A region complexity effect masquerading as object-based attention

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A large portion of the evidence for object-based attention comes from experiments using the two-rectangle paradigm introduced by Egly, Driver, and Rafal (1994), in which response times are longer when the two stimulus locations relevant to the task are on separate objects. In the new experiments presented here, response times are longer when the two locations are part of the same object but are separated by a concavity in the object, so that the region directly between the two locations is crossed by the object's boundaries. Response times when the two locations are separated by the concavity are not statistically different from when they are on two separate objects. The results are similar for a two-letter comparison task and for a spatial cuing task. Thus, in these experiments, the response time increase does not reflect the cost of shifting attention from object to object, because it appears when the two locations are on the same object, and it is not increased when they are on different objects. Instead, it seems to reflect the complexity of the region between the two stimulus locations. This finding raises questions about whether data from previous two-rectangle experiments should be attributed to object-based attention.

Introduction

Identifying a stimulus at one location while attention is at a different location incurs a cost (Posner, 1980; Posner, Snyder, Davidson, 1980), and the cost is larger when the two locations are in different objects than when they are within the same object (see Chen, 2012, for a review). These two effects of attention were demonstrated elegantly in Egly, Driver, & Rafal (1994), who showed participants displays that consisted of two parallel rectangles, followed by a cue and then a target square. The critical manipulation was the location of the square relative to the cue. They were at the same location in the valid condition, at different locations within the same rectangle in the invalid same-object condition, or at different locations in different rectangles in the invalid different-object condition. Importantly, the spatial separation between the cue and the square was the same in the latter two conditions. The results show that responses were faster in the valid condition than in the two invalid conditions and in the invalid same-object condition compared with the invalid different-object condition. These findings were taken to indicate that attention operates via the internal representation of both space and object.

Since Egly et al. (1994), there have been a large number of studies investigating object-based attention (OBA). As in Egly et al. (1994), most of these studies use a spatial cuing paradigm in which the onset of the target is preceded by an informative spatial cue. In a minority of studies, no spatial cue is used, and the task involves comparing two target stimuli such as numbers, letters, or geometric shapes. Interestingly, whereas a same-object advantage is frequently reported in the studies that use spatial cuing tasks, it is less often observed in two-target comparison tasks (e.g., Al-Janabi & Greenberg, 2016; Chen & Cave, 2019; Davis, Driver, Pavani, & Shepherd, 2000; Davis & Holmes, 2005; Davis, Welch, Holmes, & Shepherd, 2001; Harrison & Feldman, 2009; Kramer & Watson, 1996; Lamy & Egeth, 2002). In some cases, although a same-object advantage is found when the objects are horizontally oriented, a same-object cost or no object effect is observed when the objects are vertically

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oriented (Al-Janabi & Greenberg, 2016; Chen & Cave, 2019; Harrison & Feldman, 2009).

Recently, Chen and Cave (2019) pointed out that the asymmetry observed in feature-comparison tasks could be the result of a confounding factor between the locations of the targets (in the same object or in different objects) and the orientation of the target configuration (horizontal or vertical). Imagine a two-letter comparison task. Two target letters are displayed within a pair of horizontal or vertical rectangles (see Figure 1 of Chen & Cave, 2019), and the locations of the two letters are aligned either horizontally or vertically relative to one another. When the rectangles are horizontal, two letters that are horizontally aligned will both be within the same rectangle (the same-object condition), but vertically aligned letters will be in different rectangles (the different-object condition). In contrast, when the rectangles are vertical, the letters that are vertically aligned will be within the same rectangle, but horizontally aligned letters will be in different rectangles. Because responses are known to be faster when the targets are aligned horizontally rather than vertically (Corballis & Roldan, 1975; Corbett & Carrasco, 2011; Pashler, 1990; Sereno & Kosslyn, 1991; Wagemans, 1997), the same-object advantage in the horizontal object condition could reflect a horizontal benefit instead of object-based guidance of attention. Chen & Cave (2019) demonstrated this in a series of experiments that required participants to judge whether two target letters, which were either in the same rectangle or in two different rectangles, were the same. In one experiment, they arranged the data in two different ways: first by the orientation of the rectangles, and then by the orientation of the letter configuration. When the data were organized by the orientation of the rectangles, there was a reliable same-object advantage on the horizontal rectangle trials but a same-object cost on the vertical rectangle trials. Importantly, when the data were organized by the orientation of letter configuration, no object effect was found. Subsequent experiments by Chen and Cave showed better performance in the same-object trials in certain conditions, including trials in which the orientation of the rectangles correctly predicted that the letters would be oriented vertically. However, this was unlikely to be a genuine same-object advantage, because the same pattern of data emerged when there were no rectangles in the display and the onset of the letters was instead predicted by a salient orientation cue (see Figure 6 of Chen & Cave, 2019).

What might cause the differences in results between the studies that use a spatial cuing paradigm and those that involve comparing features such as shapes and sizes without a cue? One obvious difference is the requirement to switch attention in the former but not in the latter. Lamy and Egeth (2002) investigated the role of attentional shift in object-based attention using a size comparison task. They found no object effects when two target squares were presented simultaneously. However, when the squares were presented sequentially with a stimulus-onset-asynchrony (SOA) of 100 ms or 200 ms, significant object effects emerged. An object effect was also found when the task was to detect a single square preceded by an informative spatial cue. These results led the researchers to propose that the need to shift attention plays a critical role in the manifestation of object effects. A related view was expressed by Brown and Denney (2007), who investigated the cost in shifting attention under a variety of conditions and found the cost to be especially large when attention had to move from a location on an object to a background location outside an object. Based on this and similar findings, Brown and Denney (2007) propose that the object effect is caused primarily by the additional cost involved in disengaging attention from an object in the different-object condition when a task requires attentional shift.

A different factor that might be relevant here was suggested by Davis and Holmes (2005). They pointed out that in many studies on object-based attention, there are fewer luminance edges between the task relevant stimuli in the same-object condition than in the different-object condition. The extra luminance edges could disrupt the spread of attention, resulting in longer response latencies in the different-object condition.

A third factor, region complexity, is related to the first, but more general. In a typical spatial cuing experiment, the region between the cue and the target is uniform in the same-object condition; there are no object boundaries or other stimuli obstructing attentional spread within the space between the task relevant stimuli. However, in the different-object condition, the region between cue and target has a more complex organization; it includes space occupied by two different objects, a background area not occupied by any object, and the boundaries between these areas. If the attentional allocation is affected by the complexity of the region between cue and target, response latencies would be longer when the region is more complex rather than less complex. If this is the case, the same-object advantage reported in many spatial cuing experiments could reflect this region complexity effect.

The experiments described below are designed to test the effects of the latter two factors: the presence of luminance edges and the region complexity between the relevant locations. In these experiments, the two relevant stimuli will always be presented successively, so that the opportunity for shift attention during the trial will be generally consistent across conditions, and thus should not be a factor in explaining differences across conditions. In the experiments reported here, we explore whether attending to two locations separated by a nonuniform region incurs an additional cost compared

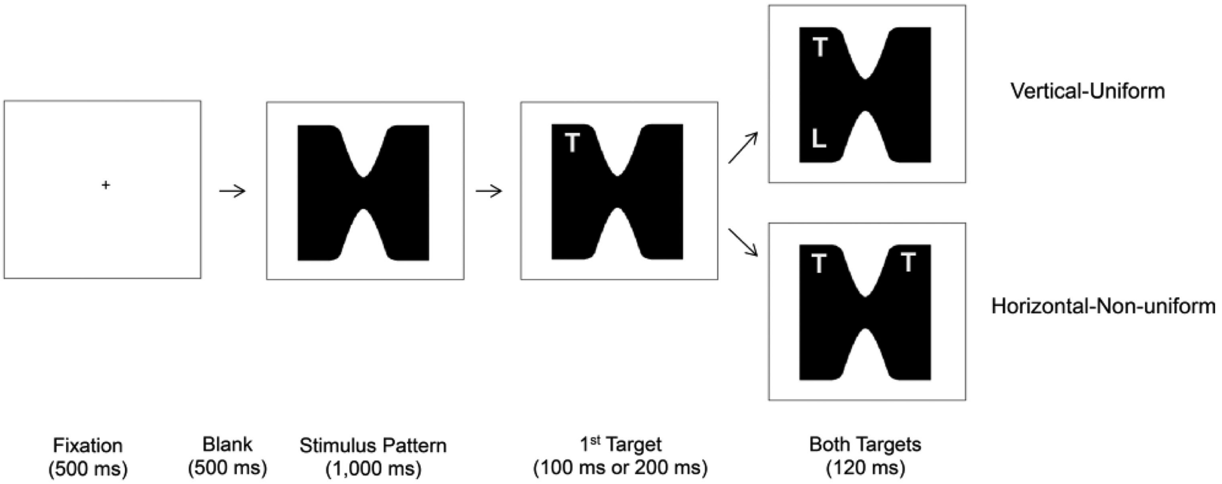

Figure 1. Examples of trials from Experiment 1. On each trial, participants saw a concave-shaped stimulus pattern followed by two sequentially presented target letters that were configured either horizontally or vertically. The region between the targets was homogenous in the uniform condition, and nonhomogenous in the nonuniform condition. The task was to judge whether the letters were the same.

with a uniform region, and whether the difference in cost, if found, could explain, at least to some degree, the object effects reported in previous studies. To manipulate region complexity within the same object, we used stimuli modified from those used by Davis and colleagues (Davis et al., 2000; Davis et al., 2001; Davis & Holmes, 2005). In one of their experiments (Experiment 2 in Davis et al., 2000), which was designed to assess whether the object effect found in previous research could be caused by a difference in the surface area associated with the attended stimuli between the same and different object conditions, they showed participants two concave-shaped stimulus patterns, one consisting of a large object (the large condition) and the other two small objects (the small condition). The task was to judge whether two simultaneously presented “notches” in the shape boundary were the same. The target notches, which were aligned horizontally or vertically, were always in the same object in the large condition. In the small condition, they were equally likely to be in the same object (with horizontal target configuration) or in two different objects (with vertical target configuration). The results showed a same-object advantage in the small condition but no difference between the horizontal and vertical trials in the large condition.

In the present study, we manipulated the region complexity in a task in which the task relevant stimuli were presented sequentially. The use of sequential presentation was to ensure that differences in performance, if found, could not be explained in terms of attentional shift because this was held constant across the experimental conditions. Our study was not designed to distinguish between the luminance edge account and the region complexity account.

In Experiment 1, we investigated the cost of attending to locations separated by a uniform versus a nonuniform region when the two locations were within the same object. In Experiment 2, we compared the cost of attending across two objects with the cost of attending across a nonuniform region within the same object. To forecast our results, we found faster responses when the attended locations were separated by a uniform region rather than a nonuniform region, but no difference in performance between attended locations separated by a nonuniform region and attended locations across different objects.

Experiment 1

Experiment 1 examines the cost in attentional movement across a uniform versus a nonuniform region. Participants saw two sequentially presented target letters at two locations in a concave-shaped object (see Figure 1), and the task was to judge whether the letters were the same. The region between the targets was either homogenous (the uniform condition) or nonhomogenous (the nonuniform condition). In the nonuniform condition, the path between the targets crossed areas that differed in luminance and in the presence of foreground versus background regions. If the complexity of the region influences the efficiency of attentional movement, RT would be longer in the nonuniform condition compared with the uniform condition.

In addition to region complexity, we also varied the SOA between the targets. Previous research has found significant object effects when the SOA between two sequentially presented targets was 100 ms or 200 ms, and the magnitude of the object effect was comparable between these two SOA conditions (Lamy & Egeth, 2002). We used the same SOAs. The goal was to determine whether a similar pattern of data would be found in the present experiment when attentional allocation was across a uniform versus a nonuniform region within the same object.

Method

Participants

Twenty-four participants (mean age = 20.8, SD = 3.5; three males) from the University of Canterbury participated in the study in exchange for course credit. This sample size was based on the number of participants in Davis et al. (2000), Davis et al. (2001), and Davis and Holmes (2005), which varied from eight to 18 across nine different experiments. These studies were chosen because the stimulus patterns in the present study were modeled after the ones in their studies.[1] All of the participants in the present study had normal, or corrected-to-normal-vision.

Apparatus and stimuli

All stimuli were presented against a white background on monitors that had a screen resolution of 1680 × 1050 with a refresh rate of 60 Hz. E-prime 2.0 (Psychology Software Tools, Pittsburgh, PA, USA) was used to present the stimuli and record responses. Participants were tested individually in two dimly lit rooms. They sat at a viewing distance of approximately 60 cm from the monitor.

Each trial began with a fixation, followed by a concave-shaped stimulus, and then two sequentially presented target letters (see Figure 1). The fixation was a centrally located black cross that subtended 0.3°. The stimulus pattern, which had two mirror-imaged concavities, was also centrally located, and the overall shape subtended 11.2° in width and height. Each concavity had a depth of 4.3°, and, at its widest part, a width of 4.8°. This pattern could appear either as shown in Figure 1, with the concavities coming into the object from above and below, or it could appear rotated 90° from this orientation, with the concavities coming in from left and right. The targets consisted of two letters in dark gray (RGB: 50, 50, 50). They were equally likely to be two Ts, two Ls, or one T and one L. Each letter was 0.9° in height and width and was presented at one of the four corners of the concave object. The letters were aligned either horizontally or vertically relative to one another. Regardless of their configuration, the center-to-center distance between the letters was always 8.1°.

Design and procedure

The experiment used a 2 × 2 × 2 repeated-subjects design. The principal manipulations were the SOA between the targets (100 ms vs. 200 ms), the configuration of the targets (horizontal vs. vertical), and the region between the targets (uniform vs. nonuniform). The three factors were independent, and all types of trials were randomly intermixed within a block.

Each trial started with the fixation for 500 ms, followed by a blank screen of 500 ms, and then a concave object oriented horizontally or vertically. After 1000 ms, the first target, which was a T or an L, would appear at one of the four corners of the object. The letter stayed on the screen for 100 ms or 200 ms before it was joined by the second target, which was also a T or an L. The letters were shown together for 120 ms before the display was replaced by a blank screen. The trial ended on response. The intertrial interval was 500 ms.

The participants' task was to judge whether the letters were the same or different. Two keys on the number pad were labelled, with the "4" key labeled "Same" for the same response and the "5" key labeled "Diff" for the different response. The participants were instructed to use their right hand to respond, with the forefinger to press the "Same" key and the middle finger to press the "Diff" key. They were also instructed to keep their eyes fixed at the fixation throughout the duration of a trial. Eye movements were not monitored during the experiment. Both speed and accuracy were emphasized, although the primary dependent measure was response time.

The experiments consisted of 24 practice trials followed by 640 experimental trials divided into four blocks. The participants were encouraged to take a short break after each block.

Results and discussion

RTs for each participant that were more than two standard deviations on either side of the mean were excluded.[2] The mean RT results are shown in Figure 2, and the error rates are shown in Table 1. In all the figures in this article, the error bars show the within-subjects standard error of the mean (Cousineau, 2005). We first examined the error rates. A 2 × 2 × 2 repeated-measures analysis of variance (ANOVA) was conducted. The only significant effect was target configuration (F [1, 23] $= 4.81$, $MSe = 7.1$, $p = 0.04$, $\eta_p^2 = 0.17$), indicating a lower error rate when the targets were configured horizontally (4.4% error) rather than vertically (5.2% error).

A similar 2 × 2 × 2 ANOVA was then performed on mean RTs. All the three main effects were significant (F [1, 23] $= 30.01$, $MSe = 239$, $p < 0.001$, $\eta_p^2 = 0.57$) for

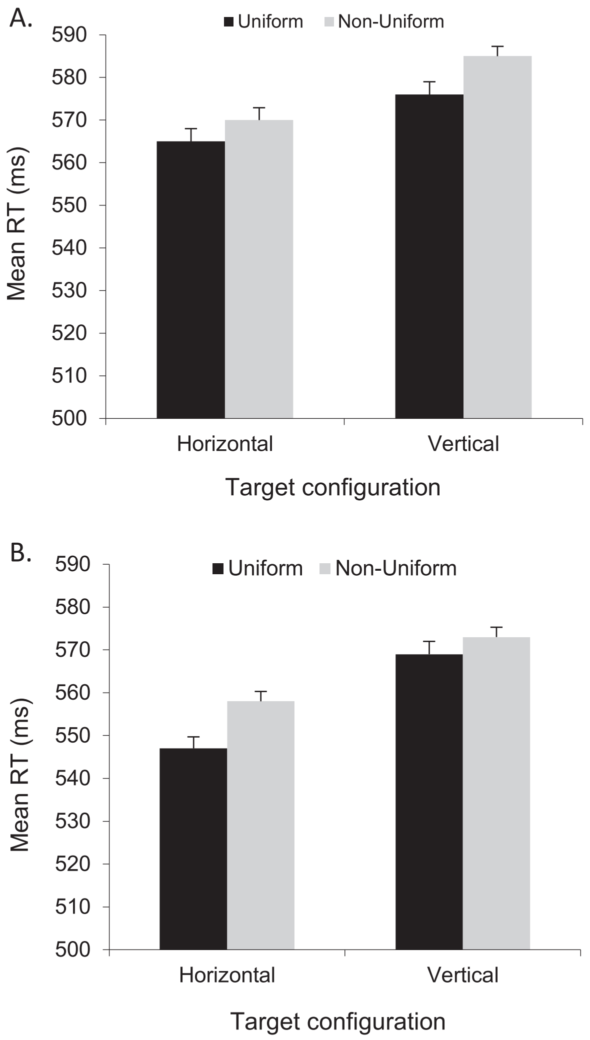

Figure 2. Results from Experiment 1. (A) The stimulus onset asynchrony (SOA) 100 ms condition. (B) The SOA 200 ms condition.

	Orientation of target configuration			
	Horizontal		Vertical	
SOA	Uniform	Nonuniform	Uniform	Nonuniform
100 ms	4.0 (0.5)	4.7 (0.5)	5.6 (0.5)	5.3 (0.4)
200 ms	3.7 (0.4)	5.0 (0.5)	4.9 (0.6)	5.1 (0.5)

Table 1. Mean error rates (percent incorrect) as a function of stimulus onset asynchrony (SOA), target configuration orientation, and the type of region between the targets, with within-subject standard errors of the mean in the parentheses for Experiment 1.

SOA; $F\,[1, 23] = 36.13$, $MSe = 326$, $p < 0.001$, $\eta_p^2 = 0.61$) for target configuration and ($F\,[1, 23] = 17.11$, $MSe = 156$, $p < 0.001$, $\eta_p^2 = 0.43$) for region. These results indicate faster responses when the SOA was 200 ms (562 ms) rather than 100 ms (574 ms), when the target configuration was horizontal (560 ms) rather than vertical (576 ms), and importantly, when the region between the targets was uniform (564 ms) compared with nonuniform (572 ms). No two-way or three-way interactions were found. There was no indication of speed-accuracy tradeoffs.

The most important finding of the experiment was the region complexity effect. Responses were faster in the uniform condition than in the nonuniform condition even though the targets were in the same object in both conditions. Although the magnitude of the difference was quite small (8 ms), this is not unusual, because similar or smaller differences have been reported in prior research (Chen, 1998; Donovan, Pratt, & Shomstein, 2017; Lamy & Egeth, 2002). In the present study, a large majority of the participants (20/24) showed longer RTs in the nonuniform than the uniform condition, the direction predicted by the region complexity effect. This result shows that allocating attention across a nonuniform region incurs an additional cost compared with allocating attention across a uniform region. In a typical cuing experiment on OBA, the region between the attentional beginning and end points is nonuniform in the different-object condition and uniform in the same-object condition. The finding in the present experiment raises the possibility that the region complexity effect could contribute to the object effects reported in prior research.

Consistent with previous studies (Chen & Cave, 2019; Chen, Humphries, & Cave, 2019; Corbett & Carrasco, 2011; Harrison & Feldman, 2009; Hein, Blaschke, & Rolke, 2017), Experiment 1 found a horizontal benefit, and the effect did not interact with either SOA or the type of region between the targets. The horizontal benefit is also in line with previous research on crowding. Greenwood, Szinte, Sayim, and Cavanagh (2017) showed that a peripheral target had a larger interference effect from flanking distractors when the stimulus array was on the vertical meridian compared with the horizontal meridian. The results in the present study augments the evidence from our previous research (Chen & Cave, 2019; Chen et al., 2019), in which we found a strong horizontal target benefit that did not interact with other factors.

Not surprisingly, RT was slower when the SOA was 100 ms rather than 200 ms. This result was to be expected, because participants had less time to process the first target before the appearance of the second target when the SOA was shorter. SOA did not interact with the region complexity effect, indicating that at this range (i.e., an SOA between 100 ms and 200 ms) the targets were processed sequentially. It is possible that a shorter SOA (e.g., 50 ms) could eliminate the region complexity effect, because the near-simultaneous onsets

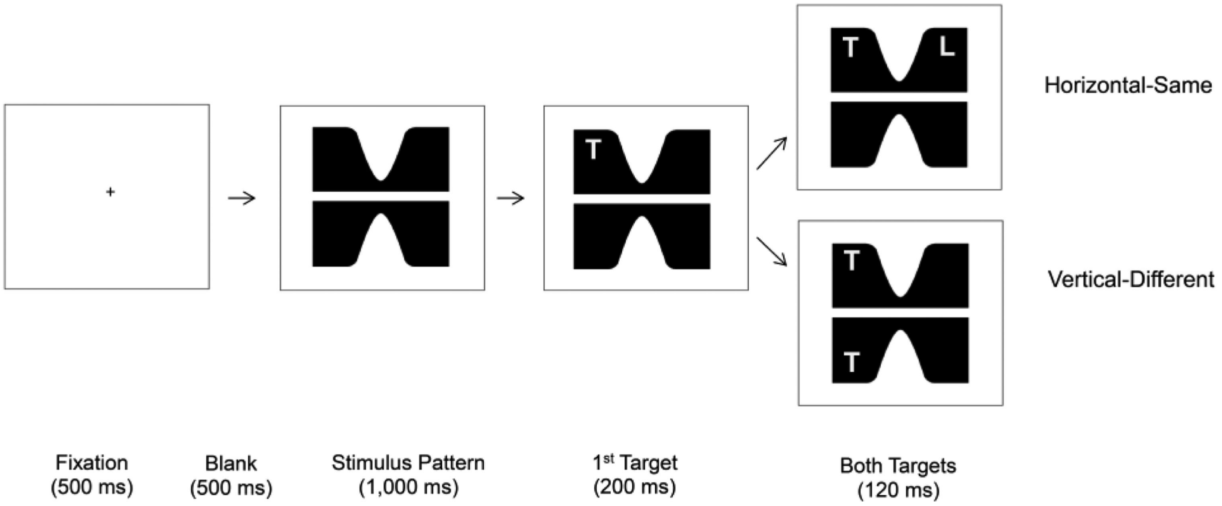

Figure 3. Examples of the 2Small trials in the comparison task from Experiment 2. The targets are equally likely to be in the same object or in different objects. In the same-object condition, the region between the targets was always nonuniform.

of the targets would induce concurrent processing of the targets.[3] It is worth noting that in tasks with two sequentially presented targets, the same-object advantage was typically found when the SOA was 100 ms or 200 ms (e.g., Lamy & Egeth, 2002), but not when it was shorter or when the targets were shown simultaneously (e.g., Chen & Cave, 2019).

Experiment 2

In Experiment 1, participants were faster at comparing letters when the region between the targets was uniform rather than nonuniform. In Experiment 2, we used two different tasks: a letter comparison task like that in Experiment 1 and a new letter identification task. In the latter task, participants saw an informative spatial cue followed by a target letter, and the task was to determine whether the target was a T or an L. The addition of the second task allowed us to test the generality of our results.

Experiment 2 also used two types of stimulus pattern. In the 1Large trials, there was a single large concave-shaped object identical to that used in Experiment 1. In the 2Small trials, the single large objects were split into two small concave-shaped objects by introducing a separation across the middle (See Figure 3). In the 1Large trials, the task relevant stimuli (i.e., the two targets in the letter comparison task, or the cue and the target in the letter identification task) were always within the same object, because there was only a single object in the display. In the 2Small trials, these stimuli were either in the same object (the 2Small-same condition) or in two different objects (the 2Small-different condition). Importantly, in both of the 2Small conditions, the region between the two stimuli was nonuniform in that it included two region boundaries. The stimuli were separated by the concavity in the 2Small-same condition and were separated by the background region between the two objects in the 2Small-different condition. If performance did not differ between these conditions, this would suggest that the object effects seen in some earlier studies can be attributed to the region complexity effect and not to attention allocated to a specific object.

Method

Participants

Forty-eight new participants (mean age = 20.4, *SD* = 3.8; 10 males) from the University of Canterbury participated in the study in exchange for course credit. All had normal or corrected-to-normal-vision. Half the participants completed the letter comparison task, and the other half the letter identification task.

Apparatus and stimuli

They were the same as those in Experiment 1 except for the following differences. Experiment 2 consisted of two types of experimental trials and one type of filler trials. The experimental trials were divided equally into 1Large and 2Small trials. In the 1Large trials, the stimulus pattern was identical to that in Experiment 1. In the 2Small trials (see Figure 3), the stimulus pattern consisted of two smaller objects, each with a single concavity identical to that in one side of the 1Large object. The two objects were mirror images of each other, either vertically or horizontally (see Figure 3 for a vertical mirror image example). The two objects had a gap of 0.76° between them. Each object measured 11.2° in width and 5.22° in height. The overall size of the stimulus pattern in the 2Small trials was the same as the size of the stimulus pattern in the 1Large trials.

In the filler trials, the stimulus pattern consisted of a single small concave-shaped object. It was identical to one of the small objects (equally likely to be the left, right, upper, or the lower one), and its location on the screen was also identical to that of the corresponding object in the 2Small trials. The purpose of the filler trials was to induce the objects in the 2Small trials to be perceived as two separate objects rather than one large object with a white stripe running through it (Chen & Cave, 2006).

In the letter comparison task, all aspects of the targets in the experimental trials (i.e., size, color, location) were the same as those in Experiment 1. In the filler trials, the two targets always appeared within the same small object, and the configuration of the targets, which was always the same as the orientation of the object, was equally likely to be horizontal or vertical.

In the letter identification task, instead of two sequentially presented targets, participants saw a cue followed by a target. The cue was a red outline rectangle measuring 1.4° in width and 1.3° in height, and the thickness of the outline was 0.1°. The location of the cue was the same as the location of the first target in the letter comparison task. The target, which was equally likely to be a T or an L, could be at the cued location or at a different location from the cue. In the latter case, its location was the same as that of the second target in the letter comparison task. The participant's response indicated whether the target was T or L; the cue was not relevant to the response.

Design and procedure

The experiment used a 2 × 2 × 2 × 2 mixed design. The first three factors are task (comparison vs identification), stimulus pattern (1Large vs. 2Small), and target configuration (horizontal vs. vertical). The fourth factor is type of separation, which refers to the region between the two task relevant stimuli. Both 1Large and 2Small trials have one condition with relatively lower separation and another condition with relatively higher separation, but the nature of the separation is fundamentally different between 1Large and 2Small trials. In the 1Large trials, the type of separation can be either uniform (lower separation) or nonuniform (higher separation), as in Experiment 1. In the nonuniform condition, the two relevant stimuli are separated by the concavity, but they are still within the same object. Thus, in the 1Large trials, the two types of separation differ in region complexity but not in number of objects. In the 2Small trials, the two types of separation are same object (lower separation) and different objects (higher-separation). In the same-object condition, the two locations are separated by the concavity, but are both part of the same object, while in the different-object condition, they are separated by the background region between the two objects. Thus, in the 2Small trials, the two types of separation differ in the number of objects, but not in region complexity. Task was a between-subjects factor. The other three variables were within-subjects factors manipulated independently, and all types of trials were presented randomly within a block.

The letter comparison task consisted of 512 experimental trials and 128 filler ones. For the experimental trials, there were as many 1Large trials as 2Small ones, and the configuration of the targets was equally likely to be horizontal or vertical. In the 1Large trials, the region between the targets was uniform in half of the trials and nonuniform in the rest of them. In the 2Small-object trials, the region between the targets was always nonuniform, but the targets were equally likely to be within the same object or between different objects. In the filler trials, the targets were always in the same object. In all the letter comparison trials, the SOA between the two targets was 200 ms. All the other aspects of the procedure were the same as those in Experiment 1.

The letter identification task consisted of 512 experimental trials and 96 filler ones. In the experimental trials, the target was at the cued location on half the trials (the 2Small-valid condition). On the rest of the trials, it was equally likely to be at a different location within the same object (the 2Small-same condition) or in a different object (the two-small different locations). In the latter two conditions, the spatial distance between the cue and the target was identical. In the filler trials, the target was at the cued location on two-thirds of the trials and at the other end of the object on the remaining trials. The procedure of the trial in the identification task was the same as that in the comparison task except that the cue was shown for 100 ms, and the target appeared 100 ms after the offset of the cue.

Results and discussion

The data were treated in the same way as in Experiment 1. Three participants' data were excluded from analyses due to high error rates. The mean RTs and error rates are in Tables 2A and 2B.

We again examined the error rates first. A 2 × 2 × 2 × 2 mixed ANOVA with task (discrimination vs. identification) as a between-subjects factor, stimulus pattern (1Large vs. 2Small), target configuration (horizontal vs. vertical), and separation type (lower vs. higher separation) as within-subjects factors. In the last

	Horizontal		Vertical		
Task	Uniform	Nonuniform	Uniform	Nonuniform	Valid
Reaction Times					
Comparison	556 (3.5)	568 (3.3)	567 (2.4)	580 (3.2)	
Identification	546 (4.4)	556 (3.0)	558 (3.8)	573 (4.8)	505 (5.3)
Error Rates					
Comparison	4.6 (0.6)	6.6 (0.7)	7.4 (0.6)	7.2 (0.6)	
Identification	4.0 (0.8)	4.4 (0.8)	4.9 (0.9)	5.3 (0.9)	2.9 (0.5)

Table 2A. Mean reaction times (in milliseconds) and error rates (percentage incorrect) as a function of task, the configuration of the task relevant stimuli, and region complexity, with within-subject standard errors of the mean in the parentheses in the 1Large trials in Experiment 2.

	Horizontal		Vertical		
Task	Same object	Different object	Same object	Different object	Valid
Reaction Times					
Comparison	561 (2.2)	558 (3.1)	574 (3.5)	568 (2.8)	
Identification	554 (4.7)	558 (5.4)	572 (4.7)	568 (3.4)	506 (5.2)
Error Rates					
Comparison	5.9 (0.5)	6.3 (0.4)	7.9 (0.6)	7.9 (0.5)	
Identification	3.8 (0.6)	3.5 (0.7)	6.0 (1.0)	3.8 (0.7)	3.2 (0.5)

Table 2B. Mean reaction times (in milliseconds) and error rates (percentage incorrect) as a function of task, the configuration of the task relevant stimuli, and object, with within-subject standard errors of the mean in the parentheses in the 2Small trials in Experiment 2. *Note:* The region between the task relevant stimuli in the same object condition was nonuniform.

factor, for the sake of statistical analyses, the uniform (lower-separation) and nonuniform (higher-separation) conditions in the 1Large trials were considered as being equivalent to the same-object (lower-separation) and different-object (higher-separation) conditions in the 2Small trials, respectively.

The ANOVA on the error rates showed only one significant effect: the main effect of letter configuration (F[1, 43] = 9.92, $MSe = 18$, $p = 0.003$, $\eta_p^2 = 0.19$), indicating a horizontal benefit. Participants made fewer errors when the task relevant stimuli were aligned horizontally (4.9% error) rather than vertically (6.3% error). The main effect of task approached significance [F[1, 43] = 3.66, $MSe = 123$, $p = 0.06$, $\eta_p^2 = 0.08$). This suggests that the participants in the identification task made fewer errors (4.5% error) compared with their counterparts in the comparison task (6.7% error). No other results were reliable.

Next, we conducted a similar ANOVA on the mean RTs. There was again a reliable horizontal benefit (F[1, 43] = 53.59, $MSe = 276$, $p < 0.001$, $\eta_p^2 = 0.55$) and an effect of separation type (F[1, 43] = 5.87, $MSe = 431$, $p = 0.02$, $\eta_p^2 = 0.12$). Participants were faster in the horizontal condition (557 ms) than the vertical condition (570 ms), and in the uniform/same-object condition (561 ms) than in the nonuniform/different-object condition (566 ms). Stimulus pattern interacted with task (F[1, 43] = 5.38, $MSe = 211$, $p = 0.03$, $\eta_p^2 = 0.11$). In the letter identification task, responses were numerally faster in the 1Large trials (558 ms) compared with the 2Small trials (563 ms). In contrast, in the letter comparison task, responses were slightly slower in the 1Large trials (568 ms) than the 2Small trials (565 ms). Subsequent analyses using Tukey's honest significant difference (HSD) tests showed no significant difference between the 1Large and 2Small trials in either the letter identification task ($p = 0.18$) or the letter comparison task ($p = 0.64$). In addition to task, stimulus pattern also interacted with separation type (F[1, 43] = 11.25, $MSe = 442$, $p = 0.002$, $\eta_p^2 = 0.21$). Importantly, whereas response latencies increased significantly from the uniform condition (557 ms) to the nonuniform condition (570 ms) in the 1Large trials ($p = 0.001$), replicating the findings in Experiment 1, no difference was found between the same-object condition (565 ms) and the different-object condition (563 ms) in the 2Small trials ($p = 0.90$). It is important to note that in the same object condition in the 2Small trials, the region between

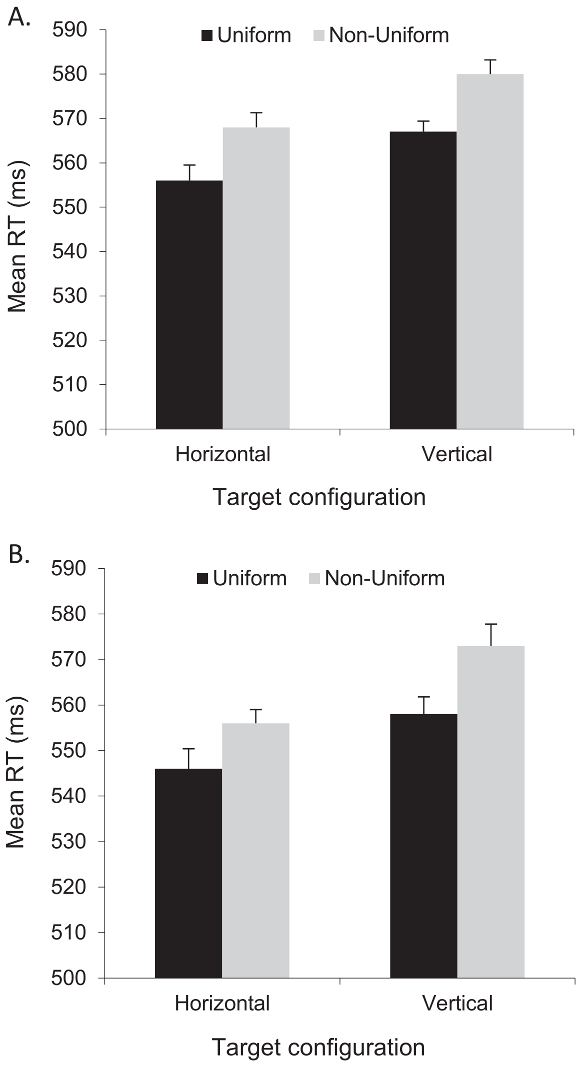

Figure 4. Region complexity effects in the 1Large trials in Experiment 2. (A) The letter comparison task. (B) The letter identification task.

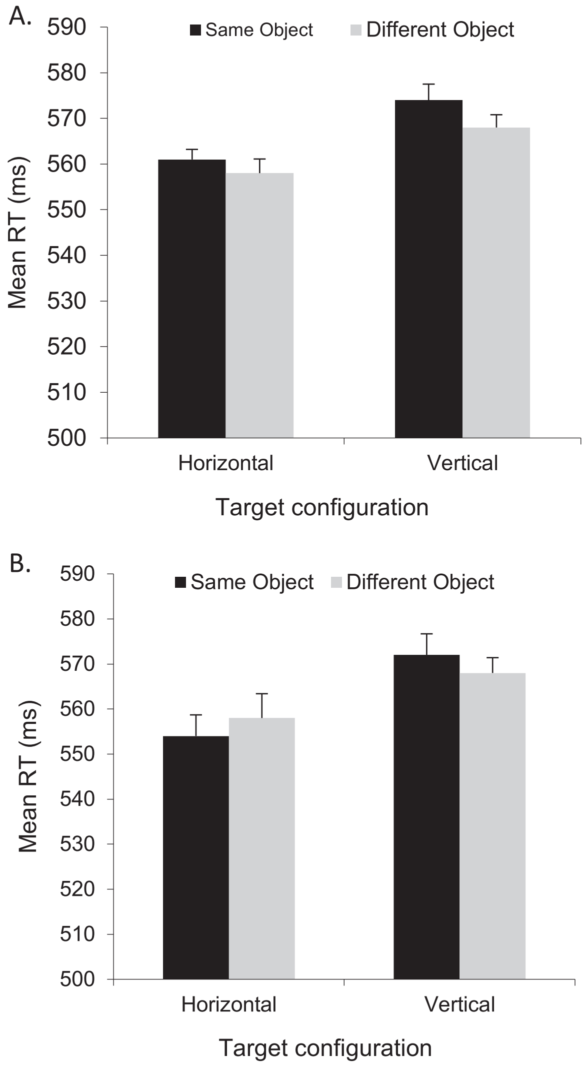

Figure 5. Object effects in the 2Small trials in Experiment 2. Note that in the same object condition, the region between the task relevant stimuli was nonuniform. Thus the absence of object effects indicates no additional cost in allocating attention between different objects compared with allocating attention across a nonuniform region within the same object. (A) The letter comparison task. (B) The letter identification task.

the task relevant stimuli was nonuniform, because they were separated by the concavity. Thus the absence of the object effect indicates that allocating attention across different objects does not impair performance any more than allocating attention across two locations on the same object separated by a nonuniform region. These results are shown in Figures 4A to 5B, with the data from the comparison and identification tasks and from the horizontal and vertical configuration trials presented separately. No other effects were found.

In a typical experiment on OBA, the region between the task relevant locations in the same object condition is homogenous, and a same object benefit is usually found. To examine whether the same pattern of data occurred in the present experiment, we performed additional analyses including only trials in which the two relevant locations were not separated by a curved concavity. Specifically, responses in the 1Large uniform conditions (equivalent to the same-object condition in a typical OBA experiment) were compared with the responses in the 2Small-different object conditions (equivalent to the different-object condition in a typical OBA experiment). Thus, in the 1Large condition, the region between the two objects was homogenous, and in the 2Small condition, the locations were separated by object boundaries and the background region between the objects. Because the surface area associated with the task relevant stimuli was held constant between the 1Large and 2Small conditions, any same object advantage could not be attributed to a difference in surface area between the same and different object conditions (Davis et al., 2000; Davis et al., 2001).

Two 2 × 2 × 2 mixed ANOVAs, with task as a between-subjects factor and target configuration and object (i.e., 1Large uniform condition vs. 2Small-different object condition) as within-subjects factors, were performed on the RT and accuracy data. The results in the RTs showed a horizontal benefit ($F[1, 43] = 15.55$, $MSe = 348$, $p < 0.001$, $\eta_p^2 = 0.27$) and an object effect ($F[1, 43] = 5.57$, $MSe = 322$, $p = 0.02$, $\eta_p^2 = 0.11$). Responses were faster when the target configuration was horizontal (554 ms) rather than vertical (565 ms). Furthermore, responses were also faster when the task relevant stimuli were in the same object (557 ms) rather than in different objects (563 ms). Although the latter result is usually taken as evidence for object-based guidance of attention, the results from Experiment 2 show that it could instead be a region complexity effect, because the same and different object conditions differed in both the number of objects and the region complexity between the task relevant stimuli. No other effects were found in the RT data.

The results in error rates showed a reliable effect of task ($F[1, 43] = 4.44$, $MSe = 63$, $p = 0.04$, $\eta_p^2 = 0.09$) and a significant horizontal benefit ($F[1, 43] = 4.93$, $MSe = 18$, $p = 0.03$, $\eta_p^2 = 0.10$). Responses were more accurate in the identification task (4.1% error) compared with the comparison task (6.5% error), and when the relevant stimuli were horizontal (4.6% error) rather than vertical (6.0% error). In addition, task interacted with object ($F[1, 43] = 5.19$, $MSe = 8$, $p = 0.03$, $\eta_p^2 = 0.11$). When the task was letter comparison, accuracy was slightly higher in the same object condition (6.0% error rate) than in the different object condition (7.1% error rate). When the task was letter identification, accuracy was slightly lower in the same object condition (4.5% error) than in the different object condition (3.6% error). However, these differences were not reliable, because Tukey's HSD tests showed no significant effect on object in either the letter comparison task ($p = 0.27$) or the letter identification task ($p = 0.51$). We do not see much evidence in these results for any differences in the spread of attention between the two tasks.

In summary, when we pull out the two conditions that correspond to conditions in standard object-based attention experiments, we find faster responses for the same-object condition than the different-object condition. The analyses described above with the additional conditions show that this difference may be due to region complexity rather than attention to a specific object.

Finally, we checked whether the spatial cue in the identification task was effective in directing spatial attention to the cued location. For both the 1Large and 2Small trials, we combined the data across the invalid conditions and compared it with the data in the valid condition, and performed two sets of t tests. For the 1Large trials, the spatial cuing effect was significant in both the RT and accuracy data ($t[22] = 8.55$, $p < 0.001$, $d = 1.82$ and $t(22) = 2.96$, $p = 0.01$, $d = 0.63$, respectively), indicating faster and more-accurate responses when the cue was valid (505 ms with 2.9% error) rather than invalid (558 ms with 4.7% error). For the 2Small trials, the spatial cuing effect was significant in the RT data ($t[22] = 8.63$, $p < 0.001$, $d = 1.84$) but not in the accuracy data ($t[22] = 1.58$, $p = 0.13$, $d = 0.34$), indicating faster responses on the valid trials (506 ms with 3.2% error) compared with the invalid trials (563 ms with 4.3% error). These results suggest that the cue was effective in directing attention to the cued location regardless of whether the display consisted of 1 object or 2 objects.

To summarize the results of Experiment 2, the region between the task relevant stimuli was uniform in a subset of the 1Large trials, and an object effect was found when responses from these trials were compared with those from the different object condition in the 2Small trials. In contrast, the region between the task relevant stimuli was always nonuniform in the 2Small-same condition, and no difference in performance was observed between these trials and those in the 2Small-different condition. These results, together with the finding of the region complexity effect in the 1Large trials, indicate that the speed of attentional movement is affected by the complexity of the region between the two relevant locations and that the object effect found in the present experiment was caused primarily by the additional cost in attentional allocation across a nonuniform region in the different-object condition.

Most studies on OBA use reaction time as the primary dependent measure. In general, response latencies are faster in cued identification tasks compared with two-target comparison tasks. However, there is no evidence that reaction time is associated with the presence or absence of an object effect. Whereas object effects have been reported in cued identification tasks with relatively long RTs (e.g., with the mean RT over 700 ms, see Al-Janabi & Greenberg, 2016), there have also been experiments using two-target comparison tasks with similar RTs but no object effects (e.g., Kramer & Watson, 1996).

General discussion

In these experiments, response times are slowed when the region between the relevant locations is crossed by object contours, but it does not matter whether these two locations are on separate objects or on the same object. In Experiment 1, the two letters to be compared were always on the same object, and yet the comparison time increased when the contours of the object dipped into the region between the letters. A similar pattern was seen in both the comparison task and the cuing task of Experiment 2 when the relevant locations were both on the same object. On the other hand, in the 2Small condition of Experiment 2, response times were no longer if the two relevant locations were on different objects than if they were on the same object with a concavity between them.

The increase in response times in these experiments does not indicate a shift of attention from one object to another because the RT increase appears when no shift between objects is necessary, and when a between-object shift is necessary, there is no additional RT increase. These results suggest that a series of studies starting with Egly et al. (1994) also may not demonstrate attentional shifts between objects; instead they reflect a cost that arises when the regions between the two relevant locations are made more complex by object boundaries.

Explaining the region complexity effect

What is it about complexity in the intervening region that increases response time? This question is intertwined with other questions about how attention selects the two relevant locations in these tasks. If we assume that the comparison task is done by first attending to one letter, and then sliding attention over to the other letter while passing over the region in between, then perhaps the attentional shift is more difficult when it passes over contours. The same explanation could explain the cuing task results if attention slides from the cued location to the target location after it appears.

However, a number of studies have argued against this sliding spotlight account (Chastain, 1992a, 1992b; Eriksen & Murphy, 1987; Eriksen & Webb, 1989; Kwak, Dagenbach, & Egeth, 1991; Murphy & Eriksen, 1987, Remington & Pierce, 1984; Sagi & Julesz, 1985; Sperling & Weichselgartner, 1995; Yantis, 1988). Another possibility is that an attentional gradient spreads out from the cued location, and that response decreases with the strength of the gradient at the stimulus location when it appears (Castiello & Umiltà, 1990; Downing, 1988; Downing & Pinker, 1985; Eriksen & St. James, 1986; Henderson & Macquistan, 1993; LaBerge, 1983; LaBerge & Brown, 1986; Mangun & Hillyard, 1987; 1988). Under this sort of explanation, the region complexity could impede the spread of the attentional gradient. In the nonuniform conditions in these experiments, attention cannot spread directly from cue to target location, but must take a roundabout path through the region connecting the two parts of the object together. One recent account claims that attention spreads within object boundaries, and that the spread can be hampered by the narrowness of the area through which it travels (Jeurissen, Self & Roelfsema, 2016). Under this account, response time is increased in these experiments when attention travels slowly through the narrow connector. This explanation is consistent with the results in visual curve tracing tasks, in which participants took longer to judge whether two dots were on the same curve when the arc length of the curve between the dots was longer, suggesting a process that traced along the curve from one dot to the other (Jolicoeur, Ullman, & Mackey, 1991). In addition, the rate of tracing decreased when the curves were closer together compared with when they were farther apart, in a way that is analogous to the slower spread of attention through narrow spaces suggested by Jeurissen et al. (2016). It is important to note that Jeurissen et al.'s account can explain the slower response times in these experiments when the two locations are separated by a concavity, but it does not explain the lack of an object effect in the 2Small condition of Experiment 2.

A third possible account can be considered for the letter comparison task. Subjects may try to attentionally select an extended region of the stimulus that includes both targets. However, if this selection includes extra contours, they may interfere with the identification and comparison of the letters, slowing responses. Subjects may be able to avoid the interference in the nonuniform trials by selecting the one target letter after the other, which would also slow responses. Alternatively, they may select two noncontiguous regions including both target letters while excluding the contours between them. If this split attention is possible, it will introduce other complications. (See Jans, Peters, & De Weerd, 2010; and Cave, Bush, & Taylor, 2010) for explorations of the possibility of split attention.)

Implications for object based attention

While these questions about the origin of the region complexity effect are not yet answered, these results clearly demonstrate that the effect that emerges in these two experiments is independent of the object organization of the stimuli, and they raise questions about how to interpret the results from Egly et al. (1994) and all of the subsequent two-rectangle studies. There is still much about these interactions to be explored in future experiments. It will be interesting to test whether the results will be the same if the relevant stimuli are created by subjective contours (Jane Raymond, personal communication, November 17, 2019) or by changing parts of the object contours rather than adding shapes within the object boundaries. The latter type of stimulus was introduced with Watson and Kramer's (1999) wrenches, and they are described by Al-Janabi and Greenberg (2016) as "of" the object rather than "on" the object. Also, Davis and Holmes (2005) suggest that object effects might only arise with outline stimuli, rather than with the filled stimuli used here. It is also important to consider how the subjects' previous experience and the instructions and other circumstances of a specific experiment induce subjects to impose an object organization onto a configuration of stimuli (Chen, 1998; Chen & Cave, 2006; Li & Logan, 2008). However, until these effects are tested with locations separated by a concavity rather than object boundaries, as was done in the current experiments, all of these effects could plausibly be attributed to region complexity rather than to object organization.

If the previous two-rectangle experiments are not evidence of a cost for shifting attention from one object to another, then where does that leave the concept of object-based attention? There are still a number of object-based attention demonstrations in other paradigms, including studies of perceptual grouping (Baylis & Driver, 1992; Driver & Baylis, 1989; Harms & Bundesen, 1983; Kramer & Jacobson, 1991) and of subjective organization (Chen, 1998; Li & Logan, 2008; Watson & Kramer, 1999), some of which have used amodally completed objects (Haimson & Behrmann, 2001; Moore, Yantis, Vaughan, 1998; Pratt & Sekuler, 2001). Thus there is still evidence for object-based attention, but it may be a more limited phenomenon than has been assumed up to now.

Keywords: object-based attention, two-rectangle paradigm, region complexity effect, location, cuing

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Footnotes

[1] The majority of the studies on object-based attention in prior research used a sample size between 10 and 20 (e.g., Chen, 1998; Egly et al., 1994; Lamy & Egeth, 2002; Moore et al., 1998). We decided to use a sample size of 24 so it would be slightly larger than the average sample size in previous studies. If a reliable region of complexity effect cannot be found with such a sample size in the present study, we deem the effect to be too small to make a meaningful comparison with the object effect found in previous studies using a spatial cuing paradigm.

[2] In all the experiments reported here, data exceeding 2 standard deviations (both above and below) from each individual participant's mean RT were excluded. This resulted in the exclusion of 3% of the data in both Experiment 1 and Experiment 2. In addition, the data from any participant whose error rate exceeded 25% in any condition were also excluded, and this resulted in the exclusion of the data from three participants in Experiment 2.

[3] Although this study does not include any experiment using an SOA of 50 ms, as part of another experiment, a group of participants completed a condition in which two targets were presented simultaneously. The stimuli and the procedure were otherwise the same as those in Experiment 1. No difference was found in RTs between the uniform and the nonuniform conditions.

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