Object closure affects the strength of object-based attentional filtering

Grace L. Nicora, Adam S. Greenberg

Department of Psychology, University of Wisconsin-Milwaukee

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Corresponding author:

Adam S. Greenberg, PhD
Department of Psychology
University of Wisconsin-Milwaukee
Milwaukee, WI
USA 53201
Email: agreenb@uwm.edu

Abstract

Shifts of object-based attention (OBA) are affected by object closure in the double-rectangle cueing paradigm (Marino & Scholl, 2005). The effect of closure on object-based selection and attentional filtering strength have not previously been investigated. Using a modified flanker paradigm (Eriksen & Eriksen, 1974), we presented subjects either a set of vertically oriented rectangles (*rectangle condition*) or those same rectangles with the horizontal top/bottom of each rectangle removed (*line condition*). In Experiments 1 & 2, a centrally presented object was flanked by four identical objects. One end of the central (target containing) object was then exogenously cued. Subjects performed a letter discrimination task on a color singleton target letter appearing on the central object in the presence of flanker letters (on flanking objects) that were either compatible or incompatible with the target response. Experiment 1 (homogeneously *rectangle* or *line* objects) showed that OBA selection is strong when objects are closed, preventing flankers from influencing performance. Experiment 2 (spatial attention control) showed that closure does not affect performance without OBA selection. Experiments 3 (flanking *line* objects) and 4 (flanking *rectangle* objects) showed that both target & flanking objects play a role in attentional filtering of distracters. During object-based attentional selection, flanking (non-selected) perceptual objects may serve to confine the effects of distracters while target (selected) perceptual objects may serve to shield the target from the effects of distracters.

Attention is the mechanism that allows us to select behaviorally relevant information while simultaneously suppressing irrelevant information, allowing for efficient interactions with our environment. The representational basis of visual attentional selection has been shown to be space-based, feature-based, or object-based (Egeth & Yantis, 1997). In the present study we investigated interactions between object-based attention (OBA) and perceptual grouping in an effort to understand how manipulations of object closure (Wagemans, J., Elder, J. H., Kubovy, M., Palmer, S. E., Peterson, M. A., Singh, M., & von der Heydt, R., 2012) can affect the strength of attentional selection.

The classic paper by Duncan (1984) tested the theory of object-based attention by asking subjects to judge characteristics of two spatially superimposed objects. He found that participants were faster when reporting characteristics of one object, and significantly slower when reporting characteristics of two objects, suggesting that a shift of (object-based) attention between objects was required in the latter case. Thus, participants exhibited a “same object advantage” in response time when the second report did not require an object-based shift of attention. Further experiments of the same investigation studied how the quality of objects (brightness, order of report, orientation) affect attentional selection, leaving unexplored the influence of other object qualities.

Marino and Scholl (2005) investigated whether object completion was necessary for OBA utilizing a variant of the double-rectangle cueing paradigm (Egley, Driver, & Rafal, 1994) in which the objects were presented either as completed rectangles or as a pair of grouped line segments (rectangles with the shorter connecting segments removed, cf. Avrahami, 1999; Kramer & Jacobson, 1991). An exogenous spatial cue was followed by a 65% valid, invalid-same object (12.5%), or invalid-different object (12.5%) probe. Results replicated both the cue-

validity effect (valid RTs faster than invalid RTs) and the object-based effect (invalid-same RTs faster than invalid-diff RTs) of Egly et al. (1994) for the completed rectangles. Importantly, they also showed these same effects for the grouped line segments condition, despite the absence of completed perceptual objects. Similar results were shown in a second experiment using a divided attention paradigm. Notably, in both experiments Marino & Scholl (2005) observed numerically smaller object-based effects in the non-closure condition versus the closure condition. They conclude that “boundary closure is a feature that helps to define what it means to be an object”, further speculating that “the strengthened objecthood of the bounded rectangles made it more difficult for attention to cross [object] boundaries—or, alternatively, for attention to disengage from one object and shift to another”.

The notion of OBA struggling to cross object boundaries or disengage object representations led us to the following two questions: (1) How does closure’s effect on the strength of attentional selection influence attentional filtering of distracters?, and (2) Do completed objects bind OBA to a selected object or rather serve to shield distracters from intruding upon selected objects? In order to explore these issues, we adapted the paradigm of Marino and Scholl (2005) to include an Eriksen flankers task (Eriksen and Eriksen, 1974), allowing us to measure response compatibility effects of distracters as a function of OBA with stronger (closed) or weaker (non-closed) perceptual objects.

It has previously been established that perceptual grouping of objects does have an effect on flanker stimulus processing during attentional selection (Kramer & Jacobson, 1991). Those results showed that target-flanker response compatibility effects were larger when objects (or features) containing the target & distracters grouped together versus when they did not. This was interpreted as a form of the same-object advantage. Although clearly relevant to the current

investigation, that study was primarily concerned with the influence of between-object grouping on flanker processing, whereas here we are interested in the influence of grouping (closure) cues that promote objecthood (not grouping between objects).

Experiment 1

Methods

Participants

Participants were 38 individuals (mean age = 23 years; 26 female, 11 male; one participant did not disclose their gender) from the University of Wisconsin-Milwaukee campus and surrounding community. A total of 7 consented individuals (4 female, 3 male) were excluded from analysis due to incomplete datasets or reporting that they performed the task incorrectly. We further intended to exclude individuals who performed below 90% accuracy, however none of the remaining participants fell below this criterion. The experiment was approved by the UWM Institutional Review Board. All participants provided written informed consent. Participants were recruited through advertisement both online and in local newspapers, as well as in-class recruitment for students. Participants were either paid \$10 or granted one hour of extra credit for a Psychology course.

Apparatus and Stimuli

Stimuli were presented on a 17-in. CRT monitor (1,024 x 768 pixel resolution, 100-Hz refresh rate). The monitor was driven by an Apple Mac Mini running OS X (Version 10.8.5). Stimuli were programed in the GNU Octave software platform (Bateman et al., 2015) with Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Chinrests were used to ensure

common head position and distance from screen for all participants. Monitors were placed 58cm from the chinrest.

During the *rectangle condition*, five rectangular object stimuli were rendered in white against a black background, measuring 12° in height and 1.5° in width, with 0.1° line thickness. The *line condition* comprised the same rectangular stimuli, but the horizontal line segments (top/bottom of each object) were removed, resulting in ten vertical line segments measuring 12° in height and 1.5° from partnered segments. Both the rectangle objects and paired line objects were spaced 2.5° from one another.

Mirroring the Eriksen flankers paradigm (Eriksen & Eriksen, 1974), the five parallel vertical objects enclosed ten letters: two letters on each object, with one located at the top end of the object and the other at the bottom end. Each letter was centered 0.75° from the nearest single horizontal and two vertical lines. Non-target letter stimuli were rendered in white using a fixed-width font and measured $0.5^\circ \times 0.5^\circ$. The target letter was always rendered in green (RGB: 0,255,0). The spatial cue was a white horizontal line measuring 1.5° wide with a 0.5° line thickness, appearing centered 0.5° above or below the center rectangle or paired line object.

Design and Procedure

Two conditions of closure were presented, paired line objects or rectangle objects. The green target letter always appeared in the center object as a 'T' or 'L'. Flanking letters were of two types: (1) a single distracting letter (referred to here as the distracter) appearing opposite the target letter, at the end of the central object, and (2) four flanking letters (referred to as flankers), two appearing to the left and two to the right of the target letter, one on each of the four flanking objects. Distracters were target response compatible, incompatible, or neutral ('X'). The flankers

were either target response compatible or incompatible. The flanking letters to the left and right of the distracter were always neutral 'X's (see Fig. 1).

The experiment consisted of eight blocks of 156 trials, presented in randomized order with a 20-s break between each, four of which comprised the *rectangle condition* and four of which comprised the *line condition*. Each block contained 75% valid cues and 25% invalid cues presented in randomized order within each block. Each trial began with a black screen for 200 ms after which the rectangle or line objects would appear. After an additional 500 ms an exogenous spatial cue (100 ms duration) appeared at the top or bottom of the target object followed again by the object display for 200 ms. The letter stimuli then appeared within the objects and remained for 2000 ms or until response.

Participants were instructed to search for the green target letter and discriminate its identity ('T' or 'L'), which was indicated by pressing the respective button on a standard QWERTY computer keyboard "as quickly and accurately as possible". They were told that the cued end of the central object was the likely location of the target letter.

Results

We conducted a 2 (Shape) x 3 (Target-Distracter Compatibility) x 2 (Target-Flanker Compatibility) within-subjects analysis of variance (ANOVA) using mean response latencies on valid trials only¹. We included only correct responses, excluding participants whose overall accuracy fell below 90 percent. The ANOVA revealed a significant main effect of Shape, $F(1,37)$

¹ All subsequent analyses were also limited to valid trials. The invalid trials were included in the design primarily to encourage object-based selection, as it has been shown that target location uncertainty must be present to evoke OBA (Drummond & Shomstein, 2010; Greenberg, 2009). The small number of invalid trials (especially once partitioned by distracter and flanker conditions) make it difficult to draw any conclusions from analysis of those data.

$= 5.58, p < 0.05, \eta_p^2 = 0.13$, where response latencies to the target were slower in the rectangle ($M = 541$ ms, $SD = 49$) condition as compared to the line ($M = 533$ ms, $SD = 48$) condition. A significant main effect of Target-Distracter Compatibility, $F(2,74) = 17.41, p < 0.01, \eta_p^2 = 0.320$, appeared in which response latencies to the target in the presence of compatible ($M = 536$ ms, $SD = 48$), neutral ($M = 532$ ms, $SD = 49$), and incompatible ($M = 543$ ms, $SD = 47$) distracter conditions were all significantly different from one another (all $t_s > 2.81, p_s < 0.001$). We, furthermore, observed a significant main effect of Target-Flanker Compatibility, $F(1,37) = 15.54, p < 0.05, \eta_p^2 = 0.29$. This effect resulted from response latencies to the target being longer when they appeared alongside incompatible ($M = 540$ ms, $SD = 48$) versus compatible ($M = 534$ ms, $SD = 48$) flankers. The omnibus ANOVA also yielded a significant two-way interaction between Target-Flanker Compatibility and Target-Distracter Compatibility, $F(2,74) = 3.45, p < 0.05, \eta_p^2 = 0.09$. This two-way interaction was qualified by a three-way interaction with all factors: Shape, Target-Flanker Compatibility and Target-Distracter Compatibility, $F(2,74) = 3.24, p < 0.05, \eta_p^2 = 0.08$. Separate analyses were performed for each level of Target-Distracter Compatibility (compatible, neutral, and incompatible) to investigate the effect of the Target-Flanker Compatibility on response latencies for both rectangle and line conditions (see Fig. 2).

Target-Distracter Compatible condition. We carried out a 2 (Shape) x 2 (Target-Flanker Compatibility) within-subjects, repeated-measures ANOVA run on mean response latencies for the Target-Distracter compatible condition. Only correct responses were included. This ANOVA revealed a main effect of Target-Flanker Compatibility, $F(1,37) = 7.14, p < 0.05, \eta_p^2 = 0.162$, in which response latencies to the target when it appeared alongside incompatible ($M = 539$ ms, SD

= 49) were slower as compared to compatible ($M = 533$ ms, $SD = 48$) flankers. Of importance, we also found a two-way interaction between the Shape and Target-Flanker Compatibility factors, $F(1,37) = 4.19$, $p < 0.05$, $\eta_p^2 = 0.102$. We conducted paired comparisons to investigate the congruency effect of the Target-Flanker Compatibility at each level of Shape. Response latencies to the target when in the line condition were shorter when flankers were compatible ($M = 526$ ms, $SD = 46$) versus incompatible ($M = 537$ ms, $SD = 51$), $t(37) = 3.14$, $p < 0.05$. This flanker effect did not, however, emerge in the rectangle condition, $t(37) = 0.58$, $p = 0.56$. The results of this analysis indicate that flanking letter stimuli can affect target detection but, importantly, only when the task-irrelevant (flanking) objects lack closure.

Target-Distracter Neutral condition. As previously, a 2 x 2 ANOVA was conducted on mean response latencies in the Target-Distracter neutral condition. Only correct responses were included. This ANOVA revealed a main effect of Shape, $F(1,37) = 6.64$, $p < 0.05$, $\eta_p^2 = 0.15$, whereby mean response latencies were slower in the presence of rectangle objects ($M = 536$ ms, $SD = 50$) than the line objects ($M = 527$ ms, $SD = 48$). Also observed was a main effect of Target-Flanker Compatibility, $F(1,37) = 15.85$, $p < 0.01$, $\eta_p^2 = 0.30$, with slower response latencies to the target in the presence of incompatible ($M = 536$ ms, $SD = 50$) versus compatible ($M = 527$ ms, $SD = 48$) flankers. No other main effects or interactions were present. Again, this pattern of results indicates that flanking stimuli can affect target detection. Unlike in the compatible distracter condition, this effect emerges irrespective of whether the task-irrelevant object is complete or incomplete. Importantly (and of primary concern to our hypothesis), however, the congruency effect was significantly modulated by object closure, as shown in Figure 2, $t(37) = 1.82$, $p < 0.05$, $\eta_p^2 = 0.04$.

Target-Distracter Incompatible condition. We, again, conducted the aforementioned 2 x 2 ANOVA for mean response intervals in the Target-Distracter incompatible condition. This ANOVA revealed no significant main effects or interactions (all $F_s < 7.14$). The results of this analysis indicate that flanking stimuli do not affect target processing when the target-distracter relationship is incompatible. Together with the above analysis of compatible/neutral distracter trials, our results show a dissociation in the role of object closure on the flanker effect dependent on the Target-Distracter Compatibility.

Discussion

In Experiment 1 we set out to investigate whether the closure of an object would modulate the strength of the attentional filter of OBA. This hypothesis was confirmed. When examining the three-way interaction that resulted from the 2 x 3 x 2 ANOVA, a significant congruency effect was observed when the Target-Distracter Compatibility was either compatible or neutral. Furthermore, this congruency effect was significantly modulated by object closure; the effect of the flankers on target processing (when distracters were compatible/neutral) was greater in the presence of the paired line objects versus rectangular objects.

Notably, the flankers had no effect when the distracter was incompatible with the target, which may signal a loss of attentional control during these high-conflict trials. We will not dwell on this result since it is not directly relevant to the interaction between OBA and object closure, on which this project is focused. However, others have also shown that perceptual conflict has a deleterious effect on both the behavior (e.g., Stroop, 1935) and neural mechanisms (Walsh et al., 2011) of selective attention. Thus, it may not be surprising to see that within-object conflict of this type (especially when it occurs on only a minority of trials) leads to behavior consistent with

limited attentional selection.

Next, we wanted to investigate whether the above-mentioned dependency of congruency effects on object closure are observable in the absence of OBA. In Experiment 2 we manipulated the spatial cue in order to eliminate OBA selection during the, otherwise, identical task/stimuli used in Experiment 1.

Experiment 2

Two hypotheses have been proposed to account for the evidence in support of an object-based guidance of attentional selection (Shomstein, 2012): Attentional Spreading and Attentional Prioritization. In the Attentional Spreading hypothesis (Richard et al., 2008), once cued to a specific location on an object, there is an automatic attentional gradient that spreads along that object from the cued location. Secondly, the Attentional Prioritization hypothesis (Shomstein and Yantis, 2002, 2004) suggests a more strategic allocation of the attentional gradient from the cued location (Greenberg, 2009; Greenberg & Gmeindl, 2008; Greenberg et al., 2015; Senturk, Greenberg, & Liu, 2016). Despite the differing hallmarks of Attentional Spreading and Attentional Prioritization theories (automaticity and strategy, respectively), both hypotheses are described with a dependence on a spatial cue to which attention is initially deployed and prioritization is ultimately highest. In this experiment we removed the cue so as to prevent an object-based form of attentional selection, leaving participants to simply complete a visual search for the target item.

Methods

Participants were 31 individuals (mean age = 22 years; 26 female, 5 male) from the University of Wisconsin-Milwaukee campus and surrounding community. One consented

individual (male) was excluded from analysis for performing below 90% accuracy overall. Experiment 2 was identical to Experiment 1 in all respects, with the only exception being an absence of the spatial cue. As a result, the object display remained on the screen for 800 ms prior to the onset of the letter stimuli.

Results

We conducted a 2 (Shape) x 3 (Target-Distracter Compatibility) x 2 (Target-Flanker Compatibility) within-subjects ANOVA using mean response latencies. A significant main effect of Target-Distracter Compatibility, $F(2, 58) = 12.611$ $p < 0.01$, $\eta_p^2 = 0.30$, was revealed with response latencies in the presence of compatible ($M = 548$ ms, $SD = 51$), neutral ($M = 543$ ms, $SD = 47$), and incompatible ($M = 555$ ms, $SD = 48$) distracters all being significantly different from one another (all t s > -3.62 , $ps < 0.05$). The omnibus ANOVA also showed a significant main effect of Target-Flanker compatibility, $F(1, 29) = 30.640$, $p < 0.001$, $\eta_p^2 = 0.51$, with the incompatible ($M = 553$ ms, $SD = 49$) flanker condition yielding longer response latencies than the compatible ($M = 545$ ms, $SD = 49$) flanker condition. Importantly, no other main effects or interactions were significant (all F s < 2.980).

Discussion

In Experiment 2, we again observed main effects of both Target-Distracter Compatibility and Target-Flanker Compatibility. However, there was no main effect of Shape nor any significant interactions. Critically, the absence of a main effect or interaction with Shape did not prevent main

effects of either Target-Distracter Compatibility or Target-Flanker Compatibility, indicating that flanker effects are still present in the absence of OBA selection. However, as shown in Figure 3, the congruency score did not modulate as a function of object closure. Since the only aspect that differed from Experiment 1 was the absence of a spatial cue, we conclude that attentional selection in Experiment 2 was not object-based. This further strengthens the results from Experiment 1, that the modulation of congruency score as a function of object closure was a result of OBA selection of the cued object.

The present results are in agreement with the findings of Al-Janabi and Greenberg (2016) in which, similarly, when no cue was present there was an absence of OBA when the target was ‘on’ an object (as ours was here). In addition, as in our Experiment 1, Al-Janabi and Greenberg (2016) observed a reemergence of OBA when a spatial cue was present. Following their suggestion, the initial narrow attention focusing effect of the cue may serve to enable prioritization of the cued object, particularly when the target appears ‘on’ the object.

Having established that OBA is vital for the object closure-dependent flanker effects on target processing observed in Experiment 1, we next investigated the role of flanking object closure. The first two experiments showed that filtering of flankers during OBA is more difficult when the target object lacks closure. However, thus far, flanking object closure has been confounded with target object closure such that we cannot determine whether the filtering difficulty is caused strictly by a lack of target object closure, or whether the lack of flanking object closure also plays an important role. Therefore, in Experiments 3 & 4, we held constant the closure of flanking objects to dissociate the effect of target object closure from that of flanking object closure. We hypothesized that only the target object closure drove object-based selection and

filtering of flankers, such that similar modulations of the flanker effect with target object closure (cf. Experiment 1 Results) would be observed both when flanking objects lacked closure (Experiment 3, Fig. 4a) or when they possessed closure (Experiment 4, Fig. 4b).

Experiment 3

Methods

Participants were 38 individuals (mean age = 25 years; 26 female, 10 male, one participant did not disclose demographic information) from the University of Wisconsin-Milwaukee campus and surrounding community. Two participants (both male) were excluded due to incomplete datasets. None of the remaining participants performed below 90% accuracy. Experiment 3 was identical to Experiment 1 in all respects, with the only exception being that flanking objects were always rendered as parallel lines, and never as rectangles. The target object continued to vary between line and rectangle conditions, by block, as previously.

Results

As in Experiments 1 and 2, we conducted a 2 (Shape) x 3 (Target-Distracter Compatibility) x 2 (Target-Flanker Compatibility) within-subjects ANOVA using mean response latencies from each participant. A significant main effect of Shape was revealed, $F(1,33) = 8.48$, $p < 0.01$, $\eta_p^2 = 0.20$, with rectangle objects ($M = 529$ ms, $SD = 45$) yielding longer response latencies than line objects ($M = 521$ ms, $SD = 44$). A significant main effect of Target-Distracter Compatibility was also observed $F(2,66) = 11.420$, $p < 0.001$, $\eta_p^2 = .26$, where compatible ($M = 525$ ms, $SD = 47$), neutral ($M = 520$ ms, $SD = 43$), and incompatible ($M = 530$ ms, $SD = 44$) distracter conditions were all significantly different from one another (all $t_s > 2.87$, $p_s < 0.01$). Additionally, a

significant main effect of Target-Flanker Compatibility was revealed, $F(1,33) = 8.973$, $p < 0.01$, $\eta_p^2 = 0.21$, in which the incompatible ($M = 527$ ms, $SD = 44$) flanker response latencies were longer than compatible ($M = 523$ ms, $SD = 45$) flanker response latencies. A significant interaction between Shape and Target-Flanker Compatibility was revealed, $F(1,33) = 4.665$, $p < 0.05$, $\eta_p^2 = 0.12$. This interaction was further examined via paired t-test of the compatible and incompatible flanker conditions for each level of shape (see Fig. 5).

Shape line condition. When the target object was rendered as parallel lines, we observed significantly faster response latencies to the target in the presence of compatible flankers ($M = 518$ ms, $SD = 44$) compared to incompatible flankers ($M = 525$ ms, $SD = 44$), $t(101) = 3.833$, $p < 0.01$.

Shape rectangle condition. When the target object was rendered as a rectangle, we observed no difference in response latencies to the target in the presence of compatible flankers ($M = 528$ ms, $SD = 46$) compared to incompatible flankers ($M = 530$ ms, $SD = 45$), $t(101) = 0.654$, $p = 0.514$.

Discussion

In Experiment 3 we aimed to dissociate the effects of target object vs. flanking object closure on OBA by holding constant the closure of the flanking objects. The task irrelevant flanking objects always lacked closure (rendered as parallel lines) while the task relevant target object changed levels of closure. We observed main effects of Shape, Target-Distracter Compatibility, and Target-Flanker Compatibility as well as a significant interaction between Shape and Target-Flanker Compatibility. Further examination of the interaction with respect to our hypothesis revealed that when the target object lacks closure, response latencies in the presence of compatible flankers are significantly shorter than in the presence of incompatible flankers.

However, when the target object is closed, there was no difference in response latencies between compatible and incompatible flanker conditions. These data support our hypothesis that the closure of the target object is important for OBA selection and filtering.

Although the results from Experiment 3 suggest that target object closure drives the object-based selection observed in Experiment 1, it remained possible that the flanking objects also play a role. Because Experiment 3 employed non-closed flanking objects, the influence of flankers on target processing was unimpeded by completed flanking object boundaries. Thus, it may be that modulation of the flanker effect was observed in Experiment 3, in part, because the flanking objects lacked closure, allowing the flankers to influence target processing (when target objects also lacked closure).

In Experiment 4, we tested whether the flanking objects play an important role in modulating the strength of OBA by rendering them as closed rectangles on all trials. Consistent with our hypothesis in Experiment 3, we predicted that flanking object closure would not contribute to OBA selection. Therefore, as in Experiment 3, we expected to observe significant flanker effects on target processing when the target object lacks closure and no flanker effects when the target object possesses closure.

Experiment 4

Methods

Participants were 38 individuals (mean age = 22 years; 30 female, 8 male) from the University of Wisconsin-Milwaukee campus and surrounding community. There were 3 (2 males, 1 female) participants excluded from analysis due to incomplete datasets. None of the remaining participants performed below 90% accuracy. Experiment 4 was identical to Experiment 1 in all respects, with

the sole exception being that flanking objects were always rendered as rectangles, and never as parallel lines. The target object continued to vary between line and rectangle conditions, by block, as previously.

Results

As in Experiments 1 through 3, we conducted a 2 (Shape) x 3 (Target-Distracter Compatibility) x 2 (Target-Flanker Compatibility) within-subjects ANOVA using mean response latencies from each participant. The ANOVA revealed a significant main effect of Target-Distracter Compatibility [$F(2,74) = 12.538, p < .001, \eta_p^2 = 0.25$]. Response latencies to the target in the presence of the compatible ($M = 540$ ms, $SD = 47$), neutral ($M = 538$ ms, $SD = 48$), and incompatible ($M = 548$ ms, $SD = 49$) distracter conditions were significantly different from one another (all $t_s > 1.702, p_s < 0.01$), except between the neutral and compatible distracter conditions ($t(37) = 1.4, p = 0.08$). Also revealed was a significant main effect of Target-Flanker Compatibility [$F(1,37) = 13.154, p = .001, \eta_p^2 = .262$]. Faster response latencies were observed when the target was in the presence of compatible flankers ($M = 539$ ms, $SD = 48$) compared to incompatible flankers ($M = 544$ ms, $SD = 48$). No other main effects or interactions were present.

Discussion

Experiment 4 aimed to further explore the role of flanking object closure in the modulation of OBA. In particular, we hypothesized that consistent closure of the flanking objects would not affect the modulation of flanker effects caused by changes in closure of the target object (as

observed in Experiment 3). Surprisingly, the results yielded no main effect or interaction with Shape, suggesting that the closed flanking objects served to throttle the modulation of flanker effects observed previously. Therefore, our hypothesis that only target object closure is important for object-based filtering of distracters has been disproven. Considered alongside the results from Experiment 3, these data provide evidence for a critical role of flanking objects in OBA.

General Discussion

Closure affects the Object-Based Attentional Filtering of Distracters

Previous work using the double-rectangle cueing paradigm has shown that object closure can influence the shifting of object-based attention when searching for a target (Marino & Scholl, 2005). Here we were interested in the effect of closure on distracter filtering during object-based selective attention. In Experiment 1 we tested the effects of homogeneous closure of a set of perceptual objects during OBA and found that closure did affect the influence of flanking distracters on target processing: participants displayed a decreased ability to filter distracters when objects lacked closure compared to when objects were fully closed. In Experiment 2 we aimed to ensure that the effects we observed were, in fact, due to OBA. We, therefore, removed the exogenous spatial cue (thus preventing the deployment of focused OBA) and consequently observed no effect of object closure on distracter filtering. We maintain that the completeness of the underlying object representation determines the strength of object-based attentional selection. Our observation that reduced closure leads to additional influence of distracters is an instantiation of a reduced strength of OBA selection. This hypothesis motivates a large set of predictions regarding interactions between perceptual organization and object-based attention.

Future work will aim to quantify the strength of OBA selection under conditions of varying degrees of object representational uncertainty.

It stands to reason that OBA, a mechanism that targets perceptual objects, should be dependent on the underlying representation of any object upon which it may act. As such, any characteristic that affects the underlying strength of the object representation (perceptual grouping, figure-ground organization, etc.) should, theoretically, have an effect on OBA (see Kimchi, 2009 for a related discussion). We note here that other representational bases of attentional selection (space-based, feature-based, etc.) should not be dependent on such characteristics of object formation. This has implications for the theoretical dissociation between OBA and other forms of attentional selection and could help us better understand the distinct computations of the neural mechanisms involved.

Role of Target Object and Task Irrelevant Objects

Demonstrations of OBA nearly all involve targets that appear ‘on’, or ‘of’ (cf. Al-Janabi & Greenberg, 2016), two or more objects (though see Barnas & Greenberg, 2016). Participants must ultimately attend to different objects on different trials, depending on target location. This paradigm is useful for understanding the nature of object-based shifts of attention but sheds little light on the *strength* of object-based attentional selection. Herein, we used a procedure in which targets always appeared on a single object (though, location *within* that object did vary) while flanking objects contained to-be-filtered distracters. This allowed us to assess the strength of object-based selection as measured by the influence of flankers on target processing (i.e., congruency score, or flanker effect). In particular, we were able to determine the relative roles of objects containing the target and objects containing the distracters in the strength of OBA

selection. Experiments 1 & 2 clearly demonstrate a critical role of the target object representation in OBA selection: when the target object representation was weaker (line condition), the distracters had a greater influence (weak selection); when the target object representation was stronger (rectangle condition), the distracters had a lesser influence (strong selection). In Experiments 3 & 4, we held constant the flanking object closure to dissociate the effect, on OBA, of target object closure from that of flanking object closure. Weaker flanking object representations (Experiment 3) led to modulation of the flanker effect as the target object representation varied; however, stronger flanking object representations (Experiment 4) prevented modulation of the flanker effect as the target object representation varied. This unanticipated finding indicates that closure of the task irrelevant flanking object influenced OBA, suggesting that OBA selects not only the target/cued object but also nearby perceptual objects, a concept that has not been incorporated in current models of OBA.

Based on this evidence, we propose that object-based attention simultaneously selects both target objects and flanking objects which play differential roles in the prioritization of visual information. Target object selection (when strong, encouraged by stronger object formation cues) serves to shield the target against the deleterious effects of distracters (i.e., a “force-field”). Flanking object selection (when strong) serves to confine the distracters so that they are unable to influence target processing (i.e., a “prison”). When target object or flanking object selection is weak (e.g., when object representations are weak due to lack of closure), the diluted shielding or confinement, respectively, allow distracters to exert greater influence over target processing.

Previous studies have shown that attentional prioritization does in fact have a tendency to spill out from the target object when flankers are present (Lou and Proctor, 2016; Greenberg, Rosen, Cutrone, and Behrman, 2015; Richard, Lee, and Vecera, 2008). Together with our current

results, these data suggest that attention is not simply a selection enhancement mechanism but also an inhibitory mechanism that acts on nearby items that are task irrelevant. Similarly, many theories/models of spatial and feature-based attention include both target enhancement along with nearby distracter suppression (Koch & Ullman, 1985; Desimone & Duncan, 1995; Tsotsos et al., 1995; Reynolds & Heeger, 2009; Buschman & Kastner, 2015). Thus, by virtue of its similar features, OBA should probably be considered a third conventional mode of attentional selection that is more parallel to spatial or feature-based attention than previously appreciated.

Conclusions

We have investigated the role of closure as it pertains to object-based attention. We have shown that closure has an important modulating effect on the strength of object-based selection and that OBA acts upon both target objects as well as nearby flanking objects. Future examination of perceptual closure on OBA could follow many routes from the more explicit lack of closure in the present study to observing differences in illusory objects.

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Fig. 1 Example stimulus sequence for Experiments 1, 3, & 4. **A** stimulus sequence: participants were presented with the object display for 800 ms followed by the appearance of an exogenous cue for 100 ms, the object display for an additional 200 ms, and then the target, distracter, and flankers all appeared on screen. Experiment 2 presented 1100 ms of the object display before target, distracter, and flankers appeared. Shown is a trial containing *rectangle* objects, *compatible* flankers, and an *incompatible* distracter. **B** Example showing the *line* objects condition stimuli. **C** Example of *compatible* flankers with a neutral distracter. **D** Example of *incompatible* flankers with a *compatible* distracter.

Fig. 2 Congruency Scores, where score value is the difference of the Target-Flanker Compatible RT subtracted from the Target-Flanker Incompatible RT. The scores were separated by Target-Distractor Compatibility condition so as to best represent the three-way interaction observed in the ANOVA. Significant differences in congruency score were found between the line and rectangle conditions when the Target-Distractor Compatibility condition was either compatible or neutral. Error bars represent the standard error of the mean.

Fig. 3 Congruency Scores, where score value is the difference of the Compatible Target-Flanker RT subtracted from the Incompatible Target-Flanker RT. No significant differences were seen as a result of the object shape. Error bars represent the standard error of the mean.

Fig. 4 Example of stimuli for Experiments 3 & 4. **A** Experiment 3, in which task irrelevant objects were always of the line objects condition. When the target object was a rectangle, the target object and the task irrelevant objects are heterogeneous. **B** Experiment 4, in which task irrelevant objects were always of the rectangle objects condition. When the target object was a line pair, the target object and the task irrelevant objects are heterogeneous.

Fig. 5 Mean response latency as a function of the target object Shape condition and the Target-Flanker Compatibility condition. When the target object was a line pair we observed significant flanker effects, but not when the target object was a rectangle. Error bars represent the standard error of the mean.