials, for both rectangles with closure [78.1% vs. 70.9%, respectively; $t(19) = 5.69, p < .01$] and groups of lines without closure [78.0% vs. 73.5%, respectively; $t(19) = 2.41, p = .03$]. The magnitude of this same-object advantage, however, was greater for rectangles than for groups of lines without closure [7.2% vs. 4.5%, respectively; $t(19) = 2.32, p = .03$.³

Discussion

The results of this experiment replicated those of Experiment 1 in one important way: We again observed a same-object advantage even for displays without closure (such as those in Figure 1C). This greatly strengthens the reliability of this result, considering that in the present experiment we used an entirely different paradigm and dependent measure than in Experiment 1. Thus, we feel confident that this result reflects something fundamental about the operation of attention and is not just a quirk of spatial cuing.⁴ Another aspect of the present experiment, however, extends Experiment 1 in a critical way: Whereas the magnitude of the cuing effect in Experiment 1 did not depend on the stimuli, here we found a significantly greater object-based effect with closed rectangles than with the unclosed grouped line segments that were otherwise identical. This result indicates that closure plays an important role in defining attentional "objects" after all, so that line tracing cannot be the sole explanation of such effects.

The detailed pattern of this effect is also worth noting. In particular, the increased magnitude of the object-based effect with closure was realized not by an increased facilitation for within-object comparisons, but rather by an increased cost for between-objects comparisons. This pattern of results suggests that the underlying effect may be more aptly described as a multiple-object disadvantage than as a same-object advantage. In other words, although the actual contours that had to be "crossed" by attention were identical in both conditions, the strengthened objecthood of the bounded rectangles made it more difficult for attention to cross these boundaries—or, alternatively, for attention to

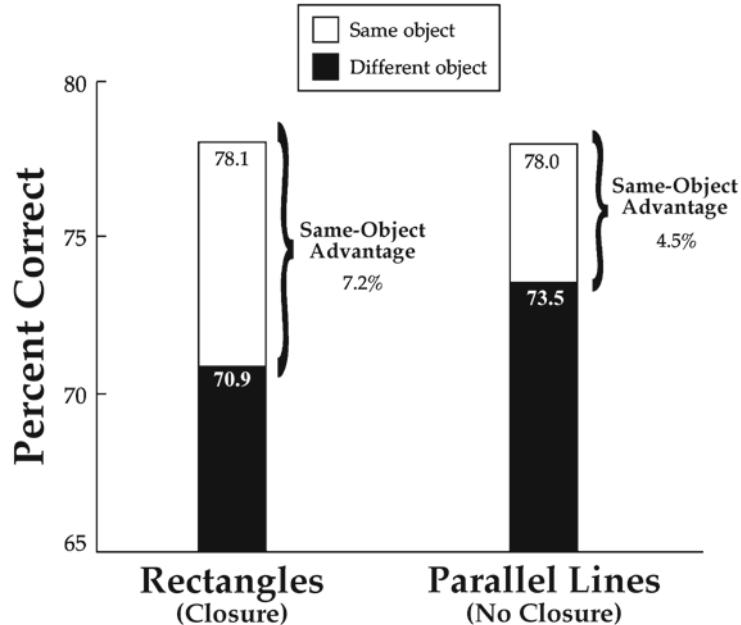


Figure 5. Subjects' accuracy in Experiment 2 (divided attention) at reporting whether or not the two probes in each trial were identical, broken down by display type.

disengage from one object and shift to another (cf. Baylis & Driver, 1993; Lamy & Egeth, 2002).

GENERAL DISCUSSION

Our results collectively fuel three conclusions. First, they confirm that object-based effects can be driven even without full-fledged objects in displays that already have grouping cues. In particular, same-object advantages in the two-rectangles display can be observed even when the ends of the rectangles are not drawn. This was confirmed using both spatial cuing (by measuring RT, in Experiment 1) and divided attention (by measuring accuracy, in Experiment 2). Second, Experiment 2 indicates that closure does contribute directly to object-based attention, confirming that line tracing cannot fully account for such effects. Using the divided-attention paradigm, we observed a significantly larger object-based effect with full rectangles than with groups of lines that lacked closure, when other cues were held constant. Third—and more tentatively, as discussed below—these results demonstrate one way in which divided attention may be a more sensitive measure than spatial cuing of the allocation of attention, at least when two especially common implementations of these measures are compared. Below, we briefly elaborate on the importance of these results.

The “Objects” of Attention

The earlier results of Avrahami (1999), who used displays such as those presented in Figure 1B, suggested a strong view in which allegedly “object”-based effects could be explained by simpler, lower level operations such as line tracing. (Line tracing is an especially relevant process for such stimuli, of course. Appeals to other simpler factors, such as symmetry, may apply in other experiments—cf. Behrmann, Zemel, & Mozer, 2000; Saiki, 2000). Our results do not support this strong view, since we observed a larger object-based effect with the closed rectangles. There is no obvious way in which the closure cue would strengthen line-tracing routines, which hypothetically operate only on the longer line segments in the rectangles. If anything, we might expect the additional orthogonal line segment to attenuate line-tracing effects. In any case, we designed our stimuli precisely to hold the most obvious line-tracing element constant while varying only the closure cue, which can still bind the line segments into bona fide objects.

Still, our results do not conflict in any way with those of Avrahami (1999) and actually support the spirit of the line-tracing view in a critical way, by demonstrating that full-fledged objects are not necessary for object-based effects. Thus, our results are also consistent with those of other recent studies that have demonstrated object-based effects with stimuli in which grouping (Marrara & Moore, 2003) or segmentation (Ben-Shahar et al., 2003, 2005) cues are employed but which lack a single closed contour—a hallmark of intuitively defined objects. Thus, it seems that the term *object-based attention* might be overly constrained.

Of course, at this point we could instead appeal to two separate processes: object-based attention and contour-based attention, for example. This type of rhetoric, however, quickly leads to a proliferation of types of attention: object-based attention, contour-based attention, group-based attention, part-based attention, and so forth. Without some reason to think that these effects are mediated by distinct processes, it seems more parsimonious to assume that all such effects reflect a single process (which we will call “*object*”-based attention), driven by multiple cues to objecthood on multiple hierarchical levels.

Spatial Cuing Versus Divided Attention: Tentative Methodological Conclusions

The paradigms employed in this study—spatial cuing (Experiment 1) and divided attention (Experiment 2)—are perhaps the two most popular methods used to study object-based attention. However, such methods have not often been contrasted when object-based effects have been explored in previous studies (though for related comparisons, see Cepeda & Kramer, 1999; Goldsmith & Yeari, 2003; Lamy & Egeth, 2002). Having done so here using the same stimuli, we suggest a tentative methodological conclusion: Divided attention (measuring accuracy) may in some cases be a more sensitive measure of subtle object-based effects. This was clear in the comparison between Experiments 1 and 2 in that the closure cue resulted in a reliably greater object-based effect only in the divided-attention study, despite the fact that this study involved fewer than half the number of subjects who participated in the spatial-cuing study. (We have also observed this difference in another recent study, in which both paradigms were used to explore how attention is constrained by static orientation-defined texture flows and by orientation-defined boundaries; see Ben-Shahar et al., 2003, 2005.) Accordingly, we urge other researchers to consider divided-attention measures when studying the role of subtle image cues in producing attentional objects. Use of such paradigms has the added advantage of making each individual trial informative, whereas in most spatial-cuing paradigms used in investigations of object-based effects, the vast majority of the collected data (viz. the valid-cue trials) must be thrown away. In any case, when spatial cuing is used, researchers should interpret null effects with caution.

At the same time, these methodological conclusions must remain tentative. In the first place, our two experiments, in addition to employing different classes of paradigms, also involved several specific task-related differences as well as different dependent measures (accuracy vs. RT). We chose this particular contrast largely because these methods are among the most popular versions of the paradigms used in the object-based attention literature. Thus, we cannot rule out the possibility that the observed differences in our study were due to the dependent measures or to some lower level task differences. Second, it is important to note that a comparison between these two paradigms is really one of “apples and oranges,” and we must acknowledge the possibility that other variants of these paradigms could prove more or less effective at

measuring object-based attention. Moreover, it remains possible that we could observe robust effects even with spatial cuing such as that used here if we were to run many more observers to increase statistical power. (For example, we did observe a fairly high false-alarm rate in Experiment 1; this is not uncommon, but the effects of such noise could be minimized by running many more observers.) Thus, although further focused research will be required to compare these two paradigms more directly, the contrast presented here can serve not as a statement about the relative power of these two paradigms in principle, but rather as a methodological heuristic for choosing between what are perhaps the two most popular methods as they have actually been used in the literature. At least as these paradigms are realized here, we observe stronger effects with divided attention while measuring accuracy, even though fewer observers are used.

Closure and Visual “Objecthood”

The effect of contour closure observed in this study is consistent with several other psychophysical results that have highlighted the importance of closure as a cue to the segmentation of visual scenes into discrete objects. To take four disparate examples: (1) Visual search studies have demonstrated that targets are detected more efficiently when they have a closed contour, even when the nature of the search target is defined along another dimension (Elder & Zucker, 1993, 1998); (2) figure-ground segregation with stimuli at near-threshold contrasts is improved with closed contours (Kovacs & Julesz, 1993); (3) subtler shape discriminations are possible with closed contours (Saarinen & Levi, 1999); and (4) even a small missing line segment which destroys closure can impair the perception of an image patch as a shadow (Rensink & Cavanagh, 2003). The contribution of the present study to this literature is the demonstration that contour closure can affect not only these lower level visual processes but also the flow of visual attention through scenes, supporting the view that closure is computed early and (in some sense) preattentively. Closed contours seem to result in a strengthening of object boundaries, which then either are less readily crossed by spreading attention or, more generally, make it more difficult to disengage from one object to shift to another. This has been suggested in other studies of attention in different contexts (e.g., in flanker experiments; Kramer & Jacobson, 1991), but this is the first direct demonstration of the importance of closure in divided-attention experiments and by the use of the popular two-rectangles stimuli.

More generally, the larger object-based effect observed here for closed contours supports the view that boundary closure is a feature that helps to define what it means to be an object—a view that has been popular in many areas of cognitive science, from studies of early vision (e.g., Spehar, 2002) to studies of higher level visual cognition (e.g., Koffka, 1935; vanMarle & Scholl, 2003) to those of infant cognition (e.g., Chiang & Wynn, 2000).

Conclusions

We conclude by endorsing the view that object-based attention is not an all-or-nothing phenomenon: Object-based effects can be independently strengthened or weakened by multiple cues to “objecthood.” More generally, these results are indicative of the complex interactions between attention and image structure: Object-based effects can be analyzed in terms of the lower level—and more carefully defined—image cues that collectively comprise visual objects. We explored one such cue—closure—and the present work can serve as a case study of how research on object-based attention can move beyond dichotomous arguments about whether attention is object based or location based, and can instead begin to determine how particular image cues influence the flow of visual attention.

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NOTES

1. We remain agnostic, however, as to whether the global grain of a display will always influence the spread of attention even in uniform patterns. Although Avrahami's (1999) results suggest such a process, another recent set of experiments consistently failed to find any such effect in static uniform texture flows having a perceptually salient grain. In these stimuli, attention flowed no more readily with the grain than against the grain (Ben-Shahar, Scholl, & Zucker, 2003, 2005). This null result was replicated in several ways and was not due to a lack of sensitivity, since the same experiments yielded object-based effects with other stimuli involving orientation-based texture segmentation.

2. We also analyzed the data broken down by the overall orientation of the rectangles. For both same-object and different-object trials, comparisons of horizontally aligned probes were faster than comparisons of vertically aligned probes. However, this global anisotropy acted independently of the same-object advantage: Both main effects were reliable, but their interaction was not. We have also observed this "horizontal advantage" in many other experiments involving both spatial-cuing and divided-attention paradigms (for discussion, see Ben-Shahar et al., 2003, 2005). In any case, because orientation was fully counterbalanced with our same/different object manipulation, it does not affect the comparisons of theoretical interest.

3. Further analyses indicated that these effects were driven more by trials in which the probes did not match (i.e., in those that had different numbers of line segments) than by trials in which the probes matched. This was true for same-object advantages with both rectangles [match, $t(19) = 0.7, p = .49$; no match, $t(19) = 3.35, p < .01$] and lines [match, $t(19) = 0.38, p = .70$; no match, $t(19) = 2.72, p = .01$]. This is the opposite pattern from that observed by Cepeda and Kramer (1999), but it is consistent with their explanation: It may be that in our displays the match trials pop out more easily due to grouping cues such as good continuation, which can be processed with relatively distributed attention and without object-based processing. (Cepeda & Kramer suggested that their match stimuli involved the more difficult comparison, yielding the opposite pattern.)

4. In contrast, Lamy and Egeth (2002) found no same-object advantage for rectangles when they used a same/different task to study grouped-array representations (wherein the probes were not parts of the objects). Their probes were thus likely parsed as new independent objects superimposed onto the rectangles and did not yield a same-object advantage. In contrast, our probes consisted of transformations in the "objects" themselves (using contours that already existed) and thus yielded a same-object advantage. In fact, Lamy and Egeth predicted that such results would be obtained with a same/different task and uniformly connected objects.