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 found that attention shifts that crossed the visual field meridians were faster horizontally than vertically, which we named a Shift Direction Anisotropy (SDA). We aimed to determine whether the SDA depends upon attention shift meridian crossings of object boundaries, target locations, or both. Participants viewed an 'L'-shaped object and responded to a target at the cued vertex location (valid) or at non-cued object locations offset horizontally (invalid-horizontal) or vertically (invalid-vertical). In Experiment 1, object boundaries and target locations were positioned either crossing or not crossing the meridians. In Experiments 2A and 2B, object boundaries were held constant (always crossing or never crossing the meridians, respectively) while target locations were manipulated (randomly crossing or non-crossing). In Experiments 3A and 3B, target locations were held constant while object boundaries were manipulated. In Experiment 4, the object was removed to determine whether object-based or space-based attentional resources were being deployed. 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.

5 Keywords: object-based attention, shift direction anisotropy, visual field meridians, attentional prioritization, attention shifts

Public Significance Statement

This study suggests that the process of selecting visual objects for attentional enhancement prioritizes information at specific locations within an object rather than at all locations.

Additionally, this study provides new evidence that the efficiency advantage of horizontal attention shifts (vs vertical shifts) during object-based selection is driven by target locations that cross the vertical visual field midline. These findings necessitate updating current theories of attentional selection to include effects of target location and object placement within the visual field.

Introduction

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 to process only pertinent information. 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., Duncan, 1984; Behrmann, Zemel, & Mozer, 1998), multiple object tracking (e.g., Pylyshyn & Storm, 1988), and dissociations in neurological patients (e.g., Egly, Driver, & Rafal, 1994; Egly, Rafal, Driver, & Starrveveld, 1994).

The now-classic study by Egly, Driver, and Rafal (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, Driver, and Rafal (1994), thus, 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, Yantis, & Vaughan, 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 failed to show a same object advantage (e.g., Avrahami, 1999; Law & Abrams, 2002; Shomstein & Behrmann, 2008; Greenberg, 2009), 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, & Sekular, 2012).

Pilz, Roggeveen, Creighton, Bennett, and Sekuler (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). 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 general 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. This observation suggests 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, it remains an open question as to whether object placement or target location is the primary driver of the SDA.

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.

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 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 & Greenberg (2016) to examine the relevance of object placement and invalid target location on the SDA.

Participants. Forty-three individuals ($M_{\text{age}} = 21.07$ years, $SD_{\text{age}} = 5.95$ 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 hour 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 x 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 et al., 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.

<<<<<Insert Figure 1 about here>>>>>

Participants fixated centrally on a white fixation cross ($0.2^\circ \times 0.2^\circ$) of a fixed-width font (Monaco, font size 20), and viewed a single median gray 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 $2.0^\circ \times 14.0^\circ$ vertical component rectangle and a $14.0^\circ \times 2.0^\circ$ horizontal component rectangle (See Fig. 1; "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.

<<<<<Insert Figure 2 about here>>>>>

The other half of trials consisted of an 'L'-shaped object that was composed of a $2.0^\circ \times 10.65^\circ$ vertical component rectangle and a $10.65^\circ \times 2.0^\circ$ horizontal component rectangle (See Fig. 2; "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. The "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° .

A red exogenous cue (RGB: [255 0 0]) also consisted of a vertical component rectangle ($0.34^\circ \times 2.0^\circ$) conjoined at a 90-degree angle with a horizontal component rectangle ($2.0^\circ \times 0.34^\circ$), and always appeared surrounding the outer edge of the object vertex. 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 centered left-to-right within the vertical component rectangle and top-to-bottom within the horizontal component rectangle. Letters were positioned so that their centers 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 types 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 percentages 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 Figures 1 and 2, 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 ms¹ 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 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.

¹A 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.

Results

Here and in subsequent experiments, individual participant data were checked for false alarm rates (responding on target absent trials) and miss rates (failing to respond on target present trials) prior to conducting any statistical analyses. Participants who responded to more than 48 catch trials (or, 25%) and/or missed 96 target-present trials (or, 10%) were discarded from the original sample because excessive false alarm and/or miss rates are indicative of disengagement in the task. As a result, 15 participants with an excessively high number of false alarms ($M = 91$ trials, $SD = 31$ trials) on catch trials and/or misses ($M = 198$ trials, $SD = 140$ trials) on target-present trials were discarded. This resulted in a final sample of 28 participants ($M_{\text{age}} = 19.82$ years, $SD_{\text{age}} = 2.20$ years; 22 women, 6 men) with a mean false alarm rate of 19 catch trials ($SD = 12$) and a mean miss rate of 26 target-present trials ($SD = 18$). The number of participants in each final sample approximated the sample sizes from our previous demonstrations of the shift direction anisotropy (Barnas & Greenberg, 2016). For the crossing condition, participants, on average, failed to respond to 3.34% of valid trials ($SEM = 0.44\%$), 3.79% of invalid-horizontal trials ($SEM = 0.69\%$), and 3.42% of invalid-vertical trials ($SEM = 0.58\%$). For the non-crossing condition, participants, on average, failed to respond to 3.47% of valid trials ($SEM = 0.52\%$), 2.98% of invalid-horizontal trials ($SEM = 0.62\%$), and 4.02% of invalid-vertical trials ($SEM = 0.61\%$). Additionally, anticipatory responses (RT less than 200 ms) were discarded.

Response latencies. The dependent variable was mean RT for correct responses. First, mean RT differences were calculated by subtracting mean raw RTs to valid targets ($M = 580.30$ ms for the crossing condition; $M = 567.81$ ms for the non-crossing condition) from mean RTs to invalid-horizontal targets ($M = 785.43$ ms for the crossing condition; $M = 729.54$ ms for the non-

crossing condition) and invalid-vertical targets ($M = 832.92$ ms for the crossing condition; $M = 746.42$ ms for the non-crossing condition). Next, mean RT differences were submitted to a 2×2 repeated measures ANOVA with Boundaries/Targets (crossing, non-crossing) and Shift Direction (horizontal, vertical) as within-subjects factors. The analysis revealed a main effect of Boundaries/Targets, $F(1,27) = 45.83, p \leq .001, \eta_p^2 = .63$, 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) versus when both the object boundaries and invalid target locations did not cross the meridians ($M = 170.17$ 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) versus vertically ($M = 215.62$ ms). These main effects were further qualified by a significant two-way interaction, $F(1,27) = 5.50, p = .027, \eta_p^2 = .17$.

<<<<<Insert Figure 3 about here>>>>>

The interaction between Boundaries/Targets 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 Fig. 3). 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) was significantly faster than vertically ($M = 252.63$ ms), $t(27) = 3.13, p = .004$. 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) were statistically equivalent to vertical shifts of attention ($M = 178.61$), $t(27) = 1.47$, $p = .153$. Thus, as shown in Figure 4, the interaction between Boundaries/Targets and Shift Direction was driven by a significantly larger and positive (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).

<<<<<Insert Figure 4 about here>>>>>

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, 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 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 the other factor constant.

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. 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 external to an object that 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) that require

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 ($M_{\text{age}} = 21.69$ years, $SD_{\text{age}} = 3.11$ 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 $2.0^\circ \times 14.0^\circ$ vertical component rectangle conjoined at a 90-degree angle with a $14.0^\circ \times 2.0^\circ$ horizontal component rectangle. On half of the trials, the target array consisted of target and non-target letters that were positioned so that their centers were 1.0° from the near end of either component rectangle (See Fig. 1; “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 centers were 4.33° from the near end of either component rectangle (See Fig. 5; “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.

<<<<<Insert Figure 5 about here>>>>>

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 ($M_{\text{age}} = 22.48$ years, $SD_{\text{age}} = 9.70$ 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 $2.0^\circ \times 10.65^\circ$ vertical component rectangle conjoined at a 90-degree angle with a $10.65^\circ \times 2.0^\circ$ horizontal component rectangle. On half of the trials, the target array consisted of target and non-target letters that were positioned so that their centers were 4.33° from the near end of either component rectangle, appearing external to the object (See Fig. 6, “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 centers were 1.0° from the near end of either component rectangle (See Fig. 2, “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.

<<<<<Insert Figure 6 about here>>>>>

Results

Experiment 2A. A total of 8 participants with an excessively high number of false alarms ($M = 82$ trials, $SD = 22$ trials) on catch trials and/or misses ($N = 125$ trials) on target-present trials were discarded. This resulted in a final sample of 28 participants ($M_{\text{age}} = 21.71$ years, $SD_{\text{age}} = 3.29$ years; 25 women, 3 men) with a mean false alarm rate of 14 catch trials ($SD = 11$) and a mean miss rate of 15 target-present trials ($SD = 18$). For the crossing targets condition, participants, on average, failed to respond to 1.75% of valid trials ($SEM = 0.41\%$), 2.16% of invalid-horizontal trials ($SEM = 0.67\%$), and 2.31% of invalid-vertical trials ($SEM = 0.71\%$). For the non-crossing targets condition, participants, on average, failed to respond to 2.00% of valid trials ($SEM = 0.51\%$), 1.64% of invalid-horizontal trials ($SEM = 0.47\%$), and 2.31% of invalid-vertical trials ($SEM = 0.70\%$). 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. First, mean RT differences were calculated by subtracting mean raw RTs to valid targets ($M = 543.87$ ms for the crossing targets condition; $M = 538.78$ ms for the non-crossing targets condition) from mean RTs to invalid-horizontal targets ($M = 799.61$ ms for the crossing targets condition; $M = 718.99$ ms for the non-crossing targets condition) and invalid-vertical targets ($M = 849.26$ ms for the crossing targets condition; $M = 739.31$ ms for the non-crossing targets condition). Next, mean RT differences were submitted to a 2 x 2 repeated measures ANOVA with Targets (crossing, non-crossing) and Shift Direction (horizontal, vertical) as within-subjects factors. The analysis revealed a main effect of Targets, $F(1,27) = 141.56, p \leq .001, \eta_p^2 = .84$, indicating a significant difference in mean RT while reallocating object-based attention to invalid target locations that crossed the meridians ($M = 280.56$ ms) versus target locations that did not cross the meridians ($M = 190.37$ 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) versus vertically ($M = 252.96$ ms). These main effects were further qualified by a significant two-way interaction, $F(1,27) = 4.92, p = .035, \eta_p^2 = .15$.

<<<<<Insert Figure 7 about here>>>>>

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) was significantly faster than vertically ($M = 305.38$ ms), $t(27) = 3.33, p = .003$. 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) were statistically equivalent to vertical shifts ($M = 200.54$ ms), $t(27) =$

1.82, $p = .080$ (see Fig 7). Thus, as shown in Figure 4, the interaction between Targets and Shift Direction was driven by a significantly larger and positive (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).

Experiment 2B. A total of 3 participants with an excessively high number of false alarms ($M = 61$ trials, $SD = 12$ trials) on catch trials and/or misses ($M = 120$ trials, $SD = 28$ trials) on target-present trials were discarded. This resulted in a final sample of 30 participants ($M_{\text{age}} = 22.87$ years, $SD_{\text{age}} = 10.11$ years; 24 women, 6 men) with a mean false alarm rate of 16 catch trials ($SD = 14$) and a mean miss rate of 16 target-present trials ($SD = 14$). For the crossing targets condition, participants, on average, failed to respond to 2.15% of valid trials ($SEM = 0.36\%$), 2.36% of invalid-horizontal trials ($SEM = 0.50\%$), and 2.22% of invalid-vertical trials ($SEM = 0.42\%$). For the non-crossing targets condition, participants, on average, failed to respond to 2.00% of valid trials ($SEM = 0.37\%$), 1.74% of invalid-horizontal trials ($SEM = 0.36\%$), and 2.36% of invalid-vertical trials ($SEM = 0.54\%$). Again, anticipatory responses (less than 200 ms) were discarded.

Response latencies. The dependent variable was the mean RT for correct responses. First, mean RT differences were calculated by subtracting mean raw RTs to valid targets ($M = 548.20$ ms for the crossing targets condition; $M = 549.42$ ms for the non-crossing targets condition) from mean RTs to targets in the invalid-horizontal location ($M = 910.47$ ms for the crossing targets condition; $M = 737.73$ ms for the non-crossing targets condition) and invalid-vertical location ($M = 870.32$ ms for the crossing targets condition; $M = 757.74$ ms for the non-crossing targets condition). Next, mean RT differences were submitted to a 2 x 2 repeated measures ANOVA with Targets (crossing, non-crossing) and Shift Direction (horizontal,

vertical) as within-subjects factors. The analysis revealed a main effect of Targets, $F(1,29) = 148.66, p \leq .001, \eta_p^2 = .84$, 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) versus locations that did not cross the meridians ($M = 198.32$ 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) versus vertically ($M = 265.22$ ms). Furthermore, the analysis revealed a significant two-way interaction, $F(1,29) = 14.73, p = .001, \eta_p^2 = .34$.

<<<<<Insert Figure 8 about here>>>>>

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) was significantly faster than horizontally ($M = 362.26$ ms), $t(29) = 2.85, p = .008$. 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) were statistically equivalent to vertical shifts ($M = 208.33$ ms), $t(29) = 1.58, p = .124$ (See Fig. 8). Thus, as shown in Figure 4, the interaction between Targets 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).

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. 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 & 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), $t(29) = 3.70$, $p \leq .001$. 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; $t(27) = 1.47$, $p = .154$).

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 when the invalid targets were contained within the boundaries of the object. And, there was no significant difference between horizontal and vertical shifts 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). 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. Although the SDA was significant in both conditions 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. We believe this 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. 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 ($M_{\text{age}} = 20.15$ years, $SD_{\text{age}} = 2.08$ 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 centers were 1.0° from the near end of either component rectangle (See Fig. 1, “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 centers were 4.33° from the near end of either component rectangle, appearing off the object (See Fig. 6, “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 ($M_{\text{age}} = 21.26$ years, $SD_{\text{age}} = 2.55$ 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 centers were 4.33° from the near end of either component rectangle (See Fig. 5, “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 centers were 1.0° from the near end of either component rectangle (See Fig. 2, “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. A total of 5 participants with an extremely high number of false alarms ($M = 74$ trials, $SD = 26$ trials) on catch trials and/or misses ($M = 133$ trials, $SD = 25$ trials) on

target-present trials were discarded. This resulted in a final sample of 28 participants ($M_{\text{age}} = 20.43$ years, $SD_{\text{age}} = 2.13$ years; 24 women, 4 men) with a mean false alarm rate of 16 catch trials ($SD = 10$) and a mean miss rate of 16 target-present trials ($SD = 17$). For the crossing object condition, participants, on average, failed to respond to 2.06% of valid trials ($SEM = .044\%$), 2.23% of invalid-horizontal trials ($SEM = 0.44\%$), and 1.93% of invalid-vertical trials ($SEM = 0.43\%$). For the non-crossing object condition, participants, on average, failed to respond to 2.10% of valid trials ($SEM = 0.47\%$), 2.60% of invalid-horizontal trials ($SEM = 0.55\%$), and 2.60% of invalid-vertical trials ($SEM = 0.59\%$). Additionally, anticipatory responses (RT less than 200 ms) were discarded.

Response latencies. The dependent variable was the mean RT for correct responses. First, mean RT differences were calculated by subtracting mean raw RTs to valid targets ($M = 531.42$ ms for the crossing object condition; $M = 518.55$ ms for the non-crossing object condition) from mean RTs to targets in the invalid-horizontal location ($M = 795.14$ ms for the crossing object condition; $M = 903.06$ ms for the non-crossing object condition) and invalid-vertical location ($M = 857.06$ ms for the crossing object condition; $M = 836.18$ ms for the non-crossing object condition). Next, mean RT differences were submitted to a 2 x 2 repeated measures ANOVA with Boundaries (crossing, non-crossing) and Shift Direction (horizontal, vertical) as within-subject factors. The analysis revealed a main effect of Boundaries, $F(1,28) = 37.35$, $p \leq .001$, $\eta_p^2 = .58$, 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) versus targets outside objects that did not cross the meridians ($M = 351.07$ ms). The main effect of Shift Direction, however, was not significant, $F(1,28) = 0.07$, $p = .789$, $\eta_p^2 = .003$, indicating no significant difference in invalid target detection RT when reallocating object-

based attention horizontally ($M = 324.12$ ms) versus vertically ($M = 321.64$ ms). Furthermore, the analysis revealed a significant two-way interaction, $F(1,28) = 65.10, p \leq .001, \eta_p^2 = .71$.

<<<<<Insert Figure 9 about here>>>>>

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) was significantly faster than vertically ($M = 325.64$ ms), $t(27) = 4.89, p \leq .001$. 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) was significantly faster than horizontally ($M = 384.51$ ms), $t(27) = 5.73, p \leq .001$ (See Fig. 9). Thus, as shown in Figure 4, the interaction between Boundaries 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 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).

Experiment 3B. A total of 10 participants with an extremely high number of false alarms ($M = 79$ trials, $SD = 19$ trials) on catch trials and/or misses ($M = 236$ trials, $SD = 46$ trials) on target-present trials were discarded. This resulted in a final sample of 29 participants ($M_{\text{age}} = 21.38$ years, $SD_{\text{age}} = 2.66$ years; 21 women, 8 men) with a mean false alarm rate of 15 catch trials ($SD = 11$) and a mean miss rate of 21 target-present trials ($SD = 18$). For the crossing object condition, participants, on average, failed to respond to 2.53% of valid trials ($SEM = .043\%$), 2.87% of invalid-horizontal trials ($SEM = 0.62\%$), and 2.37% of invalid-vertical trials ($SEM = 0.62\%$). For the non-crossing object condition, participants, on average, failed to respond to 2.69% of valid trials ($SEM = 0.48\%$), 2.73% of invalid-horizontal trials ($SEM = 0.69\%$), and

3.45% of invalid-vertical trials ($SEM = 0.70\%$). Again, anticipatory responses (RT less than 200 ms) were discarded.

Response latencies. The dependent variable was the mean RT for correct responses. First, mean RT differences were calculated by subtracting mean raw RTs to valid targets ($M = 536.52$ ms for the crossing object condition; $M = 521.80$ ms for the non-crossing object condition) from mean RTs to targets in the invalid-horizontal location ($M = 677.36$ ms for the crossing object condition; $M = 678.00$ ms for the non-crossing object condition) and invalid-vertical location ($M = 674.22$ ms for the crossing object condition; $M = 689.62$ ms for the non-crossing object condition). Next, mean RT differences were submitted to a 2 x 2 repeated measures ANOVA with Boundaries (crossing, non-crossing) and Shift Direction (horizontal, vertical) as within-subject factors. The analysis revealed a main effect of Boundaries, $F(1,28) = 11.44, p = .002, \eta_p^2 = .29$, 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) versus targets within objects that did not cross the meridians ($M = 162.01$ ms). Neither the main effect of Shift Direction and the two-way interaction did not reach significance, $ps \geq .128$.

<<<<<Insert Figure 10 about here>>>>>

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 and 137.70 ms, respectively), $t(28) = 0.28, p = .781$, as well as when the boundaries of the object did not cross the meridians ($M = 156.20$ ms and 167.82 ms, respectively), $t(28) = 1.52, p = .140$ (See Fig. 10). Thus, as shown in Figure 4,

there was no significant SDA when the boundaries of the object crossed (3.14 ms) or did not cross (11.62 ms) the meridians.

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 truly arise 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 do not 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 ($M_{\text{age}} = 20.35$ years, $SD_{\text{age}} = 2.07$ 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 centers 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 Fig. 11). Invalid-horizontal and invalid-vertical targets were equidistant from the peripheral cue.

<<<<<Insert Figure 11 about here>>>>>

Results

A total of 2 participants with an excessively high number of false alarms ($M = 104$ trials, $SD = 56$ trials) on catch trials and/or misses ($N = 150$ trials) on target-present trials were discarded. This resulted in a final sample of 29 participants ($M_{\text{age}} = 20.10$ years, $SD_{\text{age}} = 1.82$ years; 26 women, 3 men) with a mean false alarm rate of 13 catch trials ($SD = 11$) and a mean miss rate of 21 target-present trials ($SD = 20$). Participants, on average, failed to respond to 2.62% of valid trials ($SEM = 0.48\%$), 3.63% of invalid-horizontal trials ($SEM = 0.79\%$), and 2.26% of invalid-vertical trials ($SEM = 0.44\%$). Additionally, anticipatory responses (RT less than 200 ms) were discarded.

Response latencies. The dependent variable was the mean RT for correct responses. Mean raw RTs to valid trials ($M = 633.43$ ms), invalid-horizontal trials ($M = 915.29$ ms), and invalid-vertical trials ($M = 930.14$ ms) were submitted to a within-subjects, repeated measures ANOVA with Trial Type (valid, invalid-horizontal, invalid-vertical) as a single factor. Results

revealed a significant effect of Trial Type, $F(2,56) = 306.25$, $p \leq .001$, $\eta_p^2 = .92$, indicating a significant difference in target detection between the three trial types (See Fig. 12).

<<<<<Insert Figure 12 about here>>>>>

Space-based cueing effects were analyzed with a paired samples t -test between RTs to valid trials and RTs to invalid trials ($M = 922.72$ ms). A significant space-based cueing effect was observed, $t(28) = 20.52$, $p \leq .001$, indicating that detection RTs were significantly faster for valid targets as compared to invalid targets. Shift direction effects were analyzed with a paired samples t -test between RTs to invalid-horizontal and invalid-vertical trials. No SDA was observed, $t(28) = 1.48$, $p = .149$, indicating that detection RTs for invalid-horizontal targets were statistically equivalent to detection RTs for invalid-vertical targets.

Discussion

This control experiment yielded two main findings. First, we observed a significant space-based cueing effect, demonstrating that participants' attention was preferentially drawn to the cued location as opposed to either of the non-cued locations. Second, in the absence of an object percept, we observed no SDA. This latter result, coupled with our findings from the above experiments, 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 attention.

General Discussion

Previous research using the double-rectangle cueing paradigm (Egley, Driver, & Rafal, 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, Roggeveen, Creighton, Bennet, & Sekular, 2012). Our work previously investigated this dissociation by comparing the reallocation of object-based attention across the horizontal versus vertical meridian using an '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.

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 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) played no 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 conditions during which targets were 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 is consistent with the attentional prioritization hypothesis of object-based attentional selection. This theory proposes that object-based attentional prioritization is distributed to behaviorally relevant (e.g., target) locations within an object and not simply spread throughout all locations on that object (Shomstein & Behrmann,

2008; Shomstein & Yantis, 2002, 2004). Here we observed an effect of object-based attention (the SDA) that was modulated by target locations and not the shape of object boundaries. Thus, object-based attention serves to prioritize *specific* target locations and not simply *all* locations within a cued object.

Origins of the Shift Direction Anisotropy

This is now the second study showing a significant anisotropy between horizontal and vertical shifts of object-based attention (cf. Barnas & Greenberg, 2016), suggesting that it may be an important feature of this mode of selection that requires explanation. One potential source of the SDA may be related to the shapes of both the visual field and attentional window. Previous research has demonstrated that unequal visual field boundaries form a bi-elliptical shape. Fortenbaugh, Sanghvi, Silver, and Robertson (2012) measured monocular visual field extents in a group of participants and observed asymmetries in both horizontal and vertical dimensions. They concluded that the visual field is more elongated along the horizontal dimension than the vertical dimension. Relatedly, Pan and Eriksen (1993) found that the shape of the attentional window is elliptical (see also Anderson, Cameron, & Levine, 2014; Baldwin, Meese, & Baker, 2012). As the distance increased between visual stimuli lying on the meridians, Pan and Eriksen (1993) found that participants were significantly faster at making a speeded same-different judgment when the attentional window formed by the targets was a horizontal ellipse than when it formed a vertical ellipse. This finding suggests that shifts of visual attention along the horizontal meridian are afforded a greater processing advantage than shifts along the vertical meridian, commensurate with the findings we report above.

The visual system neuroanatomy may also provide an explanation for the SDA. 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 *interhemispheric* boundary along the vertical meridian (Holtzman, Sidtis, Volpe, Wilson, & Gazzaniga, 1982; 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 (Van Essen, 1985; Sereno et al., 1995), forming an *intrahemispheric* 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, & Erikson, 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).

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.

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Figure Captions

Figure 1. Trial sequence for “Crossing Object and Targets” in Experiments 1, 2A, and 3A.

Object boundaries and invalid target locations both cross the visual field meridians. (A-C) The three possible trial conditions 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.

Note: Placement of object boundaries and locations of invalid targets in relation to the visual field meridians are not drawn to scale; Dashed yellow lines represent the horizontal and vertical meridians and were not visible to participants during the experiment.

Figure 2. Trial sequence for “Non-crossing Object and Targets” in Experiments 1, 2B, and 3B.

Object boundaries and invalid target locations both do not cross the visual field meridians.

(A-C) The three possible trial conditions 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.

Note: Placement of object boundaries and locations of invalid targets in relation to the visual field meridians are not drawn to scale; Dashed yellow lines represent the horizontal and vertical meridians and were not visible to participants during the experiment.

Figure 3. Mean response latencies in Experiment 1. “Magnitude of Attention Shift” measured

for the Boundaries/Targets x Shift Direction interaction. The error bars represent the standard error of the mean for within-subjects design.

Figure 4. 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 design. Asterisks indicate significant shift direction anisotropies (significant difference from zero; all $ps \leq .008$)

Figure 5. Trial sequence for “Crossing Object, Non-crossing Targets” in Experiments 2A and 3B. Object boundaries cross, but invalid target locations do not cross the visual field meridians. (A-C) The three possible trial conditions 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.

Note: Placement of object boundaries and locations of invalid targets in relation to the visual field meridians are not drawn to scale; Dashed yellow lines represent the horizontal and vertical meridians and were not visible to participants during the experiment.

Figure 6. Trial sequence for “Non-crossing Object, Crossing Targets” in Experiments 2B and 3A. Object boundaries do not cross, but invalid target locations cross the visual field meridians. (A-C) The three possible trial conditions 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.

Note: Placement of object boundaries and locations of invalid targets in relation to the visual field meridians are not drawn to scale; Dashed yellow lines represent the horizontal and vertical meridians and were not visible to participants during the experiment.

Figure 7. Mean response latencies in Experiment 2A (object boundaries always crossed meridians). “Magnitude of Attention Shift” measured for the Targets x Shift Direction interaction in Experiment 2A. The error bars represent the standard error of the mean for within-subjects design.

Figure 8. Mean response latencies in Experiment 2B (object boundaries never crossed meridians). “Magnitude of Attention Shift” measured for the Targets x Shift Direction

interaction in Experiment 2B. The error bars represent the standard error of the mean for within-subjects design.

Figure 9. Mean response latencies in Experiment 3A (target locations always crossed meridians). “Magnitude of Attention Shift” measured for the Boundaries x Shift Direction interaction in Experiment 3A. The error bars represent the standard error of the mean for within-subjects design.

Figure 10. Mean response latencies in Experiment 3B (target locations never crossed meridians). “Magnitude of Attention Shift” measured for the Boundaries x Shift Direction interaction in Experiment 3B. The error bars represent the standard error of the mean for within-subjects design.

Figure 11. Trial sequence for Experiment 4 (Spatial Attention Control). Invalid target locations cross the visual field meridians with no object present. (A-C) The three possible trial conditions 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; Dashed yellow lines represent the horizontal and vertical meridians and were not visible to participants during the experiment.

Figure 12. Mean response latencies in Experiment 4 (Spatial Attention Control). Raw RTs measured for each Cueing Condition in Experiment 4. The error bars represent the standard error of the mean for within-subjects design.

Figures

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