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Object-based attention shifts are driven by target location, not object placement

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ABSTRACT
Object-based attention (OBA) enhances processing within an attended object. We previously showed that OBA shifts crossing the visual field meridians were faster horizontally than vertically: a Shift Direction Anisotropy (SDA). Here we aimed to determine whether the SDA depends upon meridian crossings of object boundaries, target locations, or both. Participants viewed an "L"-shaped object and responded to a target at either cued or non-cued locations offset horizontally or vertically. Meridian crossings or non-crossings of object boundaries and target locations were manipulated across five experiments (Experiments 1–3B). In Experiment 4, the object was removed to confirm that object-based (not space-based) attentional resources drive observation of the SDA. In sum, the SDA emerged only when target locations necessitated shifts that crossed the meridians, regardless of object placement, demonstrating that the SDA is driven by target location relative to the meridians and that OBA processes prioritize *specific* target locations within an object.

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Object-based attention; shift direction anisotropy; visual field meridians; attentional prioritization; attention shifts

Attentional selection acts as a gate on sensory stimuli such that only task-relevant, to-be-attended information is enhanced while task-irrelevant, to-be-filtered information is simultaneously suppressed; thus permitting higher order cognitive operations access to pertinent information only. Traditionally, attention has been conceptualized as a spatial filter, preferentially processing visual information at an attended location versus unattended locations (Posner, 1980; Posner, Snyder, & Davidson, 1980). Objects, rather than spatial locations, can also provide a representational basis of attentional selection (Egeth & Yantis, 1997), resulting in preferential processing (and enhanced performance) within the boundaries of an attended object versus an unattended object. Evidence for object-based attentional selection comes from studies employing a variety of experimental paradigms (for reviews, see Cave & Bichot, 1999; Chen, 2012; Moore, Yantis, & Vaughan, 1998; Müller & Kleinschmidt, 2003; Scholl, 2001; Shomstein, 2012), such as tasks involving judgments about object features on spatially overlapping objects, (e.g., Behrmann, Zemel, & Mozer, 1998; Duncan, 1984), multiple object tracking (e.g., Pylyshyn & Storm, 1988; Yantis, 1992), and dissociations in neurological patients (e.g., Egly, Driver, & Rafal, 1994; Egly, Rafal, Driver, & Starrveveld, 1994).

The now-classic study by Egly et al. (1994) introduced the double-rectangle cueing paradigm in which both space-based and object-based attention can be measured simultaneously. They contrasted attention shifts *within* a pair of rectangles against shifts *between* rectangles using a brief exogenous spatial cue (a brightening at one end of a rectangle; 75% valid) followed by a single target appearing in one of three possible object locations: the cued location ("valid"), the far end of the cued rectangle ("invalid-same object"), or the non-cued rectangle ("invalid-different object"). Critically, the two invalid locations were equidistant from the cue. Observers were faster to detect targets at the valid location than either invalid location, a demonstration of a space-based attention effect. Importantly, observers were also faster to detect targets at the invalid-same object location compared to the invalid-different object location, indicating that attention was not only directed to the cued *location*, but also to the cued *object*, thus producing an object-based attention effect commonly referred to in the literature as the "same object advantage". This result cannot be explained solely by a space-based mode of attention selection, since both invalid target locations were equidistant from the cue. Egly et al. (1994), thus,

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showed that space-based and object-based attentional selection are not mutually exclusive and operate in an integrated manner.

The same object advantage reflects an increased prioritization of object-based attention to the cued object, and has been observed in a variety of circumstances in which attention is deployed in an object-based manner (e.g., Abrams & Law, 2000; Atchley & Kramer, 2001; Greenberg, Rosen, Cutrone, & Behrmann, 2015; He, Fan, Zhou, & Chen, 2004; Marino & Scholl, 2005; Moore et al., 1998; Shomstein & Behrmann, 2006; Watson & Kramer, 1999; for a review, see Reppa, Schmidt, & Leek, 2012). Importantly, there is a growing body of evidence demonstrating that the same object advantage is rather inconsistent and/or weak compared to space-based attentional effects. Using the double-rectangle cueing paradigm, several studies have exhibited conditions under which they failed to show a same object advantage (e.g., Avrahami, 1999; Greenberg, 2009; Law & Abrams, 2002; Shomstein & Behrmann, 2008), or have even found a reversal of the same object advantage (a "same object cost") characterized by faster RTs at the invalid-different object location than the invalid-same object location (Chen & Huang, 2015; Davis & Holmes, 2005; Harrison & Feldman, 2009; Pilz, Roggeveen, Creighton, Bennett, & Sekuler, 2012).

Pilz et al. (2012) demonstrated that object-based attentional selection varies as a function of object orientation. Specifically, larger object-based effects (i.e., same-object advantage; Egly et al., 1994) were observed for horizontally-oriented rectangles as compared to vertically-oriented rectangles. To explain this effect, the authors postulated that attention may be more efficiently allocated along the horizontal meridian than along the vertical meridian. However, previous work from our lab showed that object orientation effects are ameliorated when controlling (in the analysis) for shifts of attention across the visual field meridians (Greenberg et al., 2014; see also Al-Janabi & Greenberg, 2016), which suggests that effects of the meridians, themselves, may be the cause of the orientation effects reported by Pilz and colleagues (2012). Furthermore, we recently demonstrated that visual field meridian crossings resulted in a faster reallocation of object-based attention horizontally than vertically (Barnas & Greenberg, 2016), which we refer to as a horizontal advantage shift direction anisotropy (SDA). Rather than utilizing the original double-rectangle cuing paradigm (Egly et al., 1994), in which attention shifts within a cued rectangle are contrasted against equidistant shifts between a cued and non-cued rectangle, we modified the object so that both vertical and horizontal attention shifts across the meridians are contained within the boundaries of a single object. This design feature avoids confounding shift direction across the meridians with object selection, as only a single object was ever available for selection. This horizontal shift advantage was observed regardless of whether shifts of attention occurred within a single cued object, or between cued and non-cued objects, suggesting a critical modulatory role of the visual field meridians on the reorienting of object-based attentional selection. Importantly, when using foreshortened objects that did not cross the meridians, no SDA was observed. These results suggest that the visual field meridians affect the efficiency with which OBA is allocated, and also necessitate updating current theories of object-based attentional selection to account for crossings of the visual field meridians. For instance, Shomstein and Yantis (2002, 2004) theorized that OBA is guided by an attentional prioritization strategy, whereby higher prioritization is afforded to target locations within an attended object compared to target locations in an unattended object. Attention is prioritized to areas in which the probability of a target appearing is higher (i.e., in the cued object) over locations in which the probability of a target appearing is lower (i.e., in the non-cued object), resulting in the unequal prioritization of attention to the invalid-same and invalid-different locations. This unequal prioritization occurs despite the fact that both locations are equidistant from the cue. Based on this account, OBA should be prioritized equally to both invalid target locations (horizontal and vertical) in our paradigm because we only compare target locations within the same object. However, attentional prioritization was unequally distributed between these locations whenever attention shifted across the meridians, indicating that observers may also prioritize dimensions of an object that appear horizontally rather than vertically, particularly when objects cross the visual field meridians. Thus, the discovery of the SDA suggests that attentional prioritization may be driven by more than simply target location probability, which is a crucial aspect of this theory.

Our previous observations have also shown that object placement within the visual field (i.e., whether or not it crosses a meridian), is an important factor in the efficiency of object-based shifts of attention. However, since target location (relative to the meridians) was confounded with object size/placement in our previous publication (in other words, targets were always located 1.0° from the near end of the object, and were always coupled with object crossings), it remains an open question as to whether object placement or target location, in relation to the meridians, is the primary driver of the SDA. The answer to this question has significant implications for theories of object-based attention. The attentional prioritization account described above (Shomstein & Yantis, 2002, 2004) is predicated on target probability flexibly guiding the allocation of attention throughout an object. The attentional spreading account (Richard, Lee, & Vecera, 2008; Vecera & Farah, 1994) suggests that object boundaries automatically guide the allocation of attention throughout an object. If the SDA is primarily driven by target location, this implies that the attentional selection of an object depends on the information within the object that is behaviourally relevant at that moment (i.e., the target). On the other hand, if the SDA is primarily driven by object size/placement, this implies that object boundaries play a more extensive role in the allocation of attentional priority. Conceptually, these two outcomes map on to support for two of the most well-established theories of object-based attention: the attentional prioritization theory (Shomstein & Yantis, 2002, 2004) would be supported if the SDA is driven by target location; the attentional spreading theory (Richard et al., 2008; Vecera & Farah, 1994) would be supported if the SDA is driven by object extent.

Here we report a series of experiments designed to investigate the contributions of invalid target location and object placement to the emergence of the SDA. Six experiments are described during which we manipulated both the boundary positions of a single cued object and the target locations across the visual field meridians. We measured RTs to detect a visual stimulus at invalid-vertical and invalid-horizontal target locations and calculated the RT difference to derive the SDA. In Experiment 1, we simultaneously manipulated the position of the object and locations of invalid targets across the meridians, such that both the object boundaries and the locations of invalid targets either crossed or did not cross the meridians. In Experiments 2A and 2B, object placement was held constant while we manipulated the invalid target locations relative to the meridians. The object boundaries always crossed (Experiment 2A) or never crossed (Experiment 2B) the meridians. In Experiments 3A and 3B, invalid target locations were held constant while we manipulated the object placement relative to the meridians. Invalid targets always crossed (Experiment 3A) or never crossed (Experiment 3B) the meridians. In Experiment 4, which served as a spatial attention control, the object was removed from the paradigm in order to determine whether object-based or space-based attentional resources were being deployed. To preview our most important results, across all six experiments, the SDA emerged only when invalid target locations necessitated shifts that crossed the meridians, regardless of whether object boundaries crossed the meridians. These findings demonstrate that the SDA is driven by target location, rather than object placement, relative to the visual field meridians. We further interpret this as evidence in support of the attentional prioritization hypothesis (Shomstein, 2012) such that object-based attention is strategic, prioritizing *specific* target locations rather than an automatic prioritization of *all* locations within a cued object.

Experiment 1: Yoked object boundaries and invalid target locations

The goal of Experiment 1 was to test conditions under which the object boundaries and invalid target locations simultaneously either crossed or did not cross the visual field meridians (See Table 1). Based on our previous work (Barnas & Greenberg, 2016), we expected to replicate our result in which no SDA emerged when both the object boundaries and

Table 1. Object-target configurations for Experiments 1–3B.

	Experiment				
	1	2A	2B	3A	3B
Crossing Object and Targets	✓	✓		✓	
Non-crossing Object and Targets	✓		✓		✓
Crossing Object, Non-crossing Targets		✓			✓
Non-crossing Object, Crossing Targets			✓	✓	

Note. In Experiment 1, both the object boundaries and the locations of invalid targets either crossed or did not cross the meridians. In Experiments 2A and 2B, object placement was held constant while invalid target locations were manipulated. In Experiments 3A and 3B, invalid target locations were held constant object placement was manipulated.

invalid target locations did not cross the visual field meridians. Conversely, when both the object boundaries and invalid target locations crossed the visual field meridians we predicted a significant SDA, driven largely by enhanced detection (faster RTs) of invalid targets located across the vertical meridian than across the horizontal meridian. This pattern of performance would confirm that meridian crossings of both the object boundaries and invalid target locations may be factors in the emergence of the SDA.

Method

Here, we used the "L"-shaped object stimuli introduced by Barnas and Greenberg (2016) to examine the relevance of object placement and invalid target location on the SDA.

Participants

Using the effect size from our first demonstration of the shift direction anisotropy ($\eta_p^2 = 0.72$; Experiment 1 of Barnas & Greenberg, 2016), a power analysis was conducted with G*Power (Version 3.1; Faul, Erdfelder, Buchner, & Lang, 2009). For $\alpha = .05$ and 95% power, the computed suggested sample size was 10. However, here and in subsequent experiments, more participants were sampled in order to account for the number of participants ultimately excluded from the final sample due to high false alarm and/or miss rates and to approximate the sample sizes from our previous demonstrations of the SDA.

Forty-three individuals ($M_{age} = 21.07$ years, $SD_{age} = 5.95$ years; 31 women, 12 men) from the University of Wisconsin-Milwaukee (UWM) and surrounding community participated in this experiment. The study was approved by the UWM Institutional Review Board. Here and in subsequent experiments, all participants provided written informed consent prior to the start of the experiment, indicated that they had normal or corrected-to-normal visual acuity, and had the option of receiving 1 h of extra credit toward a Psychology course or the standard hourly pay rate of $10 as compensation for their participation.

Apparatus and stimuli

All stimuli were presented using a 17-in. CRT monitor, with a refresh rate of 100-Hz and a resolution of $1,024 \times 768$ pixels. Stimuli were generated on an Apple Mac Mini computer running OS X (Version 10.8.5) and programmed in the GNU Octave software platform (Bateman, Eaton, Wehbring, & Hauberg, 2015) using Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Participants viewed the stimuli binocularly and performed the experiment in a dimly lit room while seated in an adjustable chair. A chin rest was used to support and stabilize participants' heads at a distance of approximately 58 cm throughout the experiment.

Participants fixated centrally on a white fixation cross (0.2° x 0.2°) of a fixed-width font (Monaco, font size 20), and viewed a single median grey object (RGB: [128 128 128]) that consisted of a vertical rectangle conjoined at a 90-degree angle with a horizontal rectangle, forming a unified "L"-shaped object, on a black background. On half of the trials, the "L"-shaped object was composed of a 2.0° x 14.0° vertical component rectangle and a 14.0° x 2.0° horizontal component rectangle (See Figure 1A; "Crossing Object and Targets"). The vertex of the "L"-shaped object was randomly positioned in one of four locations (one per screen quadrant) such that the boundaries of one object component always crossed the vertical screen meridian and the boundaries of the other component always crossed the horizontal screen meridian. The "crossing" "L"-shaped object was placed such that its nearest edge was 2.67° above or below the horizontal meridian and 2.67° to the left or right of the vertical meridian, depending on the location of the object's vertex on the screen.

The other half of trials consisted of an "L"-shaped object that was composed of a 2.0° x 10.65° vertical component rectangle and a 10.65° x 2.0° horizontal component rectangle (See Figure 1B; "Non-crossing Object and Targets"). The vertex was also randomly positioned in one screen quadrant; however, the boundaries of the horizontal and vertical object components did not cross either screen meridian. This "non-crossing" "L"-shaped object was placed such that its nearest edge was 0.67° above or below the horizontal meridian and 0.67° to the left or right of the vertical meridian, depending on the location of the object's vertex on the screen. Both crossing and non-crossing "L"-shaped objects were situated on the screen such that the distance from the vertical screen meridian to the inner edge of the vertical component rectangle matched the distance from the horizontal screen meridian to the inner edge of the horizontal component rectangle, both being 9.33°.

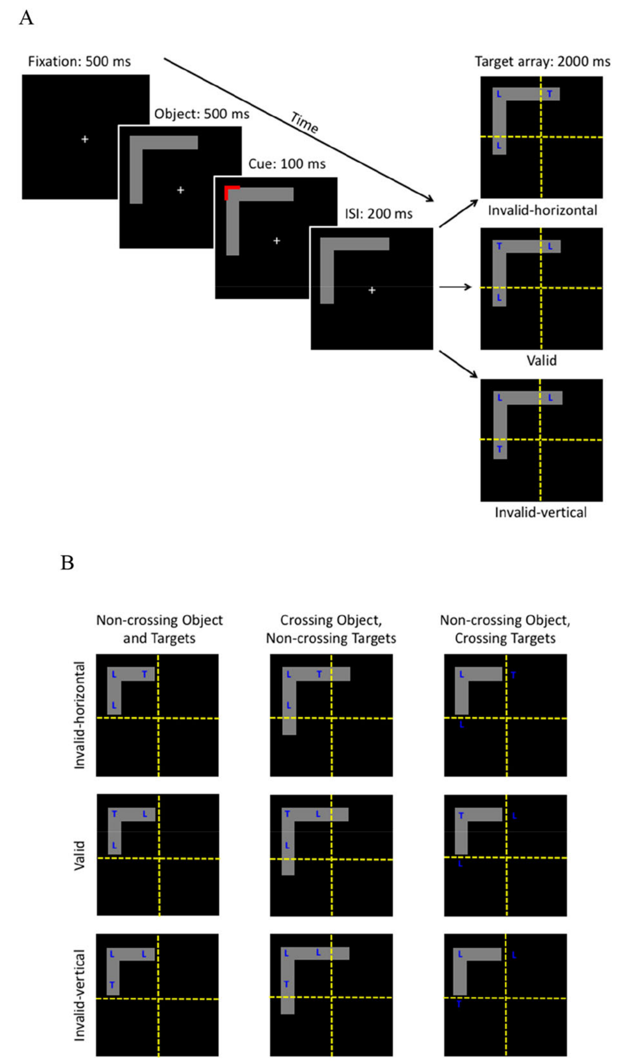

Figure 1. Trial sequence and object-target configurations. (A) Trial sequence for "Crossing Object and Targets". Trial conditions were defined by the location of the blue target "T" in relation to the red peripheral cue at the object vertex in the upper-left quadrant. (B) Object-target configurations for "Non-crossing Object and Targets", "Crossing Object, Non-crossing Targets", and "Non-crossing Object, Crossing Targets" for each trial condition. *Note*: Placement of object boundaries and locations of invalid targets in relation to the visual field meridians are not drawn to scale; dotted yellow lines represent the horizontal and vertical meridians and were not visible to participants during the experiment; trial sequence was the same for each object-target configuration across experiments.

A red exogenous cue (RGB: [255 0 0]) also consisted of a vertical component rectangle (0.34° x 2.0°) conjoined at a 90-degree angle with a horizontal component rectangle (2.0° x 0.34°), and always appeared surrounding the outer edge of the object vertex. Though 100% predictive, the cue still served to exogenously guide spatial attention to the object vertex and selection of the "L"-shaped object. The target array consisted of blue letters (RGB: [0 0 255]; Monaco, font size 20) subtending 0.67° in length and width, and consisted of a single target (the letter "T") among two non-targets (the letter "L"). Target and non-target letters were centred left-to-right within the vertical component rectangle and top-to-bottom within the horizontal component rectangle. Letters were positioned so that their centres were 1.0° from the near end of either component rectangle. Target and non-target letters on the vertical component rectangle and the horizontal component rectangle for any given "L"-shaped object were equidistant from the peripheral cue at the object vertex.

Design

The following three trial conditions were defined by the location of the target "T" at: (1) the cued location at the object vertex (valid condition), (2) the far end of the object's horizontal component rectangle (invalid-horizontal condition), or (3) the far end of the object's vertical component rectangle (invalid-vertical condition). There were 6 blocks, each containing 160 trials for a total of 960 trials. Crossing and non-crossing conditions were randomly intermixed within blocks. That is, participants were equally likely to get a crossing or non-crossing condition on any given trial. Each block consisted of 60% valid trials (96 trials per block; 576 total), 10% invalid-horizontal trials (16 trials per block; 96 total), and 10% invalid-vertical trials (16 trials per block; 96 total). To ensure selective responding, the remaining trials were composed of "catch trials" (20%; 32 trials per block; 192 total) in which only non-target letters appeared on the object. These proportions were split evenly between the two object extent conditions, such that each condition was allotted an equivalent number of trials (e.g., 8 invalid-horizontal trials per block for crossing and non-crossing conditions, or a total of 48 invalid-horizontal trials per condition).

Procedure

Before beginning the experiment, participants were instructed to maintain fixation on the central cross present throughout each trial. As shown in Figure 1A, trials began with a white fixation cross presented alone for 500 ms, which was immediately followed by the appearance of an "L"-shaped object for 500 ms. The red cue was then displayed for 100 ms and, following a 200 ms inter-stimulus interval

(300 ms cue-target SOA) from the offset of the cue, the target array appeared for 2000 ms[1] or until a response was detected. The target letter ("T") randomly appeared in one of the three possible locations (excluding catch trials). Non-targets ("L") also appeared, as placeholders, on the object in the locations that did not contain the target letter. Participants performed a detection task (RTs were recorded) and were instructed to respond as quickly and accurately as possible to the presence of the target letter while minimizing false alarms on catch trials and misses on target-present trials. The subsequent trial began following a randomly selected inter-trial interval of 400, 600, or 800 ms.

Results

Data quality

Prior to conducting any statistical analyses, individual participant data were first checked for excessively high false alarm rates (responding on target absent trials) and miss rates (failing to respond on target present trials). Here and in all subsequent experiments, participants who responded to more than 48 catch trials (or, a 25% false alarm rate) and/or missed 96 target-present trials (or, a 10% miss rate) were discarded from the original sample. These exclusion criteria were established because extreme false alarm and/or miss rates are indicative of disengagement in the task. The original sample of 43 participants had a mean false alarm rate of 19% ($SD = 18\%$) and a mean miss rate of 9% ($SD = 13\%$). Fifteen participants with an excessively high false alarm rate ($n = 9$; $M = 47\%$, $SD = 16\%$) on catch trials and/or miss rate ($n = 10$; $M = 25\%$, $SD = 18\%$) on target-present trials were discarded.[2] This resulted in a final sample of 28 participants ($M_{age} = 19.82$ years, $SD_{age} = 2.20$ years; 22 women, 6 men) with a mean false alarm rate of 10% ($SD = 6\%$) and a mean miss rate of 3% ($SD = 2\%$). Independent samples *t*-tests revealed a significantly larger false alarm rate, $t(8.72) = 6.81$, $p < .001$, $d = 3.08$, and miss rate, $t(9.10), = 3.84$, $p = .004$, $d = 1.71$, for the excluded participants compared to the included participants. Additionally, anticipatory responses (RT less than 200 ms) were discarded.

Response latencies

The dependent variable was mean RT for correct responses, reported in Table 2. First, mean RT differences were calculated by subtracting mean raw RTs to valid targets from mean RTs to invalid-horizontal targets and invalid-vertical targets. Next, mean RT differences were submitted to a 2 × 2 repeated measures ANOVA with Element (boundaries and targets: meridian crossing, meridian non-crossing) and Shift Direction (horizontal, vertical) as within-subjects factors. The analysis revealed a main effect of Element, $F(1,27) = 45.83$, $p < .001$, $\eta_p^2 = .63$, indicating a significant difference in invalid target detection RT when reallocating object-based attention when both the object boundaries and invalid target locations crossed the meridians ($M = 228.88$ ms, $SEM = 19.33$ ms) versus when both the object boundaries and invalid target locations did not cross the meridians ($M = 170.17$ ms, $SEM = 16.54$ ms). Furthermore, the analysis revealed a main effect of Shift Direction, $F(1,27) = 7.50$, $p = .011$, $\eta_p^2 = .22$, indicating a significant difference in invalid target detection RT when reallocating object-based attention horizontally ($M = 183.43$ ms, $SEM = 15.82$ ms) versus vertically ($M = 215.62$ ms, $SEM = 20.70$ ms). These main effects were

Table 2. Mean raw RTs (ms) for correct responses in Experiments 1–3B.

	Trial Condition		
	Invalid-horizontal	Invalid-vertical	Valid
Experiment 1			
Crossing Object and Targets	785.43 (8.12)	832.92 (11.49)	580.30 (12.89)
Non-crossing Object and Targets	729.54 (8.15)	746.42 (12.60)	567.81 (12.60)
Experiment 2A			
Crossing Object and Targets	799.61 (9.83)	849.26 (10.45)	543.87 (13.77)
Crossing Object, Non-crossing Targets	718.99 (10.03)	739.31 (8.53)	538.78 (11.82)
Experiment 2B			
Non-crossing Object, Crossing Targets	910.47 (10.48)	870.32 (9.12)	548.20 (13.72)
Non-crossing Object and Targets	737.73 (10.09)	757.74 (10.89)	549.42 (14.78)
Experiment 3A			
Crossing Object and Targets	795.14 (8.92)	857.06 (7.64)	531.42 (10.73)
Non-crossing Object, Crossing Targets	903.06 (12.99)	836.18 (9.14)	518.55 (9.80)
Experiment 3B			
Crossing Object, Non-crossing Targets	677.36 (5.55)	674.22 (8.83)	536.52 (9.60)
Non-crossing Object and Targets	678.00 (5.89)	689.62 (8.55)	521.80 (7.91)
Experiment 4			
Spatial Attention Control	915.29 (7.81)	930.14 (5.77)	633.43 (9.40)

Across all experiments, there were significant space-based cueing effects such that valid RTs were significantly faster than invalid RTs, *ps* < .001.
Note. Values in parentheses are *SEM*s.

further qualified by a significant two-way interaction, $F(1,27) = 5.50$, $p = .027$, $\eta_p^2 = .17$.

The interaction between Element and Shift Direction describes the significant differences in the magnitude of the SDA as a function of whether the boundaries of the "L"-shaped object and invalid target locations simultaneously crossed or did not cross the visual field meridians (See Figure 2). For crossing "L"-shaped objects and invalid target locations that necessitated shifts of attention across the meridians, a paired samples *t*-test revealed a significant SDA, such that reallocating object-based attention horizontally ($M = 205.13$ ms, $SEM = 7.58$ ms) was significantly faster than reallocating vertically ($M = 252.63$ ms, $SEM = 7.58$ ms), $t(27) = 3.13$, $p = .004$, $d = 0.43$. However, for non-crossing "L"-shaped objects and invalid target locations that did not necessitate shifts of object-based attention across the meridians, a paired samples *t*-test revealed no SDA, such that horizontal shifts of attention ($M = 161.73$ ms, $SEM = 10.90$ ms) were statistically equivalent to vertical shifts of attention ($M = 178.61$, $SEM = 9.84$ ms), $t(27) = 1.47$, $p = .153$, $d = 0.18$. We computed the JZS Bayes Factor (see Rouder, Speckman, Sun, Morey, & Iverson, 2009) for the SDA in the non-crossing condition to quantify the likelihood that the null hypothesis was true. The JZS Bayes Factor was 1.91, suggesting that the null hypothesis (that horizontal shift RTs were equivalent to vertical shift RTs) was roughly twice as likely to be true as was the alternative hypothesis (that there was a difference between horizontal and vertical shift RTs). Thus, the interaction between Element and Shift Direction was driven by a significantly larger and positive (i.e., a horizontal advantage) SDA when both the object boundaries and invalid target locations crossed the meridians (47.49 ms) versus when they did not cross the meridians (16.88 ms).

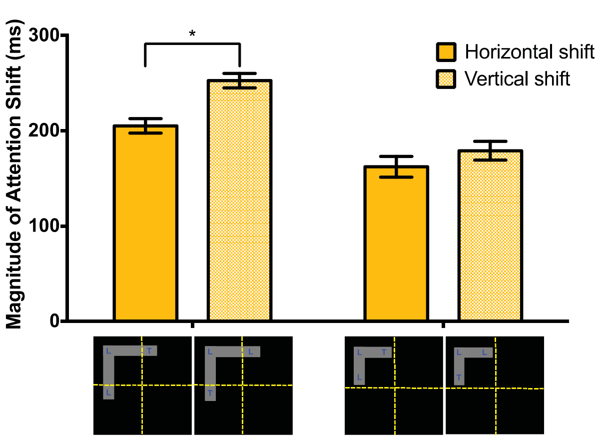

Figure 2. Mean response latencies in Experiment 1. "Magnitude of Attention Shift" measured for the Element (Boundaries and Targets) x Shift Direction interaction. The error bars represent the standard error of the mean for within-subjects design.

In order to understand what might have been happening with the individuals who were excluded due to our predefined criteria, we conducted a parallel ANOVA with all 43 participants from whom data were collected. We observed a similar main effect of Element, $F(1,42) = 14.82$, $p < .001$, $\eta_p^2 = .26$, and a marginally significant two-way interaction, $F(1,42) = 3.27$, $p = .078$, $\eta_p^2 = .07$. However, the main effect of Shift Direction did not reach significance, $F(1,42) = 0.05$, $p = .831$, $\eta_p^2 = .00$. Adding in the data from excluded participants increased the variability and overall noise in the combined data set. Further examination of the excluded data revealed that the mean RT differences were negative, indicating that valid RTs were slower than invalid RTs. This pattern of performance suggests that the excluded participations were, in addition to being unfocused during the task, unsuccessful in capitalizing on the informative nature of the cue to guide space-based attentional resources to the validly-cued target locations. In other words, these individuals may have been ignoring the spatial cue, which further justifies excluding them from the principal analysis.

Error rates

Mean error rates for each trial condition are reported in Table 3. These values were submitted to a 2×3 repeated measures ANOVA with Element (boundaries and targets: meridian crossing, meridian non-crossing) and Trial Condition (invalid-horizontal, and invalid-vertical, and valid) as within-subjects factors. There were no significant main effects or interactions, $Fs < 2$, $ps > .2$, nor any significant pairwise comparisons, $ts < 2$, $ps > .1$, indicating no statistically significant differences in error rates across trial conditions.

Discussion

Similar to our previous published findings (Barnas & Greenberg, 2016), the results from Experiment 1 revealed that shifts of object-based attention across the vertical meridian were significantly faster than shifts across the horizontal meridian. This effect,

Table 3. Mean error rates (percent of misses) in Experiments 1–3B.

	Invalid-horizontal	Trial Condition Invalid-vertical	Valid
Experiment 1			
Crossing Object and Targets	3.79 (0.69)	3.42 (0.58)	3.34 (0.44)
Non-crossing Object and Targets	2.98 (0.62)	4.02 (0.61)	3.47 (0.52)
Experiment 2A			
Crossing Object and Targets	2.16 (0.67)	2.31 (0.71)	1.75 (0.41)
Crossing Object, Non-crossing Targets	1.64 (0.47)	2.31 (0.70)	2.00 (0.51)
Experiment 2B			
Non-crossing Object, Crossing Targets	2.36 (0.50)	2.22 (0.42)	2.15 (0.36)
Non-crossing Object and Targets	1.74 (0.36)	2.36 (0.55)	2.00 (0.37)
Experiment 3A			
Crossing Object and Targets	2.23 (0.44)	1.94 (0.43)	2.06 (0.45)
Non-crossing Object, Crossing Targets	2.60 (0.55)	2.60 (0.59)	2.10 (0.47)
Experiment 3B			
Crossing Object, Non-crossing Targets	2.87 (0.62)	2.37 (0.62)	2.53 (0.43)
Non-crossing Object and Targets	2.73 (0.69)	3.45 (0.70)	2.69 (0.48)
Experiment 4			
Spatial Attention Control	3.63 (0.79)	2.26 (0.44)	2.62 (0.48)

Note. Values in parentheses are *SEM*s.

however, only occurred when the object boundaries and invalid target locations crossed the visual field meridians; horizontal and vertical shifts of attention were allocated with equal efficiency when the object boundaries and invalid target locations did not cross the meridians. Therefore, a significant horizontal advantage SDA was observed for meridian crossings, but not for non-crossings. Because the invalid-horizontal and invalid-vertical target locations were equidistant from the peripheral cue (and located on the same object), current theories of object-based attention would predict that shifts of attention to these targets should be isotropic rather than anisotropic. However, we observed a significant SDA for object/target crossings, suggesting that the performance difference between horizontal and vertical shifts of attention emerges whenever the object and associated invalid target locations cross the meridians. Taken together, these results support our hypothesis that the horizontal advantage SDA depends on object-based attention meridian crossings.

The pattern of performance observed in Experiment 1 suggests that meridian crossings of object-based attention are important factors for the emergence of the SDA. However, it remains unknown whether concurrent crossings of both object boundaries and target locations are necessary for the production of the SDA, or whether one component, alone, is responsible for this effect. Therefore, in subsequent experiments, we individually manipulated the relation between the invalid target locations and the meridians (Experiments 2A and 2B) along with the relation between the object boundaries and the meridians (Experiments 3A and 3B) while, at the same time, holding constant the non-manipulated factor.

Experiments 2A and 2B: Object boundaries constant; invalid target locations vary

The findings from Experiment 1 showed that simultaneous meridian crossings of the object boundaries and invalid target locations result in a significant horizontal advantage SDA. The goal of Experiments 2A and 2B was to assess the specific role of invalid target location on the SDA. We, therefore, held the object boundaries constant (object boundaries *always* crossed the meridians in Experiment 2A, and *never* crossed the meridians in Experiment 2B), but the invalid target locations varied (See Table 1). In Experiment 2B, invalid targets appeared external to the object boundaries. It is, therefore, reasonable to assume that the mode of attentional selection in this case would not be object-based in its purest form. Nevertheless, previous work has investigated the extent to which attention is facilitated in the surround of an object during object-based attentional selection (Greenberg et al., 2015; Kravitz & Behrmann, 2008). Those studies showed that targets external to the boundaries of an attended object received some of the attentional facilitation afforded to targets within the boundaries of the cued object. Thus, it has been suggested that the boundaries of an object slow the spread of the attentional gradient into the surround rather than preventing it from spreading (Hollingworth, Maxcey-Richard, & Vecera, 2012). For the “non-crossing object, crossing targets” configuration, the external targets would still, in theory, benefit from the attentional gradient afforded to the object.

Based on our results from Experiment 1, we hypothesized, for Experiment 2A, that (1) a significant SDA would emerge when both the object boundaries and invalid target locations crossed the meridians and (2) no SDA would emerge when the invalid target locations did not cross the meridians, despite being contained within the boundaries of an object that did cross the meridians. For Experiment 2B, we hypothesized that (1) a significant SDA would emerge when the invalid target locations crossed the meridians, despite appearing while an attended object did not cross the meridians and (2) no SDA would emerge when both the object boundaries and invalid target locations did not cross the meridians. This pattern of performance would suggest that invalid target locations (and not object boundaries) requiring shifts of attention across the visual field meridians are necessary and sufficient for the emergence of the SDA.

Method

Experiment 2A (object boundaries always crossed meridians)

All aspects of Experiment 2A were identical to those of Experiment 1, except as described below.

Participants

Thirty-six new individuals from the University of Wisconsin-Milwaukee and surrounding community ($M_{age} = 21.69$ years, $SD_{age} = 3.11$ years; 30 women, 6 men) participated in this experiment.

Apparatus, stimuli, design, and procedure

On all trials, the "L"-shaped object was composed of a 2.0° x 14.0° vertical component rectangle conjoined at a 90-degree angle with a 14.0° x 2.0° horizontal component rectangle. On half of the trials, the target array consisted of target and non-target letters that were positioned so that their centres were 1.0° from the near end of either component rectangle (See Figure 1A; "Crossing Object and Targets"), while the other half consisted of a target array in which target and non-target letters were positioned so that their centres were 4.33° from the near end of either component rectangle (See Figure 1B; "Crossing Object, Non-crossing Targets"). Crossing and non-crossing target conditions were randomly intermixed within blocks and were equally likely to appear on any given trial.

Experiment 2B (object boundaries never crossed meridians)

All aspects of Experiment 2B were identical to those of Experiment 1, except as described below.

Participants

Thirty-three new individuals from the University of Wisconsin-Milwaukee and surrounding community ($M_{age} = 22.48$ years, $SD_{age} = 9.70$ years; 26 women, 7 men) participated in this experiment.

Apparatus, stimuli, design, and procedure

On all trials, the "L"-shaped object was composed of a 2.0° x 10.65° vertical component rectangle conjoined at a 90-degree angle with a 10.65° x 2.0° horizontal component rectangle. On half of the trials, the target array consisted of target and non-target letters that were positioned so that their centres were 4.33° from the near end of either component rectangle, appearing external to the object (See Figure 1B, "Non-crossing Object, Crossing Targets"), while the other half consisted of a target array in which target and non-target letters were positioned so that their centres were 1.0° from the near end of either component rectangle (See Figure 1B, "Non-crossing Object and Targets"). Crossing and non-crossing target conditions were randomly intermixed within blocks and were equally likely to appear on any given trial.

Results

Experiment 2A

Data quality

The original sample of 36 participants had a mean false alarm rate of 15% ($SD = 17\%$) and a mean miss rate of 3% ($SD = 4\%$). Using the same exclusion criteria from Experiment 1, a total of 8 participants with an excessively high false alarm rate ($n = 8$; $M = 43\%$, $SD = 11\%$) on catch trials and/or number of misses ($n = 1$; $N = 125$ trials) on target-present trials were discarded. This resulted in a final sample of 28 participants ($M_{age} = 21.71$ years, $SD_{age} = 3.29$ years; 25 women, 3 men) with a mean false alarm rate of 7% ($SD = 6\%$) and a mean miss rate of 2% ($SD = 2\%$). An independent samples *t*-test revealed a significantly larger false alarm rate for the excluded participants compared to the included participants, $t(7.99) = 8.54$, $p < .001$, $d = 3.96$. As in Experiment 1, anticipatory responses (RT less than 200 ms) were discarded.

Response latencies

The dependent variable was the mean RT for correct responses, reported in Table 2. As in Experiment 1, mean RT differences were calculated by subtracting mean raw RTs to valid targets from mean RTs to invalid-horizontal targets and invalid-vertical targets. Next, mean RT differences were submitted to a 2×2 repeated measures ANOVA with Element (targets: meridian crossing, meridian non-crossing) and Shift Direction (horizontal, vertical) as within-subjects factors. The analysis revealed a main effect of Element, $F(1,27) = 141.56$, $p < .001$, $\eta_p^2 = .84$, indicating a significant difference in mean RT while reallocating object-based attention to invalid target locations that crossed the meridians ($M = 280.56$ ms, $SEM = 10.65$ ms) versus target locations that did not cross the meridians ($M = 190.37$ ms, $SEM = 17.69$ ms). Furthermore, the analysis revealed a main effect of Shift Direction, $F(1,27) = 9.45$, $p = .005$, $\eta_p^2 = .26$, indicating a significant difference in mean RT when shifting attention horizontally ($M = 217.98$ ms, $SEM = 19.42$ ms) versus vertically ($M = 252.96$ ms, $SEM = 19.96$ ms). These main effects were further qualified by a significant two-way interaction, $F(1,27) = 4.92$, $p = .035$, $\eta_p^2 = .15$.

For invalid target locations that necessitated shifts of attention across the meridians, a paired samples *t*-test revealed a significant SDA, such that reallocating object-based attention horizontally ($M = 255.74$ ms, $SEM = 7.45$ ms) was significantly faster than vertically ($M = 305.38$ ms, $SEM = 7.45$ ms), $t(27) = 3.33$, $p = .003$, $d = 0.43$. However, for invalid target locations that did not necessitate shifts of attention across the meridians, a paired samples *t*-test revealed no SDA, such that horizontal shifts of attention ($M = 180.21$ ms, $SEM = 10.45$ ms) were statistically equivalent to vertical shifts ($M = 200.54$ ms, $SEM = 8.03$ ms), $t(27) = 1.82$, $p = .080$, $d = 0.21$ (see Figure 3). The JZS Bayes Factor was 1.17, suggesting that the null hypothesis was likely to be true. Thus, the interaction between Element and Shift Direction was driven by a significantly larger and positive (i.e., a horizontal advantage) SDA between horizontal and vertical shifts of object-based attention when invalid target locations crossed the meridians (49.64 ms) versus when they did not cross the meridians (20.32 ms).

Mirroring our analysis of Experiment 1, we conducted a parallel ANOVA with all 36 participants from whom data were collected. We observed a similar main effect of Element $F(1,35) = 129.44$, $p < .001$, $\eta_p^2 = .79$, and significant two-way interaction, $F(1,35) = 4.38$, $p = .044$, $\eta_p^2 = .11$. The main effect of Shift Direction was marginally significant, $F(1,35) = 3.45$, $p = .072$, $\eta_p^2 = .09$.

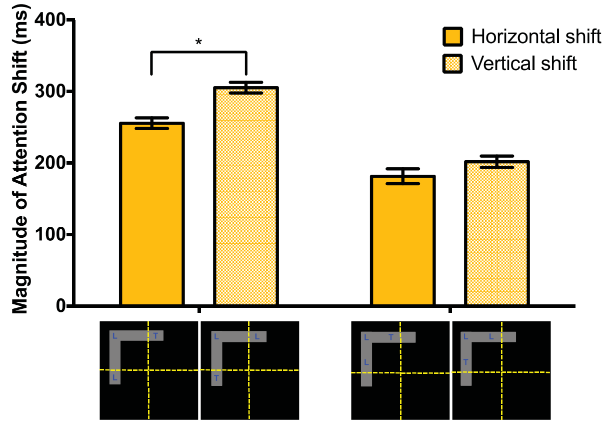

Figure 3. Mean response latencies in Experiment 2A (object boundaries always crossed meridians). "Magnitude of Attention Shift" measured for the Element (Targets) x Shift Direction interaction in Experiment 2A. The error bars represent the standard error of the mean for within-subjects design.

Error rates

Mean error rates for each trial condition are reported in Table 3. As in Experiment 1, these values were submitted to a 2×3 repeated measures ANOVA with Element (targets: meridian crossing, meridian non-crossing) and Trial Condition (invalid-horizontal, and invalid-vertical, and valid) as within-subjects factors. There were no significant main effects or interactions, $Fs < 2$, $ps > .2$, nor any significant pairwise comparisons, $ts < 2$, $ps > .2$, indicating no statistically significant differences in error rates across trial conditions.

Experiment 2B

Data quality

The original sample of 33 participants had a mean false alarm rate of 10% ($SD = 9\%$) and a mean miss rate of 3% ($SD = 4\%$). Using the same exclusion criteria from Experiment 1, a total of 3 participants with an excessively high false alarm rate ($n = 2$; $M = 32\%$, $SD = 6\%$) on catch trials and/or miss rate ($n = 2$; $M = 16\%$, $SD = 4\%$) on target-present trials were discarded. This resulted in a final sample of 30 participants ($M_{age} = 22.87$ years, $SD_{age} = 10.11$ years; 24 women, 6 men) with a mean false alarm rate of 8% ($SD = 7\%$) and a mean miss rate of 2% ($SD = 2\%$). Independent samples *t*-tests revealed no significant differences in false alarm rates, $t(1.20) = 5.05$, $p = .094$, $d = 3.39$, or miss rates, $t(1.04), = 5.25$, $p = .113$, $d = 4.70$, between the excluded and included participants. Again, anticipatory responses (less than 200 ms) were discarded.

Response latencies

The dependent variable was the mean RT for correct responses, reported in Table 2. Again, mean RT differences were calculated by subtracting mean raw RTs to valid targets from mean RTs to targets in the invalid-horizontal location and invalid-vertical location. Next, mean RT differences were submitted to a 2×2 repeated measures ANOVA with Element (targets: meridian crossing, meridian non-crossing) and Shift Direction (horizontal, vertical) as within-subjects factors. The analysis revealed a main effect of Element, $F(1,29) = 148.66$, $p < .001$, $\eta_p^2 = .84$, indicating a significant difference in invalid target detection RT while reallocating object-based attention to invalid target locations that crossed the meridians (M = 342.19 ms, SEM = 20.58 ms) versus locations that did not cross the meridians (M = 198.32 ms, SEM = 17.07 ms). The main effect of Shift Direction, however, was not significant, $F(1,29) = 0.86$, $p = .361$, $\eta_p^2 = .03$, indicating no significant difference in RT when shifting horizontally (M = 275.29 ms, SEM = 18.49 ms) versus vertically (M = 265.22 ms, SEM = 19.02 ms). Furthermore, the analysis revealed a significant two-way interaction, $F(1,29) = 14.73$, $p = .001$, $\eta_p^2 = .34$.

For invalid target locations that necessitated shifts of attention across the meridians, a paired samples t-test revealed a significant SDA such that reallocating object-based attention vertically (M = 322.12 ms, SEM = 7.03 ms) was significantly faster than horizontally (M = 362.26 ms, SEM = 7.03 ms), $t(29) = 2.85$, $p = .008$, $d = 0.34$. However, for invalid target locations that did not necessitate shifts of attention across the meridians, a paired samples t-test revealed no SDA, such that horizontal shifts of attention (M = 188.32 ms, SEM = 13.60 ms) were statistically equivalent to vertical shifts (M = 208.33 ms, SEM = 13.15 ms), $t(29) = 1.58$, $p = .124$, $d = 0.20$ (See Figure 4). The JZS Bayes Factor was 1.69, in favour of the null hypothesis. Thus, the interaction between Element and Shift Direction was driven by a significantly larger and negative (a vertical advantage) SDA between horizontal and vertical shifts of object-based attention when invalid target locations crossed the meridians (40.14 ms) versus when locations did not cross the meridians (20.01 ms).

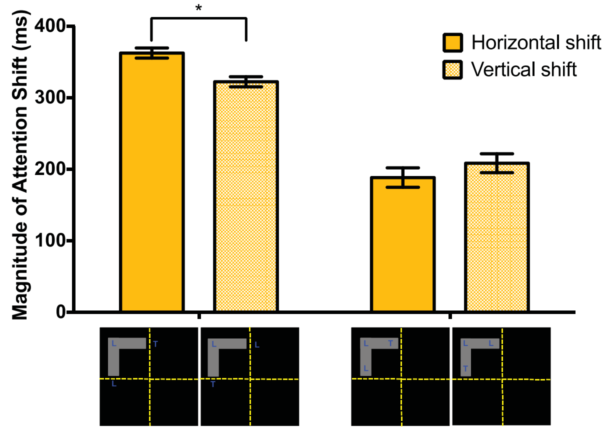

Figure 4. Mean response latencies in Experiment 2B (object boundaries never crossed meridians). "Magnitude of Attention Shift" measured for the Element (Targets) x Shift Direction interaction in Experiment 2B. The error bars represent the standard error of the mean for within-subjects design.

When including all 33 participants, we observed a similar main effect of Element, $F(1,32) = 110.16$, $p < .001$, $\eta_p^2 = .78$, and a significant two-way interaction, $F(1,32) = 15.68$, $p < .001$, $\eta_p^2 = .33$. No main effect of Shift Direction was observed, $F(1,32) = 2.71$, $p = .110$, $\eta_p^2 = .08$.

Expected vs. measured response latencies

A likely explanation for the negative SDA we observed in Experiment 2B may be the lack of target-object integration (cf. Al-Janabi & Greenberg, 2016). Strong target-object integration occurs when invalid targets are located within the boundaries of an attended object, whereas weak target-object integration occurs when invalid targets are located outside the boundaries of an attended object. When targets are weakly integrated with the object, participants must disengage attentional resources from the attended object and subsequently reallocate attention outside object boundaries (cf. Brown & Denny, 2007). We hypothesized that weak target-object integration, coupled with disengaging and re-engaging attentional resources, resulted in the vertical advantage SDA observed in this experiment. Following the method outlined in Barnas and Greenberg (2016), we used RTs to invalid target locations that were located inside the boundaries of the cued non-crossing object to calculate the *expected* mean RTs to invalid target locations that were located external (across the meridians) to the non-crossing object. This allowed us to compare measured vs. expected

RTs and, thus, determine whether or not target-object integration modulates the direction of the SDA. To accomplish this, we first calculated the average shift velocity (time/distance) from the valid target location to the invalid target locations within the non-crossing object, and then applied these velocity measures to predict the expected mean RTs to the invalid target locations outside of the object. This allowed us to compare whether the velocity of the attention shift was affected by the disengagement and re-engagement of attention due to weak target-object integration. That is, if the expected RT for the external invalid targets matched the measured RT, then participants were unaffected by weakly integrated targets and object (targets appearing outside the boundaries of the object). However, if the expected RT was significantly different from the measured RT for the external invalid targets, then we can postulate that participants were, indeed, affected by target-object integration. Significantly different expected and measured RTs would ultimately indicate that the visual field meridians and target-object integration modulate the magnitude and direction of the SDA.

The result of a one-sample *t*-test showed that measured attention shifts to the invalid target locations outside of the object (weak target-object integration; $M_{measured} = 342.19$ ms) were significantly slower than expected by the velocity to the invalid target locations inside the object (strong target-object integration; $M_{expected} = 260.70$ ms), $t(29) = 3.70$, $p < .001$. In order to ensure that this is truly an effect of weak target-object integration, we performed the same calculation on the data from Experiment 2A, in which all targets appeared within an object and, thus, were strongly integrated. No significant differences emerged between these measured and expected RTs ($M_{measured} = 280.56$ ms, $M_{expected} = 250.25$ ms; $t(27) = 1.47$, $p = .154$).

Error rates

Mean error rates for each trial condition are reported in Table 3. Again, these values were submitted to a 2×3 repeated measures ANOVA with Element (targets: meridian crossing, meridian non-crossing) and Trial Condition (invalid-horizontal, and invalid-vertical, and valid) as within-subjects factors. There were no significant main effects or interactions, $Fs < 1$, $ps > .4$, nor any significant pairwise comparisons, $ts < 2$, $ps > .1$, indicating no statistically significant differences in error rates across trial conditions.

Discussion

Similar to results from Experiment 1, we observed a significant SDA between horizontal and vertical shifts of object-based attention that crossed the meridians. Although the SDA was significant when targets were located across the meridians, the sign of the SDA varied with the object boundary condition. Specifically, the SDA was positive (i.e., a horizontal advantage) when the object boundaries crossed the meridians; but the SDA was negative (i.e., a vertical advantage) when the object boundaries did not cross the meridians. To our knowledge, this is the first observation of a negative SDA. Additionally, when the invalid target locations did not cross the visual field meridians (in this case, regardless of whether or not the object boundaries crossed the meridians) we observed no significant difference between horizontal and vertical shifts. Thus, we seem to have produced some initial evidence that, when object-based shifts of attention cross the visual field meridians, target locations (and not object boundaries) drive observation of the SDA. That is to say, the anisotropy between horizontal and vertical shifts depends on targets located across the meridians, without regard to object boundary locations.

However, there is one additional point of interest that compels comment. We believe that the vertical advantage SDA is more related to target-object integration and the mode of attentional selection rather than a feature of visual field meridian crossings. In an object cueing paradigm such as this, the representational basis of attentional selection is object-based (Kahneman & Henik, 1981), meaning that greater attentional priority is afforded to locations within the cued object than locations outside the cued object. Evidence from our lab (and others) suggests that, during object-based selection, targets appearing outside the cued object require a considerable effort for attention to shift to that off-object location (cf. Greenberg et al., 2015). In fact, one could argue that this situation would no longer make use of object-based selection mechanisms, at all; instead, using spatial attention to identify and shift to the off-object target. Here, when targets appeared outside the object boundaries we, therefore, argue that targets and object were weakly integrated and selection was no longer object-based, which caused an unusual pattern of RTs (i.e., a vertical advantage SDA) possibly due to a momentary loss of attentional control (Greenberg & Gmeindl, 2008). Further evidence in support of this claim was observed in our analysis of expected versus measured latencies based on shift velocity. Measured RTs were significantly different than expected RTs for invalid targets that crossed the meridians when located outside the boundaries of the object. However, measured RTs were not significantly different than expected RTs for targets that crossed the meridians while located inside the boundaries of the object. In the former case (targets located outside object boundaries) attention had to disengage from the object before locating the target, causing a sizeable slowing of velocity. No such change in velocity was observed in the latter case (targets located inside object boundaries). We conclude that when targets are located outside object boundaries, it illustrates a special case that is no longer of direct relevance to the efficiency of object-based attentional selection for horizontal vs. vertical shifts (which is the goal of the current study).

Taken together, these results support our hypothesis that a significant SDA emerges when target locations necessitate a shift of attention that crosses the meridians, regardless of whether or not the object boundaries cross the meridians.

Experiments 3A and 3B: Invalid target locations constant; object boundaries vary

The findings from Experiments 2A and 2B showed that invalid target locations that necessitate shifts of attention across the visual field meridians are necessary for the emergence of the SDA; but we still wondered whether this was sufficient for observing the anisotropy. Having established the influence of the invalid target locations on the SDA, the goal of Experiments 3A and 3B was to assess the role of object boundaries on the SDA. We, therefore, held the invalid target locations constant (target locations *always* crossed the meridians in Experiment 3A, and *never* crossed the meridians in Experiment 3B), but the object boundaries varied (See Table 1). Based on our results from Experiments 1 & 2, we hypothesized, for Experiment 3A, that a significant SDA would emerge when the invalid target locations crossed the meridians, regardless of object position; however, for Experiment 3B, we hypothesized that no SDA would emerge when the invalid target locations did not cross the meridians, regardless of object position. This pattern of performance would suggest that, when controlling for target location, whether or not object boundaries cross the visual field meridians does not alter the emergence of the SDA.

Method

Experiment 3A (target locations always crossed meridians)

All aspects of Experiment 3A were identical to those of Experiment 1, except as described below.

Participants

Thirty-three new individuals from the University of Wisconsin-Milwaukee and surrounding community (M_{age} = 20.15 years, SD_{age} = 2.08 years; 28 women, 5 men) participated in this experiment.

Apparatus, stimuli, design, and procedure

On half of the trials, the target array consisted of target and non-target letters that were positioned so that their centres were 1.0° from the near end of either component rectangle (See Figure 1A, "Crossing Object and Targets"), while the other half consisted of a target array in which target and non-target letters were positioned so that their centres were 4.33° from the near end of either component rectangle, appearing off the object (See Figure 1B, "Non-crossing Object, Crossing Targets"). Crossing and non-crossing object conditions were randomly intermixed within blocks and were equally likely to appear on any given trial.

Experiment 3B (target locations never crossed meridians)

All aspects of Experiment 3B were identical to those of Experiment 1, except as described below.

Participants

Thirty-nine new individuals from the University of Wisconsin-Milwaukee and surrounding community (M_{age} = 21.26 years, SD_{age} = 2.55 years; 27 women, 12 men) participated in this experiment.

Apparatus, stimuli, design, and procedure

On half of the trials, the target array consisted of target and non-target letters that were positioned so that their centres were 4.33° from the near end of either component rectangle (See Figure 1B, "Crossing Object, Non-crossing Targets"), while the other half consisted of a target array in which target and non-target letters were positioned so that their centres were 1.0° from the near end of either component rectangle (See Figure 1B, "Non-crossing Object and Targets"). Crossing and non-crossing object conditions were randomly intermixed within blocks and were equally likely to appear on any given trial.

Results

Experiment 3A

Data quality

The original sample of 33 participants had a mean false alarm rate of 13% ($SD = 13\%$) and a mean miss rate of 4% ($SD = 5\%$). Using the same exclusion criteria from Experiment 1, a total of 5 participants with an extremely high false alarm rate ($n = 4$; $M = 39\%$, $SD = 14\%$) on catch trials and/or miss rate ($n = 3$; $M = 17\%$, $SD = 3\%$) on target-present trials were discarded. This resulted in a final sample of 28 participants ($M_{age} = 20.43$ years, $SD_{age} = 2.13$ years; 24 women, 4 men) with a mean false alarm rate of 8% ($SD = 5\%$) and a mean miss rate of 2% ($SD = 2\%$). Independent samples *t*-tests revealed a significantly larger false alarm rate, $t(3,16) = 5.18$, $p = .012$, $d = 3.41$, and miss rate, $t(2.22), = 7.94$, $p = .011$, $d = 5.44$, for the excluded participants compared to the included participants. Additionally, anticipatory responses (RT less than 200 ms) were discarded.

Response latencies

The dependent variable was the mean RT for correct responses, reported in Table 2. As in Experiment 1, mean RT differences were calculated by subtracting mean raw RTs to valid targets from mean RTs to targets in the invalid-horizontal location and invalid-vertical location. Next, mean RT differences were submitted to a 2 × 2 repeated measures ANOVA with Element (boundaries: meridian crossing, meridian non-crossing) and Shift Direction (horizontal, vertical) as within-subject factors. The analysis revealed a main effect of Element, $F(1,27) = 37.35$, $p < .001$, $\eta_p^2 = .58$, indicating a significant difference in invalid target detection RT while reallocating object-based attention to invalid targets inside objects that crossed the meridians ($M = 294.68$ ms, $SEM = 16.10$ ms) versus targets outside objects that did not cross the meridians ($M = 351.07$ ms, $SEM = 15.94$ ms). The main effect of Shift Direction, however, was not significant, $F(1,27) = 0.07$, $p = .789$, $\eta_p^2 = .003$, indicating no significant difference in invalid target detection RT when reallocating object-based attention horizontally ($M = 324.12$ ms, $SEM = 17.35$ ms) versus vertically ($M = 321.64$ ms, $SEM = 14.57$ ms). Furthermore, the analysis revealed a significant two-way interaction, $F(1,27) = 65.10$, $p < .001$, $\eta_p^2 = .71$.

For objects whose boundaries crossed the meridians, a paired samples *t*-test revealed a significant SDA such that reallocating object-based attention horizontally ($M = 263.72$ ms, $SEM = 6.34$ ms) was significantly faster than vertically ($M = 325.64$ ms, $SEM = 6.34$ ms), $t(27) = 4.89$, $p < .001$, $d = 0.68$. Additionally, when object boundaries did not cross the meridians, a paired samples *t*-test revealed a significant SDA such that reallocating object-based attention vertically ($M = 317.63$ ms, $SEM = 9.69$ ms) was significantly faster than horizontally ($M = 384.51$ ms, $SEM = 11.81$ ms), $t(27) = 5.73$, $p < .001$, $d = 0.74$ (See Figure 5). Thus, the interaction between Element and Shift Direction was driven by SDAs of opposite sign. A significant positive (i.e., horizontal advantage) SDA was observed when targets appeared at locations inside the boundaries

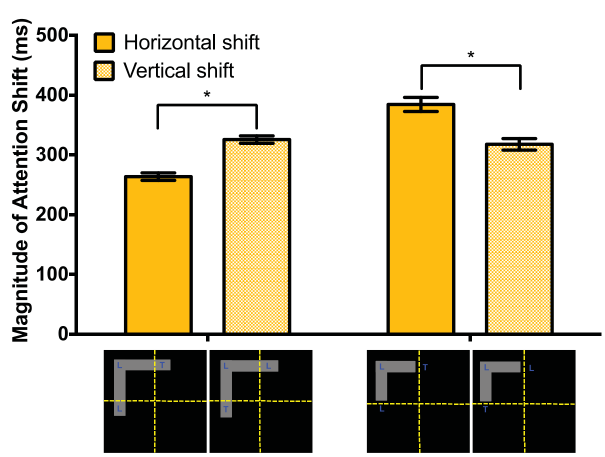

Figure 5. Mean response latencies in Experiment 3A (target locations always crossed meridians). "Magnitude of Attention Shift" measured for the Element (Boundaries) x Shift Direction interaction in Experiment 3A. The error bars represent the standard error of the mean for within-subjects design.

of an object that crossed the meridians (61.91 ms) and a significant negative (i.e., vertical advantage) SDA was observed when invalid target locations appeared outside the boundaries of an object that did not cross the meridians (66.88 ms).

When all 33 participants were included, we observed a similar main effect of Element, $F(1,32) = 28.64$, $p < .001$, $\eta_p^2 = .47$, and a significant two-way interaction, $F(1,32) = 51.25$, $p < .001$, $\eta_p^2 = .62$. No main effect of Shift Direction was observed, $F(1,32) = 0.55$, $p = .462$, $\eta_p^2 = .02$.

Error rates

Mean error rates for each trial condition are reported in Table 3. As in Experiment 1, these values were submitted to a 2 × 3 repeated measures ANOVA with Element (boundaries: meridian crossing, meridian non-crossing) and Trial Condition (invalid-horizontal, and invalid-vertical, and valid) as within-subjects factors. There were no significant main effects or interactions, *F*s < 3, *p*s > .1, nor any significant pairwise comparisons, *t*s < 2, *p*s > .1, indicating no statistically significant differences in error rates across trial conditions.

Experiment 3B

Data quality

The original sample of 39 participants had a mean false alarm rate of 16% ($SD = 16\%$) and a mean miss rate of 5% ($SD = 8\%$). Using the same exclusion criteria from Experiment 1, a total of 10 participants with an extremely high false alarm rate ($n = 10$; $M = 41\%$, $SD = 10\%$) on catch trials and/or miss rate ($n = 3$; $M = 31\%$, $SD = 6\%$) on target-present trials were discarded. This resulted in a final sample of 29 participants ($M_{age} = 21.38$ years, $SD_{age} = 2.66$ years; 21 women, 8 men) with a mean false alarm rate of 8% ($SD = 6\%$) and a mean miss rate of 3% ($SD = 2\%$). Independent samples *t*-tests revealed a significantly larger false alarm rate, $t(11.09) = 10.01$, $p < .001$, $d = 4.10$, and miss rate, $t(2.07), = 8.05$, $p = .014$, $d = 6.16$, for the excluded participants compared to the included participants. Again, anticipatory responses (RT less than 200 ms) were discarded.

Response latencies

The dependent variable was the mean RT for correct responses, reported in Table 2. Again, mean RT differences were calculated by subtracting mean raw RTs to valid targets from mean RTs to targets in the invalid-horizontal location and invalid-vertical location. Next, mean RT differences were submitted to a 2 × 2 repeated measures ANOVA with Element (boundaries: meridian crossing, meridian non-crossing) and Shift Direction (horizontal, vertical) as within-subject factors. The analysis revealed a main effect of Element, $F(1,28) = 11.44$, $p = .002$, $\eta_p^2 = .29$, indicating a significant difference in invalid target detection RT while reallocating object-based attention to invalid targets within objects that crossed the meridians ($M = 139.28$ ms, $SEM = 14.40$ ms) versus targets within objects that did not cross the meridians ($M = 162.01$ ms, $SEM = 12.59$ ms). Neither the main effect of Shift Direction and the two-way interaction did not reach significance, *p*s > .1.

Paired samples *t*-tests revealed no SDA for each condition, such that horizontal shifts of object-based attention were statistically equivalent to vertical shifts when the boundaries of the object crossed the meridians ($M = 140.85$ ms, $SEM = 5.70$ and 137.70 ms, $SEM = 5.70$ ms, respectively), $t(28) = 0.28$, $p = .781$, $d = 0.04$, as well as when the boundaries of the object did not cross the meridians ($M = 156.20$ ms, $SEM = 8.02$ and 167.82 ms, $SEM = 7.72$ ms, respectively), $t(28) = 1.52$, $p = .140$, $d = 0.16$ (See Figure 6). The JZS Bayes Factors were 4.89 and 1.81, respectively, suggesting that the null hypothesis was likely to be true in both conditions. Thus, there was no significant SDA when the boundaries of the object crossed (3.14 ms) or did not cross (11.62 ms) the meridians.

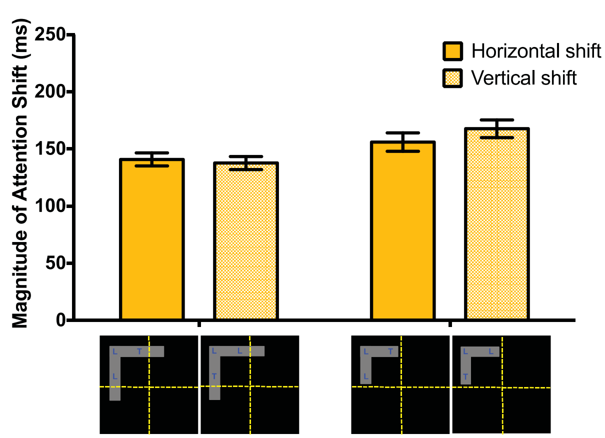

Figure 6. Mean response latencies in Experiment 3B (target locations never crossed meridians). "Magnitude of Attention Shift" measured for the Element (Boundaries) x Shift Direction interaction in Experiment 3B. The error bars represent the standard error of the mean for within-subjects design.

When all 39 participants were included, we observed a similar main effect of Element, $F(1,38) = 17.13$, $p < .001$, $\eta_p^2 = .31$. Neither the main effect of Shift Direction, $F(1,38) = 0.43$, $p = 518$, $\eta_p^2 = .01$, nor the two-way interaction, $F(1,38) = 2.46$, $p = .125$, $\eta_p^2 = .06$, were observed.

Error rates

Mean error rates for each trial condition are reported in Table 3. Again, these values were submitted to a 2 × 3 repeated measures ANOVA with Element (boundaries: meridian crossing, meridian non-crossing) and Trial Condition (invalid-horizontal, and invalid-vertical, and valid) as within-subjects factors. There were no significant main effects or interactions, *F*s < 2, *p*s > .2, nor any significant pairwise comparisons, *t*s < 2, *p*s > .05, indicating no statistically significant differences in error rates across trial conditions.

Discussion

In agreement with our previous results, disparities between RTs to detect targets at invalid-horizontal and invalid-vertical locations were observed when target locations necessitated shifts of attention across the visual field meridians, regardless of object boundary placement. As observed in Experiment 2, a horizontal advantage SDA emerged when targets appeared within object boundaries, whereas a vertical advantage SDA emerged when targets appeared outside object boundaries. We argue that this vertical advantage SDA emerges when participants must disengage from object-based selection and re-engage a non-object-based mode of selection due to weakened integration of the targets and object (see Experiment 2 Discussion). There were no significant differences between horizontal and vertical shifts of attention when target locations did not cross the visual field meridians, regardless of object placement.

These findings support our hypotheses that the SDA emerges when invalid target locations, independent of the placement of object boundaries, necessitate shifts of attention across the meridians, and does not emerge when target locations do not necessitate a shift across the meridians. Taken together, the results from Experiments 1–3 suggest that the boundaries of an object in relation to the visual field meridians are not a contributing factor in the emergence of the SDA.

Experiment 4: Spatial attention control

Throughout this manuscript, we report an asymmetry between horizontal and vertical shifts of object-based attention: the object-based attention SDA. The paradigm that we utilized in the above experiments differs from more "traditional" object-based attention paradigms in two ways. First, we were only interested in measuring the asymmetry between horizontal and vertical shifts of object-based attention (without the confound of shifting between objects) as opposed to the same object advantage that is typically measured in object-based attention paradigms. Second, we presented participants with only one object, rather than two objects, making it possible that few object-based attentional resources were necessary to perform the task. We previously demonstrated, however, that the SDA emerged when competition for object-based attentional selection was low (such as with only a single "L"-shaped object) as well as when competition for object-based attentional selection was high (such as with both cued and non-cued "L"-shaped objects; Barnas & Greenberg, 2016). Nevertheless, one might question whether the performance differences observed in the above experiments arise truly as a result of object-based attention. In order to address this issue, we performed a control experiment in which the "L"-shaped object was removed entirely from the paradigm, allowing us to determine whether or not the SDA is an effect of object-based attentional selection, at all. If we observe the SDA in the absence of the "L"-shaped object, then we can infer that the performance difference between horizontal and vertical shifts of attention is caused (at least, partially) by something other than object-based attention (since only spatial attention mechanisms should be engaged in this experiment). Conversely, if we fail to observe an SDA in the absence of the "L"-shaped object, then we can infer that the performance difference between horizontal and vertical shifts depends on object-based attention.

Method

All aspects of Experiment 4 were identical to those of Experiment 1, except as described below.

Participants

Thirty-one new individuals from the University of Wisconsin-Milwaukee and surrounding community

($M_{age} = 20.35$ years, $SD_{age} = 2.07$ years; 27 women, 4 men) participated in this experiment.

Apparatus, stimuli, design, and procedure

The "L"-shaped object was not presented during this experiment. On all trials, target and non-target letters were positioned so that their centres were 1.67° above or below the horizontal meridian and 1.67° to the left or to the right of the vertical meridian, depending on the location of cue (See Figure 7). Invalid-horizontal and invalid-vertical targets were equidistant from the peripheral cue.

Results

Data quality

The original sample of 31 participants had a mean false alarm rate of 10% ($SD = 14\%$) and a mean miss rate of 3% ($SD = 4\%$). Using the same exclusion criteria from Experiment 1, a total of 2 participants with an excessively high false alarm rate ($n = 2$; $M = 54\%$, $SD = 29\%$) on catch trials and/or number of misses ($N = 150$ trials) on target-present trials were discarded. This resulted in a final sample of 29 participants ($M_{age} = 20.10$ years, $SD_{age} = 1.82$ years; 26 women, 3 men) with a mean false alarm rate of 7% ($SD = 6\%$) and a mean miss rate of 3% ($SD = 3\%$). An independent samples t-test revealed no difference in the false alarm rates between the excluded and included participants, $t(1.01) = 2.29$, $p = .261$, $d = 2.25$. Additionally, anticipatory responses (RT less than 200 ms) were discarded.

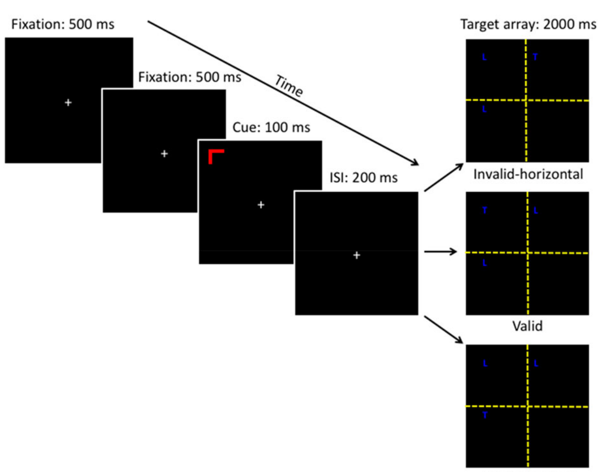

Figure 7. Trial sequence for Experiment 4 (Spatial Attention Control). Invalid target locations cross the visual field meridians with no object present. Trial conditions were defined by the location of the blue target "T" in relation to the red peripheral cue in the upper-left quadrant. *Note*: Locations of invalid targets in relation to the visual field meridians are not drawn to scale; dotted yellow lines represent the horizontal and vertical meridians and were not visible to participants during the experiment.

Response latencies

The dependent variable was the mean RT for correct responses, reported in Table 2. Mean RT differences were calculated by subtracting the mean raw RT to valid targets from mean RTs to targets in the invalid-horizontal location and invalid-vertical location, separately. Next, mean RT differences were submitted to a within-subjects, repeated measures ANOVA with Shift Direction (horizontal, vertical) as a single factor. The effect of Shift Direction was not significant, $F(1,28) = 2.20$, $p = .149$, $\eta_p^2 = .07$, indicating that detection RTs for invalid-horizontal targets ($M = 281.87$ ms, $SEM = 15.39$ ms) were statistically equivalent to detection RTs for invalid-vertical targets ($M = 296.71$ ms, $SEM = 15.79$ ms; See Figure 8). The JZS Bayes Factor was 1.90, in favour of the null hypothesis.

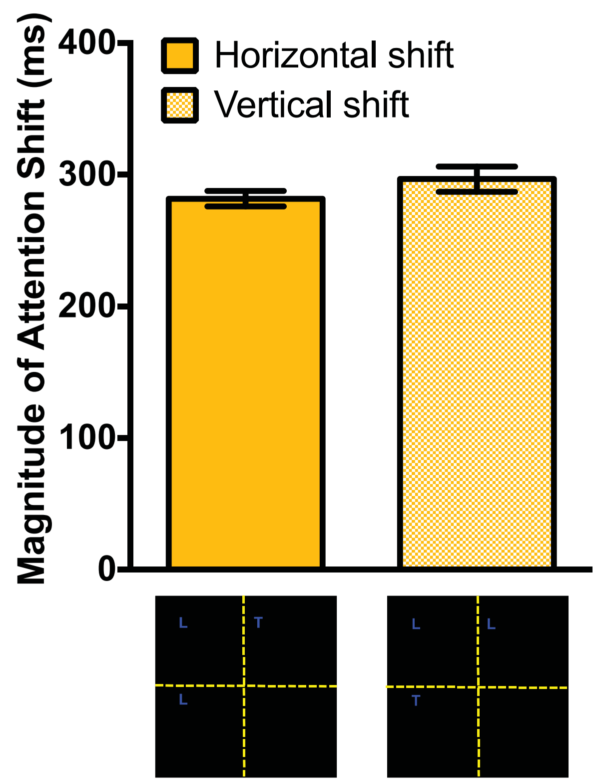

Figure 8. Mean response latencies in Experiment 4 (Spatial Attention Control). "Magnitude of Attention Shift" measured for the Shift Direction effect in Experiment 4. The error bars represent the standard error of the mean for within-subjects design.

Between-experiment analysis

To further bolster our claim that the SDA is an effect specific to object-based selection, we conducted a between-experiment analysis using these data and aggregated data from the crossing object and targets configuration (See Aggregated Analyses below) to examine the interaction between object presence and shift direction. The main difference between these two experiments was object presence – the object was present in the aggregated data and absent in the spatial control data. Mean RT differences were submitted to a 2×2 repeated measures ANOVA with Shift Direction (horizontal, vertical) as a within-subjects factor and Object Presence (present, absent) as a between-subjects factor. The analysis revealed a significant two-way interaction, $F(1,111) = 6.07$, $p < .015$, $\eta_p^2 = .05$, indicating that the magnitude of the SDA varied as a function of whether the object was present (52.76 ms) or absent (14.85 ms).

Error rates

Mean error rates for each trial condition are reported in Table 3. These values were submitted to a within-subjects, repeated measures ANOVA with Trial Condition (valid, invalid-horizontal, invalid-vertical) as a single factor. Results revealed a significant effect of Trial Condition, $F(2,56) = 4.28$, $p = .019$, $\eta_p^2 = .13$. Pairwise comparisons revealed a significantly greater error rate for invalid-horizontal trials compared to invalid-vertical trials, $t(28) = 2.42$, $p = .022$, $d = 0.40$. However, correlating error rates and RTs for each trial condition revealed significant, positive correlations, $r\text{s} > .4$, $p\text{s} < .02$, revealing the absence of a speed-accuracy trade-off.

Discussion

In this control experiment, in the absence of an object percept, we failed to observe a SDA. This result, coupled with our findings from the previous experiments herein, suggests that the SDA observed in the presence of an object percept is dependent on an object-based mode of attentional selection and cannot simply be explained by spatial selective attention.

Nevertheless, some studies have observed anisotropic shifts of attention in the absence of objects. For instance, Pauszek and Gibson (2016) used a search task in which letters could appear along one of the four cardinal axes. When participants were cued with endogenous, informative spatial words at central fixation, the researchers observed faster performance when the target appeared on the horizontal meridian than when it appeared on the vertical meridian. A number of differences between the present experiment and the study reported by Pauszek and Gibson (2016) could account for the observed discrepancy (e.g., cue-type and target locations). Importantly, though, the present experiment replicates at least one published report showing no direction-based differences in a similar spatial attention paradigm (Henderson & Macquistan, 1993). Similar to our experiment, Henderson and Macquistan (1993; Experiment 3) utilized target locations that were displayed at the corners of an imaginary square centred around a central fixation cross and arranged so that one location appeared in each visual field quadrant. When participants were exogenously cued to a possible target location, they were equally fast reallocating attention horizontally and vertically.

Aggregated analyses

While the results of each individual experiment stand on their own, we aggregated the data from the current experiments to examine whether the SDA occurs only under conditions of meridian crossings. We compared the magnitudes of the SDAs among each object-target configuration across Experiments 1–3B. Four separate univariate ANOVAs (one for each configuration) confirmed there were no significant differences in SDA magnitude across experiments, $F\text{s} < 3$, $p\text{s} > .1$; therefore, we collapsed across experiment and calculated a mean SDA magnitude for each configuration. The results of one-sample *t*-tests revealed a significant horizontal advantage SDA for the Crossing Object and Targets configuration ($M = 52.76$ ms, $SEM = 8.34$ ms), $t(83) = 6.32$, $p < .001$, and a significant vertical advantage SDA for the Non-crossing Object, Crossing Targets configuration ($M = 53.05$ ms, $SEM = 9.29$ ms), $t(57) = 5.71$, $p < .001$. The JZS Bayes Factor values for these two configurations (> 30) provided overwhelmingly strong support in favour of the alternative hypothesis. The SDAs for the Non-crossing Object and Targets configuration ($M = 15.66$ ms, $SEM = 11.85$ ms) and the Crossing Object, Non-crossing Targets configuration ($M = 8.38$ ms, $SEM = 7.99$ ms) were not significant, $t\text{s} < 2$, $p\text{s} > .1$, with JZS Bayes Factor values favouring the null hypothesis.

General discussion

Previous research using the double-rectangle cueing paradigm (Egly et al., 1994) has shown that the preferential processing of visual information as a result of object-based attentional selection can differ with the orientation of the two rectangles. A same object advantage (i.e., faster RTs to invalid target locations on a cued object versus a non-cued object) is frequently reported for horizontal objects, whereas a same object cost (i.e., slower RTs to invalid locations on a cued object versus a non-cued object) has been reported for vertical objects (Al-Janabi & Greenberg, 2016; Conci & Müller, 2009; Harrison & Feldman, 2009; Hein, Blaschke, & Rolke, 2016; Pilz et al., 2012). Our work previously investigated this dissociation by comparing the reallocation of object-based attention across the horizontal versus vertical meridian using a single "L"-shaped object (Barnas & Greenberg, 2016). We observed a shift direction anisotropy (SDA), in that shifts of object-based attention within a cued object were more efficient across the vertical meridian (a horizontal shift advantage) suggesting that an object's position within the visual field may be an important factor in the emergence of the horizontal advantage SDA.

In this study, we asked whether the disparity between horizontal and vertical shifts of object-based attention caused by the visual field meridians depends upon the placement of the object boundaries, locations of the invalid targets, or both. This was accomplished by juxtaposing meridian crossings of object boundaries and invalid target locations while measuring the anisotropy between horizontal and vertical shifts of attention. The results of all six experiments are summarized in Figure 9.

In Experiment 1, we replicated our previous results (Barnas & Greenberg, 2016): the SDA emerged when both the object boundaries and invalid target locations crossed the meridians but not when object boundaries and invalid target locations did not cross the meridians. In Experiments 2A and 2B, we held constant the placement of object boundaries which allowed us to assess the role of the invalid target locations on the SDA. When invalid target locations crossed the meridians, we observed a significant SDA; when target locations did not cross the meridians, we did not observe the SDA. Thus, when target locations necessitate a shift of attention that

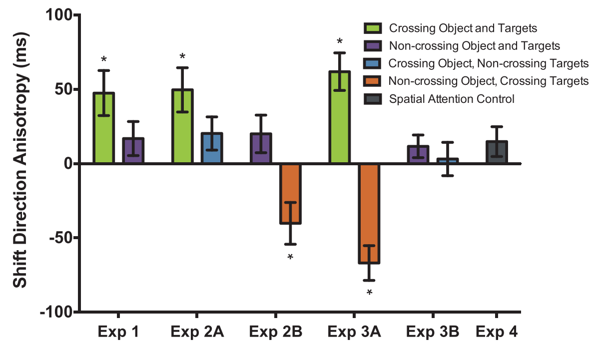

Figure 9. Shift direction anisotropies across Experiments 1–4. Shift direction anisotropies were calculated by subtracting RT difference for invalid-horizontal target location from RT difference for invalid vertical target location. Positive values indicate a horizontal shift advantage (invalid-horizontal RT < invalid-vertical RT), whereas negative values indicate a vertical shift advantage (invalid-vertical RT < invalid-horizontal RT). The error bars represent the standard error of the mean for within-subjects designs. Asterisks indicate significant shift direction anisotropies (significant difference from zero; all $ps \leq .008$).

crosses the meridians, the anisotropy emerges, regardless of whether or not the object boundaries cross the meridians. To further explore the role of object boundaries on the SDA, in Experiments 3A and 3B we held constant the invalid target locations. Again we found that when target locations required a shift across the meridians, we observed the SDA; and that when targets did not evoke a shift across the meridians, we did not observe the SDA. Importantly, as in Experiment 2, the locations of object boundaries (extending across the meridians or not) did not seem to play a role in the SDA. Finally, in Experiment 4, the object was removed from the stimulus in order to determine whether or not the SDA is, explicitly, a characteristic of object-based attentional selection. We observed no SDA in the absence of an object, suggesting that the SDA is specific to object-based attentional selection.

Notably, Experiments 2B & 3A contained a condition during which the target was not located within object boundaries; in both cases, the target location crossed the meridians but the object boundaries did not. Commensurate with target location driving the SDA, we observed significant anisotropies between horizontal and vertical shifts, however the sign of these effects was reversed (i.e., a vertical advantage SDA). This provides additional evidence that target-object integration also plays a modulatory role in object-based attention, as we've previously reported (Al-Janabi & Greenberg, 2016). In summary, these findings demonstrate that the SDA is (1) driven by target locations that require a shift of attention across the visual field meridians, (2) a phenomenon of object-based attentional selection (and not a more general measure observable when selection is not object-based), and (3) affected by target-object integration.

The pattern of performance we observed for targets within the boundaries of an object is consistent with the attentional prioritization hypothesis of object-based attentional selection as opposed to, for instance, the sensory enhancement (or, attentional spreading) hypothesis. The former theory proposes that object-based attentional prioritization is distributed to behaviourally relevant (e.g., target) locations within an object and not simply spread equally throughout all locations on that object (Shomstein & Behrmann, 2008; Shomstein & Yantis, 2002, 2004). The latter theory proposes an automatic spread of OBA resources within an attended object, such that all target locations within an object are afforded an enhancement of attentional processing (Chen & Cave, 2006, 2008; Richard et al., 2008). Consider, for instance, Experiment 2A in which the object always crossed the meridians and the target locations varied. Here, we observed an effect of object-based attention (the SDA) that was modulated by target locations (the SDA emerged only when target locations required a shift of attention across the meridians), suggesting that prioritization of attention was unequally distributed across crossing and non-crossing target locations and that target locations were not afforded equal enhancement. Thus, object-based attention seems to prioritize *specific* target locations and not simply *all* locations within a cued object.

Origins of the shift direction anisotropy

The visual system neuroanatomy may provide an explanation for the horizontal advantage. For instance, cone photoreceptor density is highest at (and declines at a faster rate from) the fovea along the horizontal meridian as opposed to the vertical meridian (Curcio, Sloan, Kalina, & Hendrickson, 1990; Curcio, Sloan, Packer, Hendrickson, & Kalina, 1987). Primary visual cortex (V1) also contains a larger representation of the horizontal meridian compared to the vertical meridian (Tootell, Switkes, Silverman, & Hamilton, 1988; Van Essen, Newsom, & Maunsell, 1984). Together, these physiological characteristics of the visual system may provide the neuroanatomical means to drive the enhanced processing of visual stimuli that require an attention shift across the vertical meridian.

Likewise, the anatomical segregations of the visual system provide another possible explanation for the performance anisotropy, as we've raised previously (Al-Janabi & Greenberg, 2016; Barnas & Greenberg, 2016). Left and right visual field representations are organized contralaterally, imposing an *inter*hemispheric boundary along the vertical meridian (Holtzman, Sidtis, Volpe, Wilson, & Gazzaniga, 1981; Reuter-Lorenz & Fendrich, 1992a). As a result, an object that crosses this interhemispheric boundary (i.e., a horizontal object) appears in both the left and right visual hemifields and has a split representation in corresponding retinotopic areas in visual cortex. Conversely, an object that does not cross the interhemispheric boundary (i.e., a vertical object) appears entirely within the left or right visual hemifield and, thus, is represented fully in the corresponding contralateral hemisphere. In addition, lower and upper visual field representations are also segregated anatomically (Sereno et al., 1995; Van Essen, 1985), forming an *intra*hemispheric boundary along the horizontal meridian (Sereno & Kosslyn, 1991). As a result, an object that crosses this intrahemispheric boundary (i.e., a vertical object) appears in both lower and upper visual hemifields, whereas an object that does not cross the intrahemispheric boundary (i.e., a horizontal object) appears entirely within the lower or upper visual hemifield. In consideration of both anatomical configurations, reallocating attention across the interhemispheric boundary, for instance, may prove to be costlier than reallocating attention across the intrahemispheric boundary, or vice versa. Based on the results reported here, the horizontal advantage that occurs when invalid target locations cross the meridians (and are inside the boundaries of an object) hints at impaired attentional reallocation across the intrahemispheric boundary. Thus, reorienting of object-based attention to targets within an object is negatively affected when shifting across the horizontal meridian as compared to the vertical meridian. This performance difference may be due to more costly interactions and additional cortical processing incurred from crossing the intrahemispheric boundary relative to the interhemispheric boundary. Indeed, previous studies have shown that the two hemispheres have somewhat independent pools of attentional resources (Alvarez & Cavanagh, 2005); but, under the proper conditions, such as high attentional demands, increased interhemispheric interactions can produce a coordinated unit that functionally expands an individual's attentional capacity, which has been observed for instance, in the auditory domain (Scalf, Banich, & Erickson, 2009). As a consequence, strengthening the interhemispheric interactions across the interhemispheric boundary could likely lead to enhanced performance along the horizontal meridian and support efficient performance during complex visual tasks (Banich, 1998; Banich & Belger, 1990; Scalf, Banich, Kramer, Narechania, & Simon, 2007).

Nominally, both visual system neuroanatomy and the anatomical segregations of the visual cortices, as described above, should affect all forms of attentional selection equally. That is to say, why would mechanisms of object-based attention be more susceptible to the shift anisotropies we have uncovered than spatial attention? We speculate that this is possibly due to the larger physical areas of the visual field that are selected when object-based attention is deployed. Several recent studies using precise visuospatial investigations have revealed elliptical visual field boundaries (Fortenbaugh, Sanghvi, Silver, & Robertson, 2012) and an elliptical shape of the attentional window (Anderson, Cameron, & Levine, 2014; Baldwin, Meese, & Baker, 2012; Pan & Eriksen, 1993) which are consistent with a horizontal attention shift advantage, particularly across the vertical meridian. However, these biases are subtle and may not become apparent unless a single object representation that crosses the vertical meridian is prioritized by attentional mechanisms. Object-based attentional selection causes extended portions of the visual field to be selected simultaneously, a phenomenon that would be unusual during a purely space-based selection. When spatial attention prioritizes a region for enhanced processing, it is typically limited to the size of a visual cortex neuron's (or group of neurons') receptive field. However, object-based attention typically selects visual field regions that encompass a far larger area. This may be necessary to see the modest directional biases that would cause the anisotropies we have reported here.

Conclusion

We investigated the contributions of target location and placement of object boundaries in relation to the visual field meridians on the SDA. We found that the SDA emerged only when invalid target locations necessitated shifts of object-based attention that crossed the meridians, regardless of object boundary placement. The anisotropy is, thus, driven by target location (rather than the placement of object boundaries) relative to the visual field meridians and object-based attention serves to prioritize *specific* target locations and not simply *all* target locations within a cued object.

Notes

1. A 2000 ms response window may have allowed participants the opportunity to make multiple saccades to the invalid target locations (despite instructions to maintain fixation). If this was indeed the case, it would be reasonable to implicate the role of eye movements and differences in saccade velocity as likely sources of the SDA. Counter to this explanation, however, previous research has found that (1) saccades made to targets in the cardinal directions had statistically equivalent peak velocities (Becker & Jürgens, 1990) and (2) eye movements made during the double-rectangle cueing paradigm produced qualitatively similar effects to those produced by manual button press responses (Şentürk, Greenberg, & Liu, 2016), suggesting that both processes are affected similarly during object-based attentional selection.
2. Based on our predefined exclusion criteria, approximately 35% of participants were eliminated from Experiment 1. Although there are no standardized exclusion criteria in the literature, the number of participants that were excluded from the present experiment approximates the exclusion rates observed previously in studies of object-based attention that also used a target-detection task. For instance, Nah and colleagues (2018; Experiment 3a) removed 30% of participants from their sample, and Kravitz and Behrmann (2011; Experiment 3) removed 37% of participants.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability

The data that support the findings of this study are available from the corresponding author, ASG, upon reasonable request.

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