THE BENEFITS OF GETTING HORIZONTAL

BY

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DISSERTATION

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ABSTRACT

The goal of much research in vision is to better understand the mechanisms of attention. This is often accomplished by using models of attention to predict how the placement of stimuli on a computer screen will affect task difficulty. However, recent research has shown there are asymmetries in visual sensitivity across different locations of the visual field and also that there might be interactions between attention and sensitivity across different locations in the visual field. We discuss the potential significance of these asymmetries for attention research, focusing on the possibility of an attentional advantage for targets appearing horizontal to an invalid exogenous cue. We review previous literature concerning this potential horizontal advantage and then describe seven experiments related to it. Experiments 1 and 2 find an advantage for targets appearing horizontal, rather than diagonal, to an invalid cue in a visual display similar to those used in the classic Posner cueing paradigm. Experiments 3 and 4 provide evidence of an advantage for horizontal targets in a display similar to those used in the object-based attention literature. Experiment 5 attempted to determine whether flanking non-targets are necessary to observe a horizontal advantage, but ended up not providing much information. Experiments 6 and 7 attempted to test between two models of the horizontal advantage and, while perhaps ruling one out, do not provide clean evidence for any. In the end, we conclude that the evidence for the horizontal advantage is strong, though there is still much to learn about.
To the haters and the losers.
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1. Introduction

The goal of much research in vision is to better understand the mechanisms of attention. Researchers are often interested in the general structure of the attentional system, and design studies to shed light on how much information we can attend to at once, the kinds of information we can select for and filter out of processing, the spatial and temporal distributions of attentional enhancement and suppression, and a variety of other questions. Often, the dependent measure used in these studies is task difficulty: some visual stimulus is to be identified and then some action (pressing a button on a computer keyboard, for example) is to be performed. Task difficulty is generally measured by either overall task success (accuracy) or the time required to successfully complete the task (response time).

Different models of attentional mechanisms predict different patterns of task difficulty. For example, it might be that attentional focus can be broken into multiple, independent spotlights to simultaneously process two spatially separated locations. In this case, distracting information positioned in between the multiple spotlights should not be more detrimental to performance than distracting information positioned somewhere else. On the other hand, if attentional focus is always unitary then simultaneous attentive processing of two spatially separated locations likely occurs by spreading attention wide enough to encompass both locations. In this case, distracting information positioned between the attended locations should be more distracting than information positioned far away because the attentional spread occupies the area between the two locations. Thus, a researcher might attempt to test between the two models by positioning distracting information either between or not between the attended locations. While this hypothetical study might seem like a perfectly reasonable way to test between the models, its validity as a test depends on several assumptions. One of these
assumptions, relevant to current purposes, is that there is similar baseline processing of distracting information at different locations in the visual field. The crucial manipulation is the location of the distracting information, and the effect being measured is the impact of distracting information on task difficulty. If the processing of visual information is better at some locations than others, and if the locations assigned to conditions do not respect this, then differential task difficulty between conditions might be difficult to interpret.

Importantly, many studies attempt to test models of attention by manipulating the spatial arrangement of visual stimuli. Models often predict differential levels of difficulty depending on the spatial arrangement of stimuli so this is natural. Once again, the assumption here is that there are no important differences in baseline processing of stimuli at different locations in the visual field (or that these differences are not confounded with spatial arrangement in a study). However, as will be expanded below, there appear both to be location-dependent differences in stimuli processing (something that vision researchers have long understood) and location-dependent, differential effects of deploying attention on stimuli processing (which is not well flushed out in the vision literature). These effects, we argue, can complicate the use of task difficulty as a means of cleanly differentiating between models. While two competing models may well predict different levels of difficulty as a function of the spatial arrangement of stimuli, we should be wary of drawing strong conclusions when other factors might also lead to differential task difficulty as a function of spatial arrangement. Understanding when and how the spatial arrangement of stimuli can affect task performance is thus important, both because it illuminates some of the mechanisms of vision and because it can help ensure the validity of experiments that confound spatial location with their manipulation of interest.

The studies that constitute this paper were conducted as an attempt to better understand
the interactions between stimuli processing, attention, and the arrangement of stimuli in space. Below, we review a portion of the literature on interactions of this sort, focusing first on low-level differences in stimuli sensitivity based on visual field location. We then turn to the topic that will constitute the bulk of this paper: an interaction between the deployment of attention to a location and the subsequent location of task-relevant stimuli such that stimuli horizontal to the deployed location appear to be more easily processed than stimuli in other locations. We review prior evidence for this effect and explain how, if real, it could alter the interpretations of some canonical visual attention paradigms. The second part of this paper describes four experiments attempting to discern whether there is an advantage for stimuli presented horizontal to a location where attention has been just deployed and whether such an advantage is a property of object-based attention or spatial attention more generally.

1.1 Processing Differences Based on Visual Field Location

Perhaps the most obvious example of differential location-based sensitivity is the processing difference between stimuli at fixation and stimuli in the periphery. Visual acuity, as indexed by both accuracy and response time, decreases as stimuli are placed farther from fixation (Carrasco, Evert, Chang, & Katz, 1995). This effect is thought to occur for a few reasons. First, spatial resolution is better at fixation than in the periphery (there are more receptors in the fovea and the fovea is magnified in the cortex) and, second, distractors can be placed closer to targets without interfering with them (through lateral inhibition/crowding/competition/normalization) in the fovea than in the periphery (Carrasco et al, 1995). This means that targets displayed close to fixation will be easier to process/identify than targets displayed away from fixation and that the detrimental effect of adding nearby distractors to a target will be greater away from fixation that
close to fixation. Importantly, these differences appear to arise from the visual system’s architecture/wiring and do not reflect regularities due to the attentional system per se.

Another important location-based difference in sensitivity is vertical meridian asymmetry. Sensitivity to stimuli that appear at some eccentricity on the upper vertical meridian is significantly reduced compared to sensitivity to stimuli that appear at the same eccentricity on the lower vertical meridian or on the horizontal meridian (Carrasco, Talgar, & Cameron, 2001). This asymmetry also holds in the area near the vertical meridian, with reduced sensitivity when stimuli fall within about 30° – 40° of angular distance from the upper vertical meridian compared to isoeccentric stimuli near the lower vertical meridian (Abrams, Nizam, & Carrasco, 2012). Abrams et al (2012) also argue that previous claims of better sensitivity in the lower visual field compared to the upper visual field as well as claims of increased sensitivity along the horizontal meridian compared to the vertical meridian might be largely explained by vertical meridian asymmetry. Vertical meridian asymmetry also appears to be exacerbated when the spatial frequency of the target increases, meaning that some types of stimuli should be expected to cause greater location-based processing differences than others.

Both the eccentricity effect and vertical meridian asymmetry show that visual sensitivity is not uniform across the visual field, and the extent of this inhomogeneity may depend on the kind of stimulus used in a task. These are important considerations when researchers design experiments to test competing models of attention. The goal of research is often to determine the structure of the attentional system by forcing it to process information in different spatial arrangements. If one spatial arrangement/condition involves stimuli appearing more often on the upper vertical meridian or at more eccentric locations than another condition, differences in task difficulty may arise that are due not to the attentional system but to visual field asymmetries in
sensitivity.

1.2 Visual Field Interactions with Attention

So far, we have seen that there are inhomogeneities in visual sensitivity across the visual field and how this complicates what might otherwise be straightforward tests of models of attention. The eccentricity effect is well known in vision research and simple design choices (placing stimuli across all conditions at isoeccentric locations) can help to relieve them. Vertical meridian asymmetry is less well known but still simple to design around (e.g., avoid placing stimuli on the upper vertical meridian). However, these are not the only issues that attention researchers must cope with. Recent work has also indicated that the deployment of spatial attention might interact with locations in the visual field asymmetrically, leading to counterintuitive location-dependent differences in processing.

Tse, Sheinberg, & Logothetis (2003) had participants complete over 25,000 trials of a change blindness task over several months. The stimuli were small red or green squares placed inside a circle (radius subtending 25° of visual angle) around fixation. On each trial participants saw a display, a blank appeared, and then the display reappeared. On each trial, one new square appeared on the second display that was not present on the first display. Participants were asked to indicate whether the new square was red or green. The new items appeared, over the totality of the trials, all over the display. This allowed the researchers to map out performance as a function of location in the visual field. Importantly, after the first display had been on for 506 ms, sometimes an exogenous spatial cue appeared in 1 of 4 positions on the screen (centered around 6.5° from fixation on either the upper vertical, lower vertical, left horizontal, or right horizontal meridians). After a varying amount of lag, the first display offset, the blank onset and then offset,
and the second display with the target onset. The cues were completely uninformative in that the targets randomly appeared across the visual field. The experiment thus allowed the researchers to see how the deployment of spatial attention (in this case in response to an exogenous cue) affected performance on the change blindness task as a function of the target location.

The results showed that, in the trials without cues, performance was near perfect at a hotspot around fixation. In the cued trials, however, this hotspot grew along fixation to encompass the location of the task-irrelevant cue. This is consistent with the exogenous cue recruiting attention. Interestingly, the researchers also found that the hotspot grew along fixation away from the cue, leading to near perfect performance in a hotspot in the hemifield (left, right, upper, or lower) opposite of where the cue appeared. Since the cue was spatially uninformative, it seems unlikely that these opposite hemifield hotspots resulted from specific strategies employed by the participants. The researchers suggest that this might result from a pooling of attention in the hemifield opposite of the cue. They also note that it could be due to attentional "momentum" where attention is pulled back toward fixation after being recruited at the location of the cue and that this momentum simply carries it to the opposite hemifield. The explanation for these effects is not clear, but they do highlight that cueing attention to a certain spatial location might have counterintuitive results on the processing of stimuli at other locations in the visual field.

1.3 Posner Cueing Task

Whereas before we saw baseline differences in processing across the visual field, these data seem to indicate that other location-based processing differences might arise when spatial attention is recruited/deployed. If recruiting attention via an exogenous cue leads to enhanced
processing in the hemifield opposite to the cue (and perhaps orthogonal to the cue), this could potentially change our interpretations of some well-known paradigms that have been used to study attention. For instance, the Posner cueing task is one of the canonical demonstrations that covert attentional shifts can speed up processing of stimuli at validly cued locations and slow down processing of stimuli at invalidly cued locations (Posner, 1980). The task involves participants fixating in the center of a screen with two boxes set along the horizontal meridian somewhat peripherally (often about 7°). At some point, one of the boxes is cued (either endogenously or exogenously) and then a target appears sometime after the cue either in the box that was cued or the box on the other side of fixation. What is found is that participants are faster to respond to the target when it is validly cued than when it is invalidly cued. The speeding of responses in the valid condition is taken to reflect the covert deployment of attention to the cued location and the difference between the valid and invalid conditions is taken to represent the cost having to re-deploy attention from the cued location to the uncued location.

Since the two cue/target locations in the Posner cueing task are isoeccentric (both 7° from fixation) and are both on the horizontal meridian, this task does not run afoul of either the eccentricity effect or the vertical meridian anisotropy. However, it is not clear whether the opposite hemifield pooling of attention following an exogenous cue that was observed in Tse et al (2003) might play a role. For instance, if a location to the left of fixation is cued and there is a subsequent pooling of attention on the right side of the screen, responses to the right side (in this case the invalid condition) might not reflect the true cost of re-deploying attention to the right side because attention might already partly be there. If this were true, then invalidly cued targets appearing in locations other than the symmetrical spot in the opposite hemifield would be expected to show a larger cost, relative to validly cued targets, than invalidly cued targets.
appearing in a symmetrical spot in the opposite hemifield. We explore this prediction in Experiments 1-4 below.

Tse et al (2003) interpret their results as reflective of an opposite hemifield pooling of attention in response to the cue. This pool could be localized to the symmetric spot in the hemifield opposite of the cue, what we’ll call the localized hotspot account, or it could be a continuous pooling of attention from the cue that extends horizontally to encompass the symmetric spot in the opposite hemifield, what we’ll call the elongated hotspot account (Figure 1). Furthermore, the performance benefit observed in Tse et al (2003) is also consistent with faster shifts of attention horizontally, or horizontally to the symmetric location in the opposite hemifield, rather than an automatic pooling of attention. For the purposes of this paper, we will be indifferent to the distinction between faster shifts of attention and automatic pooling as the studies presented below cannot differentiate between them. It is also possible that the attention hotspot is just elongated more horizontally than vertically, like an ellipse that is wider than it is tall. This elliptical hotspot could serve to position attention closer to targets appearing horizontal to a cue than to those appearing at an isoeccentric, non-horizontal location. This could reduce the time needed for attention to shift to horizontal targets, not because attention moves faster horizontally, but because there is less distance to cover.

If this horizontally symmetric advantage reflects an automatic pooling of attention in the opposite hemifield, this suggests that the classic Posner cueing task might not accurately measure the cost of re-deploying attention to an invalidly cued location (since attention is automatically deployed to the location of the invalidly cued target). Alternatively, if the horizontally symmetric advantage reflects either differences in the speed of attentional shifts or differences in how close the subsequent target is to an elliptical hotspot, this implies that there are variable, location-
dependent costs of re-deploying attention and that the Posner cueing task only accurately measures horizontally symmetric shifts.

1.4 Object-Based Attention

Another classic task where differences in stimuli placement might lead to interpretative difficulties is the Egly, Driver & Rafal (1994) object-based attention task. This task is like the Posner cueing task in that involves exogenous attentional cues that can either be valid or invalid. The task in this study, and in many follow-up studies since, involves placing two rectangles on either side of fixation (sometimes the rectangles are above and below fixation and sometimes they are to the left and right of fixation). Participants fixate while the rectangles are on the screen. Then, a brief exogenous cue appears at the end of the one of the two rectangles. After a delay, a target appears and participants are asked to respond. In valid trials, the target appears in the cued location. In invalid trials, the target can appear either at the other end of the cued rectangle or at the location on the other rectangle that is equidistant (and isoecentric) from this location. The classic effect is that, while participants take longer to respond on invalid trials than on valid trials, they also take longer to respond on invalid trials where the target appears on the uncued objects as opposed to invalid trials where the target appears on the cued objects. In other words, there appears to be a benefit when a target appears on the cued object as opposed to an uncued object. This is interpreted as evidence for object-based attention, where attending to one part of object causes attention to spread to the rest of the object.

However, the object-based attention effect is smaller than the space-based attention effect (the difference between valid and invalid trials) and is not always found (Pilz, Roggeveen, Creighton, Bennett, & Sekuler, 2012). In fact, Pilz et al (2012) ran a few modifications of the
Egly et al (1994) task where participants had to either identify a target (a ‘T’ or an ‘L’) appearing at the same locations as the Egly et al (1994) task. In one version, the target was the only item on the screen. In another version, 3 distractors (rotated ‘F’ s) appeared with the target at the other 3 ends of the rectangles. While they found robust space-based attention effects, they found small and inconsistent evidence for object-based effects. In the detection task (lone target), they found a small (about 10 ms in both tasks) advantage in the invalid condition for targets appearing on the cued object as opposed to the uncued object. However, at the participant level, only a small subset of participants showed significant object-based advantages and some even showed the opposite effect. In the discrimination task (distractors present), the effect varied dramatically depending on the orientation of the rectangles. When the rectangles were horizontally arranged (above and below fixation) there was a larger, more robust object-based effect (42 ms). When the rectangles were arranged vertically, they found a smaller (-19 ms) opposite effect: a cost for invalidly cued targets that appeared on the cued object compared to the uncued object. The researchers found similar results in a follow-up study: same-object benefits for both accuracy and response time when the objects were arranged horizontally and same-object costs when the objects were arranged vertically. However, this time they found no overall same-object benefit (averaging across orientations).

It is possible that the orientation difference in object-based attention found by Pilotz et al (2012) results from the same mechanism discussed above: an attentional benefit for targets appearing horizontal to an exogenous cue. Specifically, when the rectangles are arranged horizontally (the centers of the rectangles are above and below fixation) the invalid, same-object location lies horizontal to the location of the cue and the invalid, different-object location lies either directly above or below the cue. Thus, as in the research that we saw before, if horizontal
locations are privileged we would expect in this case to find an object-based attention effect, which Pilz et al (2012) do. However, when the rectangles are arranged vertically (the centers of the rectangles are left and right of fixation), the invalid, same-object location is directly above or below the cue while the invalid, different-object location is horizontal to the cue. In this case, we would expect to find an inverse object-based attention effect (a cost for targets appearing on the cued object), which the researchers find in response times in the discrimination task (there were similar trends in the accuracy data for both tasks). However, it is not clear from what has been presented if the benefit for targets that are horizontal to the cue (which has only been demonstrated along the horizontal midline) can explain the Pilz et al (2012) data.

Barnas & Greenberg (2016) describe potentially useful data. They used a modified object-based task to have participants search for a ‘T’ among ‘L’s. The cues and targets could appear, again, in one of four locations: the vertices of an imaginary square centered at fixation. Each location was about 8° from fixation and each was 45° from the horizontal and vertical meridians. On each trial an exogenous cue would appear at one of these locations and a target (a ‘T’) would appear either at the same location as the cue, at the horizontally symmetric vertex of the imaginary square, or at the vertical vertex either above or below the cue. ‘L’s would appear at the two locations where the target could appear (but did not on that trial). Participants were asked to respond to the presence of the target as quickly as possible and catch trials were included. Furthermore, the researchers included a large object (two grey rectangles put together to make an ‘L’) that appeared before the cue and on which the letters appeared. The vertex of this ‘L’ was located where the cue would appear (and the cue appeared on the object). Thus, after the vertex of the object was cued, the target could either appear at the vertex (a valid trial), at the end of the object that extended horizontally from the vertex (an invalid-horizontal trial), or at the
end of the object that extended vertically from vertex (an invalid-vertical trial). Besides a validity effect, they found that participants were slower (78 ms) to respond to invalid-vertical trials than to invalid-horizontal trials. Thus, they found an advantage for targets that appeared horizontally symmetric to the cue over targets that appeared vertical to the target. They interpret this finding as reflective of a location-dependent asymmetry in shifts of object-based attention (specifically, shifts of object-based attention that cross the visual field meridians). However, given that we have seen similar effects without objects (Tse et al, 2003), this might be reflective of a general property of attention rather than specifically of object-based attention.

In a third experiment, Barnas et al (2016) use a modified version of their first experiment where the arms of the ‘L’ object were reduced in length to fit within a single visual quadrant (Figure 4 in Barnas et al, 2016). There were two possible orientations for this ‘L’, either the vertex was close to fixation or far from fixation. Otherwise, the procedure in this experiment was the same as that of the last described experiment. They again found an overall benefit in the invalid-horizontal conditions compared to the invalid-vertical. Interestingly, the orientation of the ‘L’ seemed to make a difference. There was a statistically significant 62 ms benefit when the cue and object vertex were near fixation, where attention would be shifting away from fixation and a non-significant 19 ms benefit when the cue and object vertex were far from fixation. Importantly, since the targets always appeared in the same visual quadrant (and thus hemifield) as the cues, this result is seemingly inconsistent with the localized hotspot account (and inconsistent with their claim that the effect may result from crossing visual field meridians).

Unfortunately, there is a serious concern with this experiment. Cues could appear in one of two places in each quadrant of the visual field (Figure 4 from Barnas et al, 2016): either near fixation or farther from fixation. In the near fixation condition, horizontal targets appear
extended from fixation near the horizontal midline while vertical targets appear extended from fixation near the vertical midline. In the far from fixation condition, horizontal targets appeared extended from fixation near the vertical midline and vertical targets appeared extended from fixation near the horizontal midline. This is unfortunate because, as mentioned above, there are asymmetries in the sensitivity of locations in the visual field. Sensitivity to stimuli along the upper vertical midline suffers dramatically compared to sensitivity in other areas of the visual field, notably along the horizontal midline (Carrasco et al, 2001; Abrams et al, 2012). This means that, in the near fixation condition of Experiment 3 of Barnas et al (2016), horizontal targets appeared at locations known to be more sensitive than some locations where vertical targets appeared. In the far fixation condition, this was reversed: horizontal targets could appear at less sensitive locations while vertical targets always appeared on the horizontal midline. If this visual field asymmetry was driving the effect, we would expect Barnas et al (2016) to find a horizontal advantage in the near fixation condition but not in the far fixation case, which is exactly what they found. This makes it difficult to know if the effect they found was due to a horizontal advantage or due to visual field asymmetries.

In the following experiments, we attempt to better understand this apparent advantage for targets appearing horizontal to an invalid cue. At present, there seems to be some evidence for the existence of this effect but it is unclear whether it is a feature of object-based attention or a more general feature of attention. Tse et al (2003) provided some evidence that this horizontal advantage is not dependent on object-based attention but, as mentioned, there are some interpretative difficulties. In Experiments 1 – 4 below, we describe what we take to be compelling, consistent evidence for such an advantage while systematically ruling out confounds. In Experiments 5-7 we explore some of the boundary conditions of the horizontal
advantage and attempt to determine which of the models presented above might be correct: the localized hotspot account (where there is an advantage for only the horizontally symmetric spot in the opposite hemifield) or the elongated hotspot account (where there is an advantage for all targets horizontal to the cue. We are agnostic about whether such an advantage occurs because of faster shifting of attention or an automatic pooling of attention.
2. An Advantage for Horizontal Targets?

2.1 Experiment 1

In Experiment 1, we had participants complete a visual search task in which they were instructed to covertly find a face among non-faces. The target array (consisting of 1 target face and 2 non-target non-faces) was preceded by a spatial precue. The cue onset before the target array and its validity as a spatial cue was manipulated. On 50% of trials, the target appeared exactly where the cue had appeared (a valid trial). On the other 50% of trials, the target appeared on the other side of fixation in the hemifield opposite to that where the cue appeared (an invalid trial). In order to test whether there is a performance advantage for targets appearing horizontal to the cue we subdivided the invalid trials into two basic kinds: those where the target subsequently appeared horizontal to the cue and those where the target appeared diagonal to the cue.

Methods

Participants

Twelve participants were recruited from the University of Illinois at Urbana-Champaign in exchange for credit in an introductory Psychology course. All 12 gave informed consent based on the University of Illinois IRB protocol and reported normal or corrected-to-normal vision and color vision. One participant was excluded because they got fewer than 60% of the experimental (non-practice) trials correct. The analysis was conducted on the remaining 11 participants.

Apparatus, Stimuli, and Procedure

Participants were seated 57 cm (chinrest enforced) from a 24-inch LCD monitor set to a refresh rate of 100 Hz. All stimuli were derived from a single image taken from a publicly
available database (Minear & Park, 2004). This image, used as the target, was a square cutout of a grayscale, Caucasian female face subtending 1.5° x 1.5° of visual angle. Masks and non-targets were 100% phase-scrambled versions of this image.

As each trial began, participants saw a black dot at fixation on a middle gray screen for a randomly chosen time between 300 - 500 ms. Once the fixation dot disappeared, a spatial precue appeared for 50 ms before offsetting. The precue was a black outline square subtending 2.25° x 2.25° of visual angle. After the precue, the screen was blank for 50 ms before the onset of the target array. The target array, consisting of the target and two non-targets, appeared for 100 ms (Figure 1). The target was always the same square cutout face and the non-targets were different phase-scrambled versions of this face. The target appeared right-side up on half of the trials and upside down on the other half. After 100 ms, three masks appeared in the same locations as the items on the target array. These masks were phase-scrambled versions of the target face and were always different from both the non-targets and each other. The masks stayed on the screen until either a response was made or 3000 ms had passed since the target array appeared. If the participant got the trial correct, the word ‘correct’ would appear at fixation for 300 ms. If the participant got the trial incorrect, the word ‘incorrect’ would appear at fixation along with a loud tone for 300 ms. Next, a 500 ms black screen appeared before the next trial started.

Participants were instructed to covertly search the target array and indicate via keypress whether the target face on a given trial was upright (the ‘z’ key) or upside down (the ‘?’ key). Participants were told to respond quickly but without sacrificing accuracy and were strongly encouraged to keep their eyes at fixation during trials. Trials without responses were terminated after 2000 ms and marked incorrect. Participants completed 1 practice block of 48 trials (not included in analysis) and then 10 experimental blocks of 48 trials. After each block, participants
took a self-timed break. During the break their accuracy on the just-completed block was displayed along with their highest accuracy score on any previously completed block and another admonishment to keep their eyes at fixation during the trials.

The spatial precue appeared on the horizontal midline, 5° of visual angle from fixation (cue side, left or right, was counterbalanced). Cue validity was manipulated. On 50% of trials, the target appeared in the same location as the cue (they were centered at the same place on the screen). These were valid trials. On the other 50% of the trials, the target appeared in the visual hemifield opposite the cue. These were invalid trials. On invalid trials, the target appeared 5° of visual angle from fixation in one of three locations: on the horizontal midline, above the horizontal midline, or below the horizontal midline. These three types of invalid trials occurred equally often, meaning that each of these conditions (invalid-above, invalid-midline, and invalid-below) constituted about 16.7% of the total trials (50% invalid trials / 3 types of invalid trials). Targets above/below the horizontal midline were placed 50° of polar angle from the vertical midline. Two non-targets always appeared with the target. One of the non-targets was centered 1.75° of visual angle to the left or right of the target, always to the outside (away from fixation). The other non-target was centered 1.75° of visual angle above or below (chosen randomly on each trial) the target. The non-targets were placed close enough to the target that we expected them to strongly interfere/compete with it (Kastner, De Weerd, Desimone, & Ungerleider, 1998; Kastner, De Weerd, Pinsk, Elizondo, Desimone, & Ungerleider, 2001). This interference, coupled with the short exposure time before masking (100 ms), should reduce the amount of information the visual system can quickly extract about the target and help make differences in attentional deployment more obvious.

When the cue was invalid and the target appeared on the horizontal midline it was
directly horizontal from the cue. When the cue was invalid and the target appeared above or below the horizontal midline, the target was diagonal from the cue. For analysis, the invalid-above and invalid-below conditions were combined into an invalid-diagonal condition. Because each of the three invalid conditions appeared equally often and the above and below conditions are combined in the invalid-diagonal condition, the invalid-diagonal condition constituted about 33.3% of trials while the invalid-horizontal condition constituted about 16.7% of trials. The remaining 50% of trials were valid trials.

The predictions for Experiment 1 are straightforward. The previous research indicates that there might be an attentional benefit for targets appearing horizontal to an invalid cue. This could result from some horizontal pooling of attention or from a benefit for shifting attention horizontally to a target. In either case, a horizontal advantage should manifest here in terms of a behavioral benefit for the invalid-horizontal condition relative to the invalid-diagonal condition. Pilot work led us to believe that this behavioral benefit would appear as an advantage in accuracy for the invalid-horizontal condition relative to the invalid-diagonal so we focus on accuracy below.

Results

Descriptive statistics (see Figure 3): Accuracy in the valid condition (M = 91.3%, SD = 5.2%) was like that of the invalid-horizontal condition (M = 89.1%, SD = 6.5%) and both were numerically (inferential stats reported below) greater than the invalid-diagonal condition (M = 76.7%, SD = 8.3%). Similarly, response times in the valid condition were slightly faster (M = 593 ms, SD = 59 ms) than those in the invalid-horizontal condition (M = 613 ms, SD = 65 ms) and response times in both conditions were much faster than those in the invalid-diagonal condition (M = 686 ms, SD = 68 ms).
Inferential statistics (see Figure 4): To test the hypothesis that there is an attentional benefit for targets horizontal to an invalid cue we computed a difference score for each participant by subtracting the participant mean in the invalid-diagonal condition from the participant mean in the invalid-horizontal condition. This difference score represents the gain in accuracy for a given participant when the target appeared horizontally to the invalid cue compared to when it appeared diagonally to the invalid cue. (Note: all reported confidence intervals are bias-corrected, accelerated bootstrapped confidence intervals (Efron & Tibshirani, 1993) calculated using the wBoot R package (Weiss, 2016).) The group difference scores show a large benefit for horizontally displayed targets after invalid cues relative to diagonal cues (M = 12.3%, SD = 6.1%, 95% CI of the mean = [8.9%, 15.6%], dz = 2.02, BCa bootstrapped 95% CI of dz = [1.37, 3.02]).

A Monte Carlo randomization test was conducted to determine whether this observed benefit was greater than chance. Assuming the null is true (that the invalid-horizontal and invalid-diagonal conditions come from the same distribution), then for each participant their observed score in one of the conditions is equally likely to have been observed in the other condition. To simulate this, we conducted 100,000 iterations where on every iteration each participant had a 50% chance that the condition labels on their two scores were switched. After going through each participant and either switching or not switching their condition labels, differences scores were again computed and the mean difference score was taken. This process was repeated 100,000 times and 100,000 difference scores were collected. If there is no actual difference between the two conditions, then the difference score we observed in our data (12.3%) should not be extreme compared to the distribution of difference scores generated in the randomization test. Of the 100,000 iterations run, 0 produced a difference score with an absolute
value as great or greater than the observed one. The p-value is thus < .001 (Phipson & Smyth, 2010).

Exploratory statistics: While the primary analysis in Experiment 1 concerns accuracy, a glance at the response time data (Figure 4) shows trends like those in the accuracy data. Difference scores were computed for the response times of the two conditions of interest. We subtracted each participant’s response time in the invalid-horizontal condition from their response time in the invalid-diagonal condition. These difference scores showed that responses in the invalid-diagonal condition took substantially longer than those in the invalid-horizontal condition (M = 73 ms, SD = 37 ms, 95% CI of the mean = [51 ms, 93 ms], dz = 1.96, 95% CI of the effect size = [0.83, 3.14]). A randomization test (using the same procedure as above and uncorrected for multiple corrections/exploratory analyses) was conducted. Of the 100,000 iterations, 101 produced a difference score with an absolute value as great or greater than the observed one (73 ms), p = 0.001.

Discussion

Experiment 1 revealed a large accuracy benefit when targets appeared horizontal to the invalid cue relative to when they appeared diagonal to the cue. Note that due to the display setup in Experiment 1 (see Figure 5 below) the visual distance between the targets in the invalid-diagonal condition and the cue is slightly less than the visual distance between the targets in the invalid-horizontal condition and the cue. It is even more surprising, then, that participants are much better at detecting targets that appear horizontal to the invalid cue because those targets are farther away than targets appearing diagonal to the cue.

This result is consistent with previous literature showing what appears to be either a pooling of attention horizontal to the cue (Tse et al, 2003) or a benefit for shifting attention
horizontally rather than vertically (Pilz et al, 2012; Barnas et al, 2016). However, while Tse et al (2003) found an accuracy advantage in a change detection task for targets that appeared in the hemifield opposite to the cue, only three participants were analyzed in the study and the effects were not ultra-consistent between participants. Pilz et al (2012) also found a response time advantage for targets appearing horizontal (relative to vertical) to an exogenous cue in an object-based attention task. However, again, the horizontal advantage found by the researchers was not always present. Barnas et al (2016) followed up on the Pilz et al (2012) study and found a seemingly consistent horizontal (relative to vertical) response time advantage in an object-based attention paradigm (though some of their studies have important confounds, see section 1.5 above). Both Pilz et al (2012) and Barnas et al (2016) interpreted the horizontal advantage as a property of object-based attention, which is not surprising given that both sets of researchers were using object-based attention paradigms). However, the present results, along with those of Tse et al (2003), indicate that the horizontal advantage is likely not due to peculiarities of object-based attention, but rather apply more fundamentally to spatial attention itself.

If this the above is correct, this might affect both our interpretations of some classic cognitive psychology paradigms and refine our understanding of the costs of the re-deployment of attention. For instance, both the Egly et al (1994) object-based attention paradigm and the Posner (1980) cueing task involve exogenous cues followed by targets that sometimes appeared horizontal to the cue after it was invalid. The results of Experiment 1 could imply that the cost of redirecting attention after an invalid cue found in the Posner cueing task might be a large underestimate of the cost of redirecting attention non-horizontally. Participants in the Posner task redirect attention horizontally after an invalid cue, however Experiment 1 seems to show that horizontal redirections are substantially easier than diagonal redirections, even when diagonally
placed targets are closer than horizontally placed targets.

Before drawing strong conclusions, there are a few concerns with Experiment 1 that might complicate things. First, because of the way the displayed were arranged (see Figure 5 below), the positions on the midline where the targets appeared represent the center of mass of possible target locations. One strategy that participants might have used is to “split the difference” and attentionally weight these midline positions. This strategy could explain the performance benefit in the invalid-horizontal condition relative to the invalid-diagonal because targets always appear on the midline in the invalid-horizontal condition and never in the invalid-diagonal condition. If participants preferentially deployed attention to the midline we would expect them to be better at detecting targets in the invalid-horizontal condition relative to the invalid-diagonal.

Another similar concern relates to the spatial probability of targets. As noted, 50% of trials were valid, about 33.3% of trials were invalid-diagonal, and about 16.7% of trials were invalid-horizontal. Since all cues appeared on the horizontal midline, all targets in the valid condition also appeared on the horizontal midline. Targets also appeared in the horizontal midline in the invalid-horizontal condition, meaning that, overall, targets appeared on the horizontal midline about 66.7% of the time. Previous researchers have argued that the spatial probability of a target can influence the deployment of attention (Geng & Behrmann, 2002). The idea is that the visual system can learn where in space targets are more likely to appear and can use this information to preferentially process these locations. If this is true, then participants in Experiment 1 may have learned that targets are twice as likely to appear on the midline than above or below the midline and may have thus preferentially deployed attention there. This would result in performance benefits for targets on the midline (invalid-horizontal) relative to
those off the midline (invalid-diagonal). Put simply, participants may have just learned to attend to where the targets were likely to appear. We address the spatial probability confound in Experiment 2.

2.2 Experiment 2

In Experiment 2, we attempted to replicate Experiment 1 while controlling the spatial probability of targets. In Experiment 1, the spatial precue always appeared on the horizontal midline. This meant that targets in the valid condition always fell on the midline, making the midline a highly probable place for targets to appear. In Experiment 2, we fixed this confound by making the targets appear equally often at all six locations (Figure 5). On both valid and invalid trials, the cue had a 16.7% chance of appearing at any location. When cues were valid, the targets thus appeared equally often at all six locations. When cues were invalid, the target appeared equally often at all three of the locations in the visual hemifield opposite the cue (across from fixation). Thus, over the course of the experiment and within each block, targets appeared equally often at all six locations. If the horizontal advantage found in Experiment 1 was due to participants learning the likely locations of targets, we should not find the effect in Experiment 2.

Similarly, in Experiment 2 the strategy of preferentially deploying attention to the midline would not differentially affect any one condition over another. In Experiment 1 targets in both the valid and the invalid-horizontal conditions always appeared on the midline and they never appeared on the midline in the invalid-diagonal condition. In Experiment 2, targets appeared on the midline 1/3 of time in all 3 conditions. Thus, while preferentially attending to the midline would increase performance for targets on the midline, it would not benefit one
condition over another.

Methods

Participants

Fourteen participants were recruited from the University of Illinois at Urbana-Champaign in exchange for credit in an introductory Psychology course. All 14 gave informed consent based on the University of Illinois IRB protocol and reported normal or corrected-to-normal vision and color vision. Two participants were excluded because they got fewer than 60% of the experimental (non-practice) trials correct. The analysis was conducted on the remaining 12 participants.

Apparatus, Stimuli, and Procedure

The apparatus, stimuli, and procedure were all identical that described in Experiment 1. The only difference between Experiment 1 and Experiment 2 was the placement of the stimuli. In Experiment 1, cues always appeared on the horizontal midline. In Experiment 2, cues could appear at any of the 6 locations where targets could appear (Figure 5). Cues were again valid on 50% of trials and invalid on 50% of trials. When invalid, the cues appeared equally often at all three of the locations on the other side of fixation from the cue. For each cue location (on invalid trials) there is one target location that is directly horizontal to it and two that are diagonal from it. We again combined the two diagonal locations into one invalid-diagonal condition to compare to the invalid-horizontal condition.

Results

Descriptive statistics (see Figure 6): Accuracy in the valid condition (M = 86.9%, SD = 8.8%) was higher that of the invalid-horizontal condition (M = 82.1%, SD = 6.0%) and both were higher than the invalid-diagonal condition (M = 76.1%, SD = 10.1%). Similarly, response
times in the valid condition were much faster ($M = 644$ ms, $SD = 76$ ms) than those in the invalid-horizontal condition ($M = 724$ ms, $SD = 70$ ms) and response times in the invalid-diagonal condition ($M = 749$ ms, $SD = 87$ ms) were a bit slower than those in the invalid-horizontal condition.

Inferential statistics (see Figure 7): To test the hypothesis that there is a benefit for targets horizontal to an invalid cue we again computed a difference score for each participant by subtracting the participant mean in the invalid-diagonal condition from the participant mean in the invalid-horizontal condition. This difference score represents the gain in accuracy for a given participant when the target appeared horizontally to the invalid cue compared to when it appeared diagonally to the invalid cue. The group difference scores ($M = 6\%$, $SD = 7.3\%$, 95% CI of the mean = [2.7\%, 10.7\%], $dz = 0.83$, 95% CI of the effect size = [0.29, 1.28]) show a benefit for horizontally displayed targets after invalid cues relative to diagonal cues. We again conducted a randomization test to determine whether the observed difference was greater than that expected by chance. The procedure was the same as in Experiment 1. Of the 100,000 iterations run, 829 produced a difference with an absolute value as great or greater than the observed difference (6\%), returning $p = 0.008$.

Exploratory analyses: Difference scores (invalid-diagonal minus invalid-horizontal) were again computed using the response times of the two conditions of interest. These difference scores revealed that responses in the invalid-diagonal condition took slightly longer than those in the invalid-horizontal condition ($M = 25$ ms, $SD = 43$ ms, 95% CI of the mean = [2 ms, 49 ms], $dz = 0.58$, 95% CI of the effect size = [-0.07, 3.14]). A randomization test (using the same procedure as above and again uncorrected for multiple corrections/exploratory analyses) was conducted. Of the 100,000 iterations, 6914 produced a difference score with an absolute value as
great or greater than the observed one (25 ms), \( p = .069 \). Note the marginal results: the confidence interval for the mean does not include zero but the confidence interval for the effect size does. Furthermore, the randomization test returned a \( p \) value just greater than the traditional cutoff. This is not overwhelming evidence for an actual difference in response times, but it is also not good evidence against there being a real but small effect.

**Discussion**

In Experiment 2 we again found that participants were more accurate (6.1%) when targets appeared horizontal to an invalid cue relative to when targets appeared diagonal to an invalid cue. We found a similar result in Experiment 1, however the spatial probability of targets was confounded with targets appearing horizontal to the invalid cue. Here, we find a similar result after controlling for spatial probability. We thus conclude that spatial probability is unlikely to (completely) explain the effect. Similarly, we addressed concerns about participants preferentially placing their attention on the midline (center of mass) by de-confounding target appearance on the midline with condition. Participants may well be preferentially attending to the midline. Accuracy was higher when targets appeared on the midline (86.0%) than when it appeared either above or below the midline (80.4%), however this was driven more by accuracy being lower when targets appeared below the midline (77.5%) than above the midline (83.4%). In any case, this strategy cannot explain the effect observed in Experiment 2.

It is worth noting the differences in results between Experiments 1 and 2. Overall accuracy rates were lower and response times were higher in Experiment 2 compared to Experiment 1. This is consistent with the task in Experiment 2 being more difficult due to the greater spatial uncertainty of the target. Perhaps because of the increased difficulty, the effect size observed in Experiment 2 (\( dz = .83 \)) was much smaller than the one found in Experiment 1.
(dz = 2.02). Furthermore, the response times in the invalid-horizontal condition and invalid-diagonal condition are much more similar (25 ms difference) in Experiment 2 than in Experiment 1 (73 ms difference). Taken together, this could mean that some of the effect observed in Experiment 1 is explainable by either the spatial probability of the target or the center of mass strategy, though the results of Experiment 2 indicate that it is unlikely to explain the entire effect.

Despite controlling for the spatial probability of targets and de-confounding target appearance on the midline from condition, there is another concern with Experiment 2. In Experiment 1, since all cues were on the horizontal midline, the distance between the cue and the target was slightly less in the invalid-diagonal condition than in the invalid-horizontal condition. This made it particularly surprising that participants were much better at detecting a target when it was horizontal to the cue compared to diagonal to the cue. In Experiment 2, though, the distances are not as well controlled. When cues appear on the midline the situation is the same as in Experiment 1: invalid-diagonal targets are closer than invalid-horizontal targets. However, when cues are above or below the midline, invalid-diagonal targets are now farther from the cue than invalid-horizontal targets. When a cue appears in the top left location in Figure 5, the position directly horizontal to the cue is closer to the target than the position on the midline (a diagonal location) and much closer to the target than the position on the bottom right (the other diagonal location). Since cues appeared above or below the midline 66.7% of the time, this means that invalid-diagonal targets were more likely to be farther away from the cues than invalid-horizontal targets. If behavioral performance is inversely related to the distance between an exogenous cue and the target, as some researchers have argued (Henderson, 1991; Henderson & Macquistan, 1993), this might explain why participants in Experiment 2 were better in the invalid-horizontal condition than in the invalid-diagonal. However, it is worth noting that this
explanation would not explain the effect observed in Experiment 1 (since targets in the invalid-diagonal condition were closer to the cues than targets in the invalid-horizontal condition). We address this concern in Experiment 3.

2.3 Experiment 3

In Experiment 3, we attempted to replicate the findings of Experiments 1 and 2 while controlling for the concerns noted above: spatial probability of targets, center of mass attentional deployment, and differential distances between cues and targets. We did this by taking the same task as in Experiments 1 and 2 and using a new display arrangement: a square with four cue/target positions, one at each vertex (Figure 8). Cues could appear at any of the four locations on the square and, when the cue was invalid, the target could either appear horizontal to the cue across the vertical midline (invalid-horizontal) or vertical to the cue across the horizontal midline (invalid-vertical). Targets appeared equally often at all locations in all conditions. There were no target positions in a center of mass for participants to preferentially attend, no targets on the horizontal midline, and the distance between the targets and cues in the invalid-horizontal position was equivalent to the distance between targets and cues in the invalid-vertical condition. If the distance confound in Experiment 2 explains the effect observed in Experiment 2 and if either spatial probability or the center of mass strategy in Experiment 1 explains the effect found in Experiment 1 we should find no differences between the invalid-horizontal and the invalid-vertical conditions in Experiment 3. If, on the other hand, there is an attentional advantage for targets appearing horizontal to an invalid-cue relative to targets presented non-horizontal to a cue, then performance in the invalid-horizontal condition should be higher than performance in the invalid-vertical condition in Experiment 3.
Methods

Participants

Twelve participants were recruited from the University of Illinois at Urbana-Champaign in exchange for credit in an introductory Psychology course. All 12 gave informed consent based on the University of Illinois IRB protocol and reported normal or corrected-to-normal vision and color vision.

Apparatus, Stimuli, and Procedure

Experiment 3 was identical to Experiment 1 except for the following. In Experiment 3, participants completed 1 practice block of 64 trials (not included in analysis) and 6 experimental blocks of 64 trials each. In Experiment 3, the display was an imaginary square centered at fixation. The vertices of the square were located 5° of visual angle from fixation and are the locations where the cues and targets appeared. The distance between any two vertices along a side of the imaginary square was about 7.1° of visual angle. Starting from the upper half of the vertical midline (which would be 0° of polar angle) the vertices appeared at 45°, 135°, 225°, and 315° of polar angle, respectively.

Another departure in Experiment 3 was that the locations of the two phase-scrambled non-targets that appeared next to the targets were fixed such that they always appeared on the two sides of the target facing away from fixation. For instance, if the target appeared at the top right vertex of the square, the non-targets would appear above and to the right of the target. If the target appeared at the bottom left of the vertex, the non-targets would appear below and to the left of the target. Cues were again valid on 50% of trials and invalid on 50% of trials. When invalid, the target could appear in one of two positions: either on the vertex directly horizontal to the cue or on the vertex directly vertical to the cue. When invalid, the target never appeared at
the vertex diagonal to the cue.

Results

Descriptive statistics (Figure 9): Accuracy in the valid condition (M = 90.2%, SD = 3.9%) was higher than in the invalid-horizontal condition (M = 85.4%, SD = 5.5%) and accuracy in both conditions were substantially higher than in the invalid-vertical condition (M = 75.6%, SD = 8.5%). Similarly, response times in the valid condition were much faster (M = 585 ms, SD = 70 ms) than those in the invalid-horizontal condition (M = 667 ms, SD = 107 ms) and response times in the invalid-vertical condition (M = 701 ms, SD = 124 ms) were somewhat slower than those in the invalid-horizontal condition.

Inferential statistics (Figure 10): We again computed a difference score for each participant by subtracting the participant mean in the invalid-vertical condition from the participant mean in the invalid-horizontal condition. This difference score will be positive when a participant’s accuracy is higher in the invalid-horizontal condition than in the invalid-vertical condition. The group difference scores show a large benefit for horizontal, relative to vertical, targets after invalid cues (M = 9.8%, SD = 8.2%, 95% CI of the mean = [5.8%, 14.7%], dz = 1.2, 95% CI of the effect size = [0.71, 1.66]). A randomization test was conducted to determine whether this observed difference was greater than that expected due to chance. The procedure was the same as in Experiment 1. Of the 100,000 iterations run, 42 produced a difference score with an absolute value as great or greater than the observed difference (9.8%), returning a p < 0.001.

Exploratory analyses: Once again, we computed response time difference scores. We subtracted each participant’s response time in the invalid-horizontal condition from their response time in the invalid-vertical condition. The differences scores revealed that responses in
the invalid-vertical condition took perhaps a little longer than those in the invalid-horizontal condition (M = 34 ms, SD = 45 ms, 95% CI of the mean = [13 ms, 64 ms], dz = 0.75, 95% CI of the effect size = [0.32, 1.23]). A randomization test (using the same procedure as above and uncorrected for multiple corrections/exploratory analyses) was conducted. Of the 100,000 iterations, 2282 produced a difference score with an absolute value as great or greater than the observed one (34 ms), p = 0.023. We seem to have a bit more evidence in Experiment 3 than in Experiment 2 for a small difference in response times between horizontal targets and non-horizontal targets. However, again, the evidence not terribly strong.

Discussion

Experiment 3 produced similar results to Experiments 1 and 2: following an invalid cue, participants performed significantly better when targets appeared at a location horizontal to the cue than when targets appeared in non-horizontally to the cue. Experiment 3 also extends Experiments 1 and 2 by providing evidence that the advantage for targets appearing horizontal to an invalid cue observed in the first two experiments is actually an advantage for horizontal targets and not just a detriment for diagonal targets. Since we find a similar advantage for horizontally presented targets relative to vertically presented targets here, we can increase our confidence that horizontally presented targets might be special.

Furthermore, as mentioned above, previous researchers have found an advantage for horizontal targets following an exogenous cue. Pilz et al. (2012) and Barnas et al. (2016) showed such an advantage in the context of an object-based attention paradigm and, reasonably, concluded that the advantage was likely to be a property of object-based attention. In Experiments 1 and 2 we provide evidence that this effect might not be limited to object based attention. Experiment 3 now replicates Experiments 1 and 2 using stimuli placement like that
used in Pilz et al (2012) and Barnas et al (2016), thus increasing confidence that the present effects are reflective of the same mechanisms as those observed by previous researchers.

Experiment 3 also alleviated a concern about Experiment 2. Recall that the invalid-diagonal targets were usually farther away from the cue than the invalid-horizontal targets. This means that participants might have performed worse in the invalid-diagonal condition relative to the invalid-horizontal condition because they needed more time to deploy attention to farther away targets. Experiment 3 solved this problem by controlling the distance between cues and targets between conditions: targets were 7.1° of visual angle from cues in all conditions. Since we still find an advantage for horizontal targets, we conclude that the distance confound in Experiment 2 does not explain the entire effect.

However, the display arrangement in Experiment 3 gives rise to a different concern. The display in Experiment 3 was an imaginary square centered at fixation (Figure 8). When the cue was invalid, targets in the invalid-horizontal condition always appeared in a different visual hemifield (left or right) than the cue had previously appeared in while targets in the invalid-vertical condition always appeared in the same visual hemifield as the cue had previously appeared in. Some researchers have argued that the left and right cortical hemispheres have different pools of attentional resources (Alvarez and Cavanaugh, 2005; Franconeri, Alvarez, & Enns, 2007) and that processing of difficult visual tasks is thus easier when the stimuli fall into different visual hemifields as opposed to the same hemifield (though see Scalf & Beck, 2010 and Clevenger & Beck, 2014). If true, this might mean that cues and targets in the invalid-horizontal condition of Experiment 3 were processed by separate pools or resources while the cues and targets in the invalid-vertical condition were processed by the same pool of resources. This might cause a benefit in performance for the invalid-horizontal condition relative to the invalid-vertical
condition by virtue of the invalid-vertical condition being more resource intensive. We should note that while Experiment 3 suffers from this concern, the previous experiments do not. In both Experiments 1 and 2 targets in both the invalid-horizontal and invalid-diagonal conditions appear in the visual hemifield opposite to the cue. In other words, there is no asymmetry between conditions in terms of hemifield load.

2.4 Experiment 4

In Experiment 4, we attempted to address the concern with Experiment 3 that asymmetrical hemifield load might explain the observed advantage for horizontal relative to vertical targets. We did this by altering the stimuli placement relative to Experiment 3. In Experiment 3, the stimuli appeared at the vertices of an imaginary square centered at fixation (Figure 8). This led to two invalid conditions: one where the targets appeared directly horizontal to the cue and one where the targets appeared directly vertical to the cue. In Experiment 4, we rotated the imaginary square either left or right so that both invalid conditions involved targets appearing diagonally from the cue, meaning there were no horizontal targets (Figure 11). However, we kept the asymmetrical hemifield load from Experiment 3. When an invalid cue appeared the target could either appear (diagonally) in the same hemifield as the cue or (diagonally) in the opposite hemifield as the cue. If the advantage for horizontal targets that we found in Experiment 3 occurred because of an asymmetrical hemifield load we should find a similar difference in Experiment 4. However, if the advantage was due to an attentional benefit for horizontally presented targets following invalid cues, we should not find such a difference here.

Methods
Participants

Thirteen participants were recruited from the University of Illinois at Urbana-Champaign in exchange for credit in an introductory Psychology course. All 13 gave informed consent based on the University of Illinois IRB protocol and reported normal or corrected-to-normal vision and color vision. One participant was excluded because they got fewer than 60% of the experimental (non-practice) trials correct. The analysis was conducted on the remaining 12 participants.

Apparatus, Stimuli, and Procedure

Experiment 4 was identical to Experiment 3 except for the following. In Experiment 4, the display was a rotated imaginary square (Figure 11). There were two versions of the display. One version had the vertices placed (with 0° of polar angle being on the upper half of the vertical midline) at 75°, 165°, 255°, and 345° of polar angle, respectively (left panel of Figure 11). The other version had vertices placed at 15°, 105°, 195°, and 285° of polar angle, respectively (right panel of Figure 11). Each participant was assigned to one of the two display types with assignment alternating back and forth as participants came in. Participants only saw trials of one display type. The vertices of the square were again located 5° of visual angle from fixation and were the locations where the cues and targets appeared. The distance between any two vertices along a side of the imaginary square was about 7.1° of visual angle. Cues were again valid on 50% of trials and invalid on 50% of trials. When invalid, the target could appear in one of two positions: either on the vertex in the same visual hemifield as the cue or on the vertex in the opposite visual hemifield as the cue. When invalid, the target never appeared at the vertex diagonal to the cue.

Results

Descriptive statistics (see Figure 12): Accuracy in the display where the first vertex on
the right was placed 75° from the upper vertical midline (left panel of Figure 11) (M = 81.4%, SD = 10.9%) did not substantially differ from accuracy in the other display (right panel of Figure 11) (M = 80.6%, SD = 4.4%). Accuracy in the valid condition (M = 84.9%, SD = 7.0%) was higher than that in both the invalid-different hemifield condition (M = 76.3%, SD = 10.2%) and the invalid-same hemifield condition (M = 77.7%, SD = 8.9%). Response times in the valid condition were much faster (M = 698 ms, SD = 75 ms) than those in both the invalid-different hemifield condition (M = 748 ms, SD = 69 ms) and the invalid-same hemifield condition (M = 768 ms, SD = 80 ms).

*Inferential statistics* (see Figure 13): We again computed a difference score for each participant. We subtracted the participant mean in the invalid-same hemifield condition from the participant mean in the invalid-different hemifield condition. This difference score will be positive to the extent that a participant was more accurate in the invalid-different hemifield condition than in the invalid-same hemifield condition. The group difference scores show only a minimal difference between the two conditions (M = -1.4%, SD = 6.3%, 95% CI of the mean = [-5.9%, 1.3%], dz = 0.42, bootstrapped 95% CI of the effect size = [-0.6, 0.79]). We again conducted a randomization test to determine whether the observed difference was greater than that expected due to chance. The procedure was the same as in previous experiments. Of the 100,000 iterations run, 47546 produced a difference with an absolute value as great or greater than the observed difference (-1.4%), returning p = 0.475.

*Exploratory analyses*: We analyzed the response time scores for both the invalid-same hemifield condition and the invalid-different hemifield condition. We again computed difference scores. We subtracted each participant’s response time in the invalid-same hemifield condition from their response time in the invalid-different hemifield condition. The differences scores
revealed a small benefit for the invalid-different hemifield condition ($M = 20 \text{ ms}, \text{SD} = 31 \text{ ms}, 95\% \text{ CI of the mean} = [1 \text{ ms}, 35 \text{ ms}], dz = 0.64, 95\% \text{ CI of the effect size} = [-0.21, 1.42])$. A randomization test (using the same procedure as above and uncorrected for multiple corrections/exploratory analyses) was conducted. Of the 100,000 iterations, 4858 produced a difference score with an absolute value as great or greater than the observed one (20 ms), $p = 0.049$.

**Discussion**

In Experiment 4 we were interested in determining whether the benefit for horizontal targets found in Experiment 3 was due to asymmetric hemifield load rather than an actual advantage for targets presented horizontal to an invalid cue. We tried to test between these two accounts by preserving asymmetric hemifield load while removing horizontal targets. When cues were invalid, some targets appeared diagonally in the same hemifield as the cue and some appeared diagonally in the opposite hemifield as the cue. If hemifield load was responsible for the effect in Experiment 3 we should have found an advantage for those targets appearing in a different hemifield for the cue, which we did not. In fact, performance when targets appeared in a different hemifield (76.3%) was effectively identical to performance when targets appeared in the same hemifield as the cue (77.7%). This increases our confidence that asymmetric hemifield load does not explain the effect observed in Experiment 3.

Experiment 4 has another property of interest: in the invalid condition, the target appeared at two levels of steepness (relative to horizontal) from the cue. If the horizontal midline is $0^\circ$ of polar angle, the target appears either $60^\circ$ of polar angle above or below the cue in the same hemifield condition and $30^\circ$ of polar angle above or below the cue in the different hemifield condition. This might be important if there is a continuous detriment to performance
the more un-horizontal (i.e., steeper) the shift of attention is between the cue and the target. This might be true under a variety of models of the effect. If horizontally presented targets benefit because shifting attention horizontally is easier/faster than shifting attention non-horizontally, the more horizontal component there is in a shift vector the better performance might be.

Thus, we might expect performance to be better when shifting 30° than shifting 60° because there is a larger horizontal component to the 30° shift vector. Alternatively, we might also expect a gradation of performance if there is an automatic, horizontal deployment of attention following an exogenous cue (either a localized one in the opposite hemifield or one emanating horizontal to the target). If the automatic deployment of attention is a distribution rather than a point mass we might expect that attentional shifts that end up closer to the distribution (here the 30° of polar angle shifts) would benefit more than attentional shifts ending farther from the distribution. In this case, the benefit would not arise from the horizontal component of a shift per se, but from the ending nearness of an attentional shift to the automatically deployed attentional distribution. However, we did not observe any accuracy difference between these differently steep shifts.

The lack of accuracy advantage for targets appearing more horizontal to the cue might help rule out certain accounts of the phenomenon (though the experiment was not designed to test between steepness and so conclusions should be considered cautiously). If the speeded shift account of the effect is correct, the lack of difference in Experiment 4 might indicate that horizontal shifts are categorically different than diagonal or vertical shifts. In other words, shifting attention to a location diagonal to an invalid cue might not consist of simply summing some magnitude of horizontal shift with some magnitude of vertical shift. Horizontal shifts, then, might benefit because they involve leveraging some structural aspect of the brain, like the symmetrical architecture of the cortical hemispheres. For instance, deploying attention to a
certain location in the left visual field might involve higher order areas sending signals to the right cortical hemisphere. It is possible that these higher order signals, which might originate in less lateralized areas, propagate to both hemispheres or must be inhibited from propagating to both hemispheres in order to achieve a lateralized attentional signal. In other words, the wiring between the lateralized visual areas and the unified higher order areas might be a bit kludgy. If the higher order areas are connected to symmetrical locations in visual areas, then sending a signal to one location in the left hemisphere might prime the system to increase activity at a symmetrical location in the right hemisphere. This account would also be consistent with the automatic deployment of attention in the opposite hemifield observed in previous work (Tse et al, 1993).

Furthermore, the lack of difference between the same-hemifield and different-hemifield conditions might be some evidence against a certain flavor of the automatic deployment account. When the cue is invalid, the target ends up much closer to a horizontal (and symmetrical) location in the different-hemifield condition than in the same-hemifield condition (see Figure 11). If the automatic deployment account is correct and there is a somewhat large distribution of attention either horizontal to the target or in a location horizontally-symmetric to the cue, then we might expect a benefit for targets that ended up closer to that distribution (invalid-different) than targets that ended up farther away from it (invalid-same). However, we did not find much evidence for such a difference. It is worth pointing out that we did find a small amount of evidence for a response time benefit for invalid-different targets relative to invalid-same targets. While this evidence is not entirely convincing, it certainly does not rule out the possibility that there is a small response time benefit. This would, of course, meter the considerations just mentioned.
To recap a bit, in Experiment 1 we found a large performance advantage for targets appearing horizontal to an invalid cue relative to targets appearing diagonal to it. In Experiment 2, we replicated the effect while ruling out spatial probability as a potential cause. In Experiment 3, we found another performance advantage for targets appearing horizontal to an invalid cue. This time, though, the advantage was relative to targets appearing vertical to an invalid cue. We also ruled out distance between the targets and cue as a potential cause. In Experiment 4, we eliminated targets appearing horizontal to an invalid cue and failed to find a performance advantage. This was important because it ruled out asymmetric hemifield load as a potential cause of the effect.

Each of the first three experiments provides some support for a benefit for targets appearing horizontal to an exogenously cued location. Taken together, they appear to provide relatively strong evidence for the existence of such an effect. Furthermore, these experiments imply that the horizontal advantage found in the previous literature is not, as claimed, solely a feature of object-based attention and may be a more general feature of attention. In the next section, we discuss an experiment testing whether the flanking non-targets are necessary for the horizontal advantage to arise. We then report two experiments designed to test between the localized and the elongated hotspot accounts.
3. Boundary Conditions

3.1 Experiment 5

In Experiment 5, we attempt to see whether the flanking non-targets used in the previous experiments are necessary to find an advantage for horizontal targets. Figure 2 shows the non-targets that have previously appeared next to the targets. The non-targets were used to increase the difficulty of the task. They were phase-scrambled versions of the target face and thus shared low-level visual properties with the target. They were also placed close enough to the target (centered 1.75° of visual angle from the center of the target) that we expected them to interfere via crowding/competition (Kastner et al, 1998). The idea is that when targets and non-targets appear, their representations will be similar enough and close enough to interfere with each other. This interference (or competition) will reduce the quality of the representations and increase the need for attention to resolve that interference (Desimone & Duncan, 1995; Reynolds & Heeger, 2009). Thus, the flankers mainly serve to increase the sensitivity of the experiment to differences in attentional deployment. However, while the real world is nearly always cluttered, experiments in perception/attention often involve uncluttered displays. This makes it worthwhile to investigate whether the clutter we have previously used is necessary to find the effects. In Experiment 5, we attempted to determine this by running an experiment like Experiment 3 (with the square display) while manipulating whether the flanking non-targets were present.

Methods

Participants

In Experiment 5 we effectively double the number of conditions that were run in Experiment 3. This meant we had fewer trials per condition in Experiment 5 than in Experiment
3. In order to alleviate that loss in power, we increased our target number of participants from 12 to 20. Twenty participants were recruited from the University of Illinois at Urbana-Champaign in exchange for credit in an introductory Psychology course. All 20 gave informed consent based on the University of Illinois IRB protocol and reported normal or corrected-to-normal vision and color vision. One participant was excluded because they got fewer than 60% of the experimental (non-practice) trials correct. The analysis was conducted on the remaining 19 participants.

**Apparatus, Stimuli, and Procedure**

   Experiment 5 was identical to Experiment 3 except for the following. In Experiment 5, participants completed the same set of conditions as in Experiment 3 along with a duplicate copy of those conditions where no flanking non-targets ever appeared (only the target, followed by a mask, appeared after the cue). So, in Experiment 5 there were six conditions: valid, invalid-horizontal, invalid-vertical, valid-flankers, invalid-horizontal-flankers, and invalid-vertical-flankers. In Experiment 3, participants completed 384 total trials. With valid and invalid trials appearing equally often, there were 192 valid and 192 invalid trials. When the cue was invalid, horizontal and vertical trials appeared equally, so there were 96 invalid-horizontal and 96 invalid-vertical trials. Experiment 5 included twice as many conditions as Experiment 3, so the trials per cell was halved. There were 192 trials where the non-targets appeared and 192 when they did not. 96 trials were invalid (in both non-target conditions) and 48 trials were invalid-horizontal and 48 trials invalid-vertical.

**Results**

*Descriptive statistics* (see Figure 14): For reporting the results, the conditions where flankers appeared will have “flankers” or, in the plots, “f” attached to them. Accuracy in the valid condition (M = 94.1%, SD = 5.7%) was slightly higher than that in the invalid-horizontal
condition (M = 92.2%, SD = 6.6%) and accuracy in the invalid-vertical condition was lower (M = 87.7%, SD = 12.3%) than in either the valid or invalid-horizontal. Accuracy in the valid-flankers condition (M = 80.8%, SD = 12.9%) was higher than that in the invalid-horizontal-flankers condition (M = 74.3, SD = 11.1%) and accuracy in the invalid-vertical-flankers condition (M = 68.9%, SD = 14.6%) was lower than that in both the valid-flankers and the invalid-horizontal-flankers conditions.

Similarly, response times in the valid condition (M = 567 ms, SD = 67 ms) were substantially faster than those in both the invalid-horizontal condition (M = 631 ms, SD = 85 ms) and the invalid-vertical condition (M = 643 ms SD = 102 ms). Response times in the valid-flankers condition (M = 620 ms, SD = 79 ms) were faster than those in the invalid-horizontal-flankers condition (M = 697 ms, SD = 88 ms) and the invalid-vertical-flankers condition (M = 707 ms, SD = 109 ms).

Inferential statistics (see Figure 15): We again computed difference scores for each participant. We computed one difference score by subtracting a participant’s mean accuracy in the invalid-vertical condition from their accuracy in the invalid-horizontal condition. We computed a second difference score in the same way for the invalid-vertical-flankers and invalid-horizontal-flankers conditions. Again, these difference scores will be positive to the extent that a participant was more accurate when targets were presented horizontal, comparing to vertical, following an invalid cue. The group difference score when flankers were not present showed a reasonably large but just barely detectable advantage for horizontal over vertical targets (M = 4.5%, SD = 10.2%, 95% CI of the mean = [0.009%, 10.1%], dz = 0.44, 95% CI of the effect size = [0.08, 0.80]). We conducted a randomization test to determine whether the observed difference was greater than that expected due to chance. The procedure was the same as in previous
experiments. Of the 100,000 iterations run, 7368 produced a difference with an absolute value as
great or greater than the observed difference (4.5%), returning $p = 0.07$. Again, a discrepancy.
The bootstrapped confidence intervals for both the mean difference and the effect size do not
(just barely) contain zero, returning a significant result, while the randomization test returns a
non-significant result.

The group difference score when flanking non-targets were present also showed a
reasonably sized but just detectable advantage for horizontal over vertical targets ($M = 5.5\%, \ SD
= 10.1\%, 95\% \text{ CI of the mean} = [0.009\%, 10.4\%], dz = 0.51, 95\% \text{ CI of the effect size} = [0.01,
0.95])$. We conducted another randomization test. Of the 100,000 iterations run, 3808 produced a
difference with an absolute value as great or greater than the observed difference (5.5%),
returning $p = 0.04$. In this case, both the randomization test and the bootstrapped confidence
intervals return a just detectable significant result.

*Exploratory analyses:* Even though accuracy is the primary measure, we were again
interested if there were any response times effects of interest. We were also interested in the
conflicting results produced by different tests of the difference scores. We address the latter first.
As noted above, in the no flankers condition, the bootstrapped confidence intervals for both the
difference scores and its associated effect size do not include zero even though the randomization
test returns $p = 0.07$. A two-sided, one sample test of the difference scores was conducted via
BCa bootstrapping using the *wBoot* R package (Weiss, 2016), returning $p = 0.01$. This seems to
indicate reasonable evidence for better performance with horizontal compared to vertical targets.
A similar test was conducted on the difference scores when flankers were present to test whether
performance was better for horizontal compared to vertical targets. This test returned $p = 0.02$
while the initial randomization test produced $p = 0.04$. Again, the BCa bootstrap test indicates
slightly better evidence than the randomization test.

Given the conflicting test results, we tried a different analysis technique as well. We analyzed the group accuracy difference scores via mixed model logistic regressions using the lme4 software package in R (Bates, Maechler, Bolker, & Walker, 2014). First, we report the results for the conditions when flankers were not present. Accuracy on each trial (1 or 0) was regressed onto condition (invalid-horizontal vs invalid-vertical) as a fixed effect and participant as a random effect. The resulting estimates for the conditions, converted from log-odds/log-odds ratios into probabilities of accuracy, are as follows (Table 1, left panel): invalid-horizontal (E = 0.94, 95% CI = [0.91, 0.97], invalid-vertical (E = 0.908, 95% CI = [0.81, 0.958]). (Note: these confidence intervals are not bootstrapped.) The z-value returned for the null hypothesis that there is no difference between these two conditions (i.e., a two-sided test) is -3.23, p = 0.001. So, the logistic regression analysis (p = 0.001) and the BCa bootstrap analysis (p = 0.01) both indicate reasonable evidence for a horizontal advantage when flankers were not present while the randomization test (p = 0.07) does not.

The same model was fit to the conditions when flankers were present (Table 1, right panel). Accuracy on each trial (1 or 0) was regressed onto condition (invalid-horizontal-flanker vs invalid-vertical-flanker) as a fixed effect and participant as a random effect. The resulting estimates for the conditions, converted from log-odds/log-odds ratio to probabilities of accuracy, are as follows invalid-horizontal-flankers (E = 0.759, 95% CI = [0.698, 0.81], invalid-vertical (E = 0.702, 95% CI = [0.585, 0.798]). (Note: these confidence intervals are not bootstrapped.) The z-value returned for the null hypothesis that there is no difference between these two conditions is -2.67, p = 0.007. Again, both the logistic regression analysis (p = 0.007) and the BCa bootstrap analysis (p = 0.02) indicate slightly better evidence for a horizontal advantage when flankers are
We now turn to the response time data. We computed two sets of difference scores for the response times, one when flankers were not present and one when flankers were present. We computed the scores by subtracting response times in the invalid-horizontal condition from those in invalid-vertical condition. Considering the conditions where flankers were not present, the difference scores indicate that responses were slightly faster with horizontal targets (M = 12 ms, SD = 30 ms, 95% CI of the mean = [-2 ms, 25 ms], dz = 0.39, 95% CI of the effect size = [-0.12, 0.87]). We conducted another randomization test. Of the 100,000 iterations run, 10,839 produced a difference with an absolute value as great or greater than the observed difference (12 ms), returning p = 0.11. The same analyses were conducted on the difference scores when the flankers were present. The difference scores again indicate that responses were slightly faster with horizontal targets (M = 10 ms, SD = 57 ms, 95% CI of the mean = [-23 ms, 30 ms], dz = 0.18, 95% CI of the effect size = [-0.40, 0.73]). Of the 100,000 iterations of the randomization test, 48,034 produced a difference with an absolute value as great or greater than the observed difference (10 ms), returning p = 0.48.

**Discussion**

In Experiment 5 we attempted to extend Experiment 3 by testing whether flanking non-targets are necessary to find an advantage for horizontal targets. The condition in Experiment 5 when flanking non-targets were present was a direct replication of Experiment 3, though with half as many trials per cell. It is worth noting that performance in the flankers condition of Experiment 5 was both substantially worse and substantially noisier than in Experiment 3 (Table 2). This could be due to different participants, fewer trials per cell in Experiment 5, or perhaps simply more overall uncertainty in Experiment 5 relative to Experiment 3. The flankers trials in
Experiment 5 (a direct replication of Experiment 3) were intermixed with trials in the no flankers condition. This means that participants could not predict whether there would be one item or three items on the screen on any given trial. It is perhaps counterintuitive that intermixing easier trials would make difficult trials more difficult, but participants might have a slightly different strategy for resolving the target when it appears alone than when it appears with non-targets. The spatial envelope of selection, if you will, is larger when the non-targets are present and it is possible that switching between smaller and larger selection envelopes might be difficult. Similar carryover effects have been observed when intermixing high and low perceptual load tasks (Theeuwes, Kramer, & Belopolsky, 2004). Whatever the explanation for the performance differences, we observed a reduced advantage for horizontal targets in the flankers condition of Experiment 5 (5.5%) compared to Experiment 3 (9.8%).

Despite the magnitude differences, we did replicate the advantage for horizontal compared to vertical targets that we found in Experiment 3. We were also interested in whether the flankers were necessary to observe this advantage. The answer to this question is a bit less clear. While we did observe a reasonably sized horizontal advantage when flanking non-targets were not present (4.5%) the statistical tests are mixed. Even if we think that the logistic regression analysis and the BCa bootstrap test return significant results because they are more powerful (and not because they make more/different assumptions than the randomization test) we are left with a small effect from only one study. We thus conclude that we do not have good evidence to conclude either way (i.e., the results are not terribly informative).

3.2 Experiment 6

We have seen evidence in the previous experiments for a performance advantage for
targets appearing horizontal to an invalid cue. However, so far we do not have much of a handle on why this occurs. Pilz et al (2012) and Barnas et al (2016) interpret similar effects that they observed as an advantage for horizontal targets generally. On the other hand, Tse et al (2003) suggest that the advantage might occur in a more localized region of the hemifield opposite to an exogenous cue. In Experiment 6, we attempt to tease apart these two accounts.

Figure 16 shows the displays used in Experiment 6. The task was like the previous experiment. The cues could appear in any of the four locations on the screen (the stimuli sizes were scaled to control for cortical magnification and therefore the boxes are different sizes in Figure 16). Once the cue appeared, the target could either appear in the same location as the cue (a valid trial) or in one of the locations in the hemifield opposite to the cue (an invalid trial). Each of these locations is horizontally symmetric to one of the two locations in the other hemifield and asymmetric to the other. The localized hotspot in the opposite hemifield account predicts that targets in the invalid condition that appear symmetrical to the target will show a benefit compared to targets in the invalid condition that appear asymmetrical to the target.

Methods

Participants

Fifteen participants were recruited from the University of Illinois at Urbana-Champaign in exchange for credit in an introductory Psychology course. All 15 gave informed consent based on the University of Illinois IRB protocol and reported normal or corrected-to-normal vision and color vision.

Apparatus, Stimuli, and Procedure

We used the same apparatus and task as in previous experiments (including the flanking non-targets). However, both the stimuli sizes and positions have changed. Cues and targets
appeared in one of four positions (Figure 16) along the horizontal midline. There were two inner positions located 4° of visual angle from fixation and two outer positions located 8° of visual angle from fixation. Since the stimuli appeared at different eccentricities, they were scaled to account for cortical magnification (Duncan & Boynton, 2003). In Experiments 1-5, all stimuli subtended 1.5° of visual angle and appeared at 5° of visual angle eccentricity from fixation. In this experiment, the inside stimuli subtended about 1.25° of visual angle at 4° of visual angle eccentricity and the outside stimuli subtended about 2.2° of visual angle at 8° of visual angle eccentricity. The distance between the two inner positions was 8° of visual angle and the distance between the two outer positions was 16° of visual angle. The timing parameters will be same as in previous experiments.

Experiment 6 again consisted of 50% valid and 50% invalid trials. The cues were equally likely to appear at all four locations. When invalid, the target appeared equally often in one of the two locations in the opposite hemifield. One of the locations was horizontally symmetric from the cue and one was horizontal but asymmetric. So, 25% of trials were invalid-symmetric and 25% were invalid-asymmetric. The position of the targets, inside or outside, was counterbalanced with respect to these conditions. Participants completed 480 total trials. When an invalid cue appeared at one of the inside locations, the target appeared either 8° of visual angle from the cue or 12° of visual angle from the cue. When an invalid cue appeared in one of the outside locations, the target appeared either 12° of visual angle from the cue or 16° of visual angle from the cue.

Importantly, while the cortical magnification correction was intended to control for eccentricity effects, there are still potential distance effects. When the cue appears at one of the inside locations, the symmetric target location is closer to the cue (8° of visual angle) than the
asymmetric target location (12° of visual angle). Alternatively, when the cue is at one of the outside locations the symmetric target location will be farther away from the cue (12° of visual angle) than the asymmetric target location (16° of visual angle). If distance matters, then we might expect the symmetry effect to be attenuated or enhanced by distance. To alleviate this concern, we will group both cases (cue outside and cue inside) together in the primary analysis and look at the effect of symmetry averaged across them.

Results

Descriptive statistics (see Figure 17): Accuracy in the valid condition (M = 90.5%, SD = 6.8%) was higher than accuracy in the invalid-symmetrical condition (M = 85.6%, SD = 8.8%). Accuracy in the invalid-symmetric condition, however, was effectively identical to accuracy in the invalid-asymmetric condition (M = 85.7%, SD = 7.9%). Response times in the valid condition were much faster (M = 633 ms, SD = 89 ms) than those in both the invalid-symmetric condition (M = 682 ms, SD = 105 ms) and the invalid-asymmetric condition (M = 690 ms, SD = 121 ms).

Inferential statistics (see Figure 18): We again computed a difference score for each participant. We subtracted the participant mean in the invalid-asymmetric condition from the participant mean in the invalid-symmetric condition. This difference score will be positive to the extent that a participant was more accurate in the invalid-symmetric condition than in the invalid-asymmetric condition. The group difference scores show no difference between the two conditions (M = 0.0%, SD = 3.9%, 95% CI of the mean = [-2.2%, 1.7%], dz = -0.01, bootstrapped 95% CI of the effect size = [-0.56, 0.57]). We again conducted a randomization test to determine whether the observed difference was greater than that expected due to chance. The procedure was the same as in previous experiments. Of the 100,000 iterations run, 91765
produced a difference with an absolute value as great or greater than the observed difference (0.0%), returning $p = 0.92$.

*Exploratory analyses:* We analyzed the response time scores for both the invalid-symmetric condition and the invalid-asymmetric condition. We again computed difference scores. We subtracted each participant’s response time in the invalid-asymmetric condition from their response time in the invalid-symmetric condition. The differences scores revealed a small benefit for the invalid-symmetric condition ($M = 8$ ms, $SD = 36.6$ ms).

A randomization test (using the same procedure as above and uncorrected for multiple corrections/exploratory analyses) was conducted. Of the 100,000 iterations, 41946 produced a difference score with an absolute value as great or greater than the observed one (8 ms), $p = 0.42$.

**Discussion**

We did not find any evidence for a difference between performance in the invalid conditions when the target was symmetric to the cue and when the target was asymmetric to the cue. This is seemingly inconsistent with the localized hotspot account. According to this account, attention either automatically pools in, or is quicker to shift to, the symmetric spot in the hemifield opposite to the cue. This means that symmetric locations should be show a benefit relative to asymmetric locations, which we did not find. The elongated hotspot account, on the other hand, claims that attention either pools horizontally from the cue or is faster to shift horizontally from the cue. This account predicts that targets horizontal to the cue should perform equally well regardless of whether they are symmetric to the cue, which is consistent with the present results. It should also be noted that Experiment 3 in Barnas et al (2016) is seemingly inconsistent with the localized hotspot account. While there are concerns with that experiment (recall that they confounded visual meridian asymmetry with their manipulation), they did find
some evidence for a response time advantage for within-hemifield horizontal targets. According to the localized hotspot account, we should only find a horizontal advantage for targets appearing in the hemifield opposite to the cue and not for targets appearing in the same hemifield as the cue.

### 3.3 Experiment 7

Experiment 7 is another attempt to test between the localized hotspot and the elongated hotspot accounts. In Experiment 6, we tested a prediction of the localized hotspot account by holding the horizontal aspect of target placement constant and varying symmetry with respect to the cue. In Experiment 7, we similarly test a prediction of the elongated hotspot account. The elongated hotspot account predicts that, following an invalid cue, horizontal targets appearing in the same hemifield as the cue should show a benefit relative to vertical targets appearing in the same hemifield as the cue (note that the localized hotspot account predicts no difference between these different kinds of targets). We tested this prediction by creating a display where cues and targets can appear in the same hemifield (Figure 19). After an invalid cue, the target appeared in one of two locations in the same hemifield as the cue: either directly horizontal or directly vertical to the cue. If performance is better for within-hemifield, horizontal targets than within-hemifield, vertical targets, this would be consistent with the elongated horizontal hotspot account and inconsistent with the localized hotspot account. Conversely, if performance is not better for within-hemifield, horizontal targets, this would be inconsistent with the elongated hotspot account and consistent with the localized hotspot account.

As noted above, the third experiment of Barnas et al (2016) is like Experiment 7 here. They also used displays where both cues and targets always appeared in the same hemifield and
the targets could be either horizontal or vertical to the preceding cue. They found a statistically
significant response time advantage (62 ms) for targets appearing horizontal to a preceding cue,
but only when those targets were to the outside of the corresponding cue (i.e., when the target
was to the left of the cue when both were on the side of screen left of fixation and when the
target was to the right of the cue when both were on the side of the screen right of fixation). They
also found a smaller but not statistically significant advantage (20 ms) for horizontal targets that
were to the inside of the preceding cue. Taken together, this might be some evidence against the
localized hotspot account. However, Barnas et al (2016) confounded their conditions of interest
with the vertical meridian asymmetry. Experiment 7 provides a within-hemifield test of the
localized hotspot account that does not confound visual field asymmetry with the conditions of
interest. Abrams et al (2012) only found evidence for reduced sensitivity at locations about 30° -
40° of polar angle from the upper vertical midline. In Experiment 7, all stimuli will be centered
at least 45° of polar angle from the upper vertical midline, thus removing reduced sensitivity as a
possible explanation for any effects.

Methods

Participants

Fifteen participants were recruited from the University of Illinois at Urbana-Champaign
in exchange for credit in an introductory Psychology course. All 15 gave informed consent based
on the University of Illinois IRB protocol and reported normal or corrected-to-normal vision and
color vision.

Apparatus, Stimuli, and Procedure

We used the same apparatus and task as in previous experiments, but both the stimuli
sizes and positions have changed. In Experiment 7, cues and targets appeared in one of eight
positions (Figure 19) above and below the horizontal midline. There were four inner positions located 4° of visual angle from fixation and four outer positions located about 8.1° of visual angle from fixation. We again scaled the stimuli to account for cortical magnification (Duncan & Boynton, 2003). The scaled inside stimuli subtended about 1.25° of visual angle and the scaled outside stimuli subtended about 2.2° of visual angle. Within a hemifield, the stimuli appeared at any of the four vertices of an imaginary square. The distance from any vertex to the within-hemifield vertices either directly horizontal or directly vertical is about 5.7° of visual angle. The inside upper vertex is 45° from the upper visual midline and the outside upper vertex is about 72° from the upper visual midline. The lower vertices are placed in symmetric locations. The timing parameters were the same as in previous experiments.

Experiment 7 again consisted of 50% valid and 50% invalid trials. The cues appeared equally often at all eight locations. When invalid, the target appeared equally often in one of the two locations within the same hemifield as the cue: either directly horizontal or directly vertical to the cue. So, 25% of trials were invalid-horizontal and 25% were invalid-vertical. Participants completed 448 total trials. (Note: slight differences in the number of trials between experiments are due to counterbalancing conditions with different numbers of levels.)

Results

Descriptive statistics (see Figure 20): Accuracy in the valid condition (M = 81.3%, SD = 9.7%) was higher than accuracy in the invalid-horizontal condition (M = 76.4%, SD = 8.4%). Accuracy in the invalid-horizontal condition, however, was only slightly higher than accuracy in the invalid-vertical condition (M = 74.7%, SD = 9.1%). Response times in the valid condition were much faster (M = 728 ms, SD = 126 ms) than those in both the invalid-horizontal condition (M = 778 ms, SD = 113 ms), and response times in the invalid-horizontal condition were
somewhat faster than those in the invalid-vertical condition (M = 799 ms, SD = 95 ms).

*Inferential statistics* (see Figure 21): We again computed a difference score for each participant. We subtracted the participant mean in the invalid-vertical condition from the participant mean in the invalid-horizontal condition. This difference score will be positive to the extent that a participant was more accurate in the invalid-horizontal condition than in the invalid-vertical condition. The group difference scores show a small but not statistically significant difference between the two conditions (M = 1.7%, SD = 8.0%, 95% CI of the mean = [-1.7%, 6.2%], dz = 0.22, bootstrapped 95% CI of the effect size = [-0.35, 0.76]). We again conducted a randomization test to determine whether the observed difference was greater than that expected due to chance. The procedure was the same as in previous experiments. Of the 100,000 iterations run, 41,310 produced a difference with an absolute value as great or greater than the observed difference (1.7%), returning p = 0.41.

*Exploratory analyses*: We analyzed the response time scores for both the invalid-horizontal condition and the invalid-vertical condition. We again computed difference scores. We subtracted each participant’s response time in the invalid-asymmetric condition from their response time in the invalid-vertical condition. The differences scores revealed a small benefit for the invalid-horizontal condition (M = 19 ms, SD = 47 ms). A randomization test (using the same procedure as above and uncorrected for multiple corrections/exploratory analyses) was conducted. Of the 100,000 iterations, 15392 produced a difference score with an absolute value as great or greater than the observed one (19 ms), p = 0.15.

As mentioned above, Barnas et al (2016) found a statistically significant within-hemifield benefit for horizontal targets only when those targets appeared to the outside of the cues (there was a directionally similar but not statistically significant effect when target appeared to the
inside of the cues). We investigated whether a similar pattern appeared in our data. In Experiments 1-3 and 5, we observed a benefit for targets appearing horizontal to a preceding cue. However, in each case, the direction of shifting attention was to the outside (away from fixation). Experiment 7 introduced a new condition where targets could appear to the inside of cues and where the direction of shifting attention was to the inside (toward fixation). We thus wanted to compare shifts of attention toward fixation to those away from fixation.

We also observed a large difference in performance between targets appearing in the four spots closer to fixation (4° of visual angle from fixation) compared to targets appearing in the four spots farther away from fixation (8.1° of visual angle). In the valid condition, accuracy for targets closer to fixation was lower (78.5%) and response times for accurate trials slower (722 ms) than targets farther away from fixation (84.4% and 744 ms). Similar effects appeared for both the invalid conditions. This meant we could not cleanly compare horizontal shifts away from a cued location to vertical shifts away from the same location because each shift would land on a target at a different eccentricity. We thus conditioned not on cue location, but on target location. We compared performance at a given target location when the preceding cue was horizontal to the target to performance when the preceding cue was vertical to the target (Figure 22).

We again computed a difference score for each participant. We subtracted the participant mean in the invalid-vertical condition from the participant mean in the invalid-horizontal condition for each of the two target location conditions. These difference scores will be positive to the extent that a participant was more accurate in the invalid-horizontal condition than in the invalid-vertical condition (Figure 23). The group difference scores a small but not statistically significant detriment for horizontal targets when they were located closer to fixation (M = -1.8%,
SD = 12.8%, 95% CI of the mean = [-7.7%, 5.3%], dz = -0.14, bootstrapped 95% CI of the effect size = [-0.74, 0.46]). The group differences also show a larger and just barely significant benefit for horizontal targets when they appeared farther away from fixation (M = 5.2%, SD = 9.2%, 95% CI of the mean = [0.009%, 10%], dz = 0.57, bootstrapped 95% CI of the effect size = [0.02, 1.1]).

Randomization tests (using the same procedure as above and uncorrected for multiple corrections/exploratory analyses) were conducted on each set of difference scores. For the cases in which the targets were close to fixation, 58,212 out of the 100,000 iterations produced a difference score with an absolute value as great or greater than the observed one (-1.8%), p = 0.58. For the cases in which the targets were far from fixation, 4,930 out of the 100,000 iterations produced a difference score with an absolute value as great or greater than the observed one (5.2%), p = 0.049.

**Discussion**

The results of Experiment 7 (especially in conjunction with Experiment 6) are a bit puzzling given the framework with which we’ve been discussing the horizontal advantage and imply that we don’t yet have a good handle on the psychological dynamics underlying the effect. In Experiment 7 we developed a task to test between the localized hotspot and the elongated hotspot accounts. We used a display where cues and targets would appear in the same hemifield. The targets could appear either horizontal or vertical to the cue. The localized hotspot account explains the horizontal advantage as a benefit for targets in a symmetric spot in the hemifield opposite to the cue, so it predicts that we should not observed a within-hemifield horizontal advantage. The elongated hotspot account, on the other hand, predicts an advantage for all targets horizontal to the cue and so also predicts a within-hemifield advantage. The results
Experiment 7 are muddled. We did not find good evidence for a benefit for horizontal targets. There was both a small accuracy benefit and a small response time benefit but neither were statistically significant.

We did, however, find a benefit for horizontal targets when they were located away from fixation (when attention was shifting away from fixation). When targets were located near fixation (and attention was shifting toward fixation) we did not find a horizontal advantage. We should point out that the target location analysis was not our primary analysis and that post hoc subsetting of the data should decrease our confidence in the results of the subsetting. These results, however, are consistent with the results of Barnas et al (2016), who also only found a within-hemifield horizontal advantage when attention was shifting away from fixation. This could imply that the horizontal advantage only occurs when shifting attention away from fixation. This possibility does not square nicely with the accounts we have been discussing. The localized hotspot account is seemingly inconsistent with it, though the elongated hotspot account can be modified to account it. We have so far been discussing the elongated hotspot as a bidirectional advantage for targets, meaning that targets on both sides of a cue would show a benefit. It is possible, however, that the advantage is unidirectional and only arises when a target is on the outside of the cue. It is not clear, however, why targets away from fixation should be privileged. This is also somewhat inconsistent with the elliptical hotspot view, where the attentional hotspot is wider than it is tall and this positions attention closer to horizontal targets. On the face of it, there is no reason to expect the attentional ellipse to be biased away from fixation, but this is certainly a possibility.
4. Conclusion

We have presented evidence for a performance advantage for targets appearing horizontal to an invalid exogenous spatial cue. Previous research has provided some evidence for such an advantage, though it has either been difficult to interpret or the interpretations appear too narrow considering our results. Tse et al (2003) provided some evidence for a horizontal advantage, though their results were not entirely consistent. Both Pilz et al (2012) and Barnas et al (2016) provided more evidence for a horizontal advantage in an object-based attention paradigm. Both groups of researchers were investigating object-based attention and they both reasonably interpreted their findings as revealing something about the mechanisms of object-based attention. Pilz et al (2012) only found an object-based effect when it was confounded with the horizontal advantage. They thus concluded that object-based attention might be a brittle effect. Barnas et al (2016) directly investigated the horizontal advantage in an object-based attention paradigm. While they find consistent evidence for it (in terms of response times) they also conclude that it reflects an asymmetry in object-based attention. Here, we have shown that the effect is likely a more general feature of spatial attention.

Experiments 1 and 2 found large accuracy advantages for horizontal relative to diagonal targets using a display type like those used in the classic Posner cueing task (Posner, 1980). Importantly, the results of Experiments 1 and 2 indicate that we might need to qualify the traditional interpretations of Posner cueing task. There is much still to understand, but these results imply that the costs of redirecting attention to an invalidly cued target might vary substantially depending on the location of the target relative to the cue. If the horizontal advantage is reflective of an automatic pooling of attention, Experiments 1 and 2 indicate that the Posner cueing task vastly underestimates the general cost of redeploying attention. On the other
hand, if the horizontal advantage is reflective of differential speeds for redirecting attention to
different locations, this might imply that the Posner task only measures a best-case scenario for
the redeployment of attention. Understanding the variable costs of redeploying attention will be
important for future vision researchers to ensure, as discussed in the introduction, that tests of
models are not confounded with location-dependent effects.

Experiments 3 and 4 provide evidence for a large benefit for horizontal targets using a
display type like those in the classic object-based attention tasks (Egly et al, 1994). Interestingly,
Pilz et al (2012) used a version of the classic task and found evidence for a same-object benefit
only when same-object benefit was confounded with the horizontal advantage. In fact, they
found evidence for a different-object benefit (the opposite of the classic effect) when the
different-object benefit was confounded with the horizontal advantage. In other words, it seems
like the object-based effect in Pilz et al (2012) might be partially or completely explained by the
horizontal advantage. Our results correspondingly indicate that the horizontal advantage might
be a general feature of spatial attention, rather than a property of object-based attention.

Experiment 5 replicates Experiment 3 and fails to provide much information about
whether the flanking non-targets we used in our task are necessary to find the effect.

Experiments 6 and 7 were designed to provide information about which of the considered
accounts (localized hotspot or elongated hotspot) might be correct. Experiment 6 tested an
implication of the localized hotspot model that horizontal targets in the hemifield opposite the
cue that are symmetric to the cue should show an advantage relative to the targets that are not
symmetric. However, we found no difference between targets, symmetric or not. This implies,
along with the third experiment of Barnas et al (2016), that the localized hotspot account as
described is not correct.
Experiment 7 tested a prediction of the elongated hotspot account. The elongated hotspot account (at least the bidirectional version) predicts that that we should find a horizontal advantage even for targets in the same hemifield as cues. However, we did not find an overall difference between targets horizontal to a within-hemifield cue and targets vertical to a cue. When conditioning on target locations, we did find a benefit for horizontal targets when the targets were on the outside of the displays (when attention was redirected away from fixation). We noted that Barnas et al (2016) found a similar result using a similar task, and suggest that this might imply a modification of the elongated hotspot account: the horizontal advantage may only arise when attention moves to a target away from fixation.

One potential limitation on the generality of this work is that all experiments were done using images of a human face. Face processing, of course, is known to be lateralized so it is natural to wonder whether such lateralization might play a role here. However, we looked back at the data from Experiments 1-3 and 5 (those showing a clear horizontal advantage) broken out by the visual field of the target and found no differences. There were small fluctuations between the magnitudes of the horizontal advantage but it was directionally the same in both visual fields for all experiments and very similar in magnitude. Furthermore, the none of experiments conducted by previous researchers showing a similar effect used faces. Tse et al (2003) used colored dots, and both Pilz et al (2011) and Barnas et al (2016) used letters. We thus conclude that the horizontal advantage is likely not specific to faces.

Throughout this paper, we have been agnostic about the underlying mechanism for the horizontal advantage. At least two possibilities come to mind: attention could automatically pool or spread in a certain direction or location in response to an exogenous cue. We might also think about the advantage as arising because horizontal shifts of attention are just easier than vertical
shifts. Furthermore, there could be a hybrid account where the attention hotspot deployed in response to an exogenous cue is elliptical (wider than it is tall) and this puts the hotspot closer to horizontal targets than equidistant vertical targets (and so subsequent attentional shifts would be faster). The studies presented above do not distinguish between these views, and future work should address which of them (or other accounts that have yet to be considered) might explain the horizontal advantage.

While it is unfortunate that we have not been able to develop a solid model of the horizontal advantage, it is worth noting that we have provided what appears to be very strong evidence for its existence. We have also shown strong evidence that it is not just a feature of object-based attention, and, along with the work of Carrasco and colleagues detailed in the introduction, this suggests that researchers need to very carefully consider the locations of stimuli when designing experiments to test between models of vision and attention. We have also suggested that the existence of the horizontal advantage should spur us to think more carefully about the possibility that there are variable costs of redeploying attention depending on stimuli locations.
5. Figures and Tables

**Figure 1**: Different accounts of the horizontal advantage. Top left: the elongated hotspot account posits an automatic pooling of attention horizontal to the target that extends into the other hemifield. Top right: the localized hotspot account posits an automatic pooling of attention in the symmetric position of the hemifield opposite of the target. Bottom left: attention hotspots could be elongated more along the horizontal than vertical axis. Bottom right: attention could be faster to shift horizontally than vertically.
Figure 2: Example displays from Experiment 1. Top left: a valid trial. Top right: an invalid-horizontal trial. Bottom: invalid-diagonal trials. Note: the cue (black outline box) and the target array (face and two non-faces) did not actually appear on the screen at the same time. The cue appeared for 50 ms, followed by a 50 ms blank, then the target array for 100 ms, followed by masks until response.
Figure 3: Results from Experiment 1. Top: accuracy as a function of condition. Bottom: response time as a function of condition. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of group. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.
**Figure 4:** Participant-level accuracy differences between the invalid-horizontal and the invalid-diagonal conditions in Experiment 1. The y-axis represents how much higher accuracy was in the invalid-horizontal condition compared to the invalid-diagonal condition. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of group. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.

**Figure 5:** Possible cue and target locations from Experiment 2. Both the cue and target appeared equally often at all 6 positions.
Figure 6: Results from Experiment 2. Top: accuracy as a function of condition. Bottom: response time as a function of condition. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of group. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.
**Figure 7:** Participant-level accuracy differences between the invalid-horizontal and the invalid-diagonal conditions in Experiment 2. The y-axis represents how much higher accuracy was in the invalid-horizontal condition compared to the invalid-diagonal condition. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of participant-level difference scores. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.

**Figure 8:** Possible cue and target locations from Experiment 3. Both the cue and target appeared equally often at all 4 positions.
Figure 9: Results from Experiment 3. Top: accuracy as a function of condition. Bottom: response time as a function of condition. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of group. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.
**Figure 10:** Participant-level accuracy differences between the invalid-horizontal and the invalid-vertical conditions in Experiment 3. The y-axis represents how much higher accuracy was in the invalid-horizontal condition compared to the invalid-vertical condition. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of participant-level difference scores. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.

**Figure 11:** Possible cue and target locations in both types of displays used in Experiment 4. Participants were assigned to one of the two display types and all of their trials used their assigned display type.
Figure 12: Results from Experiment 4. Top: accuracy as a function of condition. Bottom: response time as a function of condition. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of group. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.
Figure 13: Participant-level accuracy differences between the invalid-different and the invalid-same conditions in Experiment 4. The y-axis represents how much higher accuracy was in the invalid-different condition compared to the invalid-same condition. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of participant-level differences scores. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.
Figure 14: Results from Experiment 4. Top: accuracy as a function of condition. The three left-most conditions are those without flanking non-targets. Bottom: response time as a function of condition. The three left-most conditions are those without flanking non-targets. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of group. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.
Figure 15: Experiment 5 participant-level accuracy differences between the invalid-horizontal and the invalid-vertical conditions when flanking non-targets did not appear (left) and when flanking non-targets did appear (right). The y-axis represents how much higher accuracy was in the invalid-horizontal condition compared to the invalid-vertical condition. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of participant-level difference scores. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.

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Table 1: Regression tables for exploratory analyses in Experiment 5. Left: Mixed model logistic regression of the conditions where flankers were not present. Per trial accuracy (Acc) was regressed with condition (invalid-horizontal vs invalid-vertical) as a fixed effect and participant as a random effect. Right: Mixed model logistic regression of the conditions where flankers were present. Per trial accuracy was regressed with condition (invalid-horizontal vs invalid-vertical) as a fixed effect and participant as a random effect. Reported are the odds ratios (OR), the confidence intervals (CI), and the p value.
Table 2: Percent accuracy and, in parentheses, percent standard deviation by condition for Experiment 3 and the flankers condition of Experiment 5. Performance in Experiment 3 was better and less variable than in the equivalent conditions in Experiment 5.

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<td>85.4 (5.5)</td>
<td>74.3 (11.1)</td>
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<td>Invalid-Vertical</td>
<td>75.6 (8.5)</td>
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Figure 16: Cue and target locations used in Experiment 6. Cues could appear in any of the 4 locations. Subsequent targets would either appear in the cued location (valid) or in one of the 2 locations in the other hemifield (invalid). On invalid trials, targets could appear either in a symmetrical or asymmetrical location relative to the cue.
Figure 17: Results from Experiment 6. Top: accuracy as a function of condition. Bottom: response time as a function of condition. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of group. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.
Figure 18: Participant-level accuracy differences between the invalid-symmetric and the invalid-asymmetric conditions in Experiment 3. The y-axis represents how much higher accuracy was in the invalid-symmetric condition compared to the invalid-asymmetric condition. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of participant-level difference scores. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.

Figure 19: Target and cue locations in Experiment 7. Cues appeared equally often at all eight locations. When the cue is invalid, targets appear within the same hemifield as the cue at either the location directly horizontal to or directly vertical to the cue. Outside positions are placed about 8.1° and the inside positions 4° of eccentricity relative to fixation.
Figure 20: Results from Experiment 7. Top: accuracy as a function of condition. Bottom: response time as a function of condition. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of participant-level difference scores. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.
Figure 21: Participant-level accuracy differences between the invalid-horizontal and the invalid-vertical conditions in Experiment 7. The y-axis represents how much higher accuracy was in the invalid-horizontal condition compared to the invalid-vertical condition. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of the participant-level difference scores. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.
Figure 22: Results from Experiment 7. Top: accuracy as a function of condition. The suffix ‘in’ denotes that the target was located at a position close to fixation while the suffix ‘out’ denotes that a target was located at a position far from fixation. Bottom: response time as a function of condition. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of participant-level difference scores. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.
Figure 23: Participant-level accuracy differences between the invalid-horizontal and the invalid-vertical conditions in Experiment 7. The suffix ‘in’ denotes that the target was located at a position close to fixation while the suffix ‘out’ denotes that a target was located at a position far from fixation. The y-axis represents how much higher accuracy was in the invalid-horizontal condition compared to the invalid-vertical condition. Each dot represents one participant, and is slightly jittered to the left or right for readability. The distributions are kernel density plots of the participant-level difference scores. The white bars represent BCa bootstrapped 95% confidence intervals (Efron & Tibshirani, 1993). The horizontal line in the center of each white bar is the group mean.
6. References


