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Gradients and Ranges of Visually Selective Attention Based on Location, Objects, Color, and Size: Gradients are Universal, but Range is Uniquely Spatial

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GRADIENTS AND RANGES OF VISUALLY SELECTIVE ATTENTION BASED ON LOCATION, OBJECTS, COLOR, AND SIZE: GRADIENTS ARE UNIVERSAL, BUT RANGE IS UNIQUELY SPATIAL.

A Dissertation Presented

by

WILLIAM S. BUSH

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ABSTRACT

GRADIENTS AND RANGES OF VISUALLY SELECTIVE ATTENTION BASED ON LOCATION, OBJECTS, COLOR, AND SIZE: GRADIENTS ARE UNIVERSAL, BUT RANGE IS UNIQUELY SPATIAL.

SEPTEMBER 2012

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Two interesting properties of the distribution of spatially selective attention have been noted in the behavioral and electrophysiological literature. First, there is a graded field of attention that expands from the center of the attended area. Second, the size of the attended area can be adjusted to be either larger or smaller in order to match the demands of the current task. Five event-related potential (ERP) studies are presented that extend these findings in several important ways; 1) The time frame of these two distribution properties is different. Results are consistent with a two stage model of spatial attention in which visual processing is initially enhanced for all stimuli presented near the center of the attended area as indexed by the amplitude of the first negative peak in the waveform (N1). Subsequently, the effects of narrowing or expanding the attentional field to the relevant size affects visual processing as indexed by the amplitude of the second negative peak (N2). 2) Object boundaries had limited impact on either the spread of the initial gradient of spatial selection or the scale of attention. 3) When selecting visual stimuli for attentive processing based on features such as color and size there is also a gradient of facilitation, but the impact of this graded selection on visual processing is not observed until later in processing, and is indexed by the amplitude of the selection negativity (SN). Furthermore, similar to the lack of interaction between object boundaries and the range of cued locations, the gradients of feature-based selection are not affected by the range of cued features.

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CHAPTER I

INTRODUCTION

The complexity of the visual world is such that we are confronted with more stimuli than we can effectively process at once. Selective attention is our means of preferentially processing the most pertinent visual information. Imagine for instance that you are searching for your car in a crowded parking lot. If you know the general location where your car is parked, you will be able to find it in a relatively short period of time. However, if while you were gone someone moved your car to another location within the parking lot, now it would take significantly longer to find the car because your expectations about the car's location do not match its actual location. Similarly, if someone were to repaint your car a different color in your absence, it would increase the time it took to find the car, again because the color does not match your expectations of what your car will look like. While these examples are on a large scale, searching for an object in a large parking lot, they parallel the way we select stimuli within a single fixation. When we search for things within a scene in the visual world, we form expectations about where important visual stimuli will appear, and what colors, sizes, orientations, and other features they will have. Selective attention allows us to devote more processing to pertinent information and filter out the less useful stimuli in the environment. When applied to selecting among competing visual stimuli, as in the searching for a parked car example, this is referred to as visual attention.

Spatial Attention

Visual attention is the mechanism used to preferentially process important stimuli, and spatial selection is the most thoroughly studied form of visual attention. Spatially

selective attention allows for preferential processing of informative locations in the visual field. This processing advantage can be measured in the form of improved behavioral performance at attended locations. For instance, when a target stimulus is presented in a region of the visual field that has been previously cued, it elicits a faster response than if the same target is presented in an unattended region (Posner, Nissen, & Ogden, 1978; Posner, Snyder, & Davidson, 1980; Eriksen & St. James, 1986; Downing & Pinker, 1985). There is also evidence that spatial attention is employed in visual search tasks. When a probe stimulus is presented after a search array, response time (RT) is faster at the location of the target compared to the locations of distractors (Cepeda, Cave, Bichot, & Kim, 1998). This processing advantage suggests spatial attention has been deployed at the target location in order to evaluate that stimulus. While much is understood about the overall allocation of spatial visual attention, there is still debate as to how attention is distributed at different levels of perceptual processing.

The concept of a "spotlight" of attention was one of the first metaphors to describe the distribution of selective processing (Posner, Snyder, & Davidson, 1980). The spotlight model assumes that the attended area has a fixed size and precisely defined borders. Since the spotlight of attention was proposed, it has become clear that the distribution of spatial attention is more flexible than this model suggests. Measurements of the spatial allocation of visual attention have led to two fundamental extensions of the spotlight model (see Cave & Bichot, 1999 for a review). One set of findings suggests that the borders of the attended region are not discrete, but that instead there is a graded distribution of attention centered on the cued location (Downing & Pinker, 1985; LaBerge & Brown, 1986; Mangun & Hillyard, 1988). A gradient of attention is

supported by studies finding that the greater the distance between the cued location and a subsequent target, the longer it takes to respond to the appearance of the target (Downing & Pinker, 1985; Downing, 1988; Shulman, Sheehy, & Wilson, 1986). LaBerge and Brown (1986) defined the gradient of visual attention in detail by varying the range and density of items in the display. RTs were dependent on both the target's location relative to the center of the attended area and the density of possible locations. This indicates that the spread of the selective gradient was adjusted to match the range of possible target locations. This is an interesting property of the gradient of spatial attention as it suggests a sensitivity to bottom up influences from items in the visual scene.

A second set of findings suggests that the size of the attended area can be expanded or contracted to match task demands. Evidence for a scalable area of attention comes from behavioral studies in which changing the size of the cued area affected the response times to targets. When Eriksen and St. James (1986) cued 1, 2, or 3 adjacent squares (out of a circle of eight squares), response times were fastest when one square was cued, and became progressively slower as the number of cued squares increased. Castiello and Umilta (1990) confirmed that the size of the cued region, and not the number of cued locations, was responsible for these differences. Search times are also reduced following a small cue relative to a large cue (Greenwood & Parasuraman, 1999). Eriksen and St. James (1986) termed this expanding and contracting of the attended area a "zoom lens" of attention. They proposed that as the cue size increases, the size of the attended region also increases, and therefore less attentional resources are available for any specific location within the attended area.

It is unclear whether the gradient of selection occurs at the same stage of

processing as the variable sized attended area shown in studies supporting the zoom lens model. One reason to posit separate mechanisms is LaBerge and Brown's (1986) finding that response times to the targets at fixation did not differ between conditions inducing large and small spreads of the gradient of attention. This suggests that there was no cost associated with increasing the spread of the gradient, which is contrary to the predictions of the zoom lens model that increasing the size of the attended area decreases attention for the central location within that area. A second reason to predict multiple stages of selection comes from the observation that the size of the attended area is not always scaled appropriately in situations where it would be beneficial. This has been demonstrated using a search task in which the target appeared in an array containing high interference distractor items that were similar to the target (Müller, Mollenhauer, Rösler, & Kleinschmidt, 2005). An optimal strategy in this task would be to reduce the scope of attention so that it only includes the location where a target is likely to be presented, and ignore the other locations entirely. However, response times were slower when the high interference distractors appeared at squares neighboring the target compared to when the high interference distractors were more distant. This distance effect suggests that the nearby distractors were within the attended region. The existence of attentional effects such as distractor interference in regions spreading beyond the cued location suggests that narrowing attention to a small area is not always possible.

The gradient and zoom lens models make somewhat different predictions about how attention would be distributed when selecting a small area in a crowded visual scene. On one hand, there is an automatic gradient of attention that spreads from the center of the attended area and does not completely inhibit nearby locations that could contain

distractors. This suggests the spread of spatial attention is relatively automatic, as it seems to occur even when it is not beneficial to performing the task. On the other hand, task manipulations that expand or contract the attentional field affect the speed of the behavioral response, suggesting that top down control of the scale of spatial attention is possible. Some models of spatial attention have attempted to reconcile these results within a single stage of selection. Luo, Greenwood, and Parasuraman (2001) proposed a model in which attention is distributed as a gradient that is expanded or contracted based on task demands. It is unclear whether this model predicts a fundamental limit in the amount of attentional resources available. In studies demonstrating a zoom lens of attention, the response time to stimuli in the center of the attended region varied with cue size, suggesting attention is resource bound such that spreading attention to a wider area requires moving attention away from the center (Eriksen & St. James, 1986; Castiello & Umilta, 1990; Greenwood & Parasuraman, 1999). Conversely, in demonstrations of a gradient of attention, response times at the center of the attended region were unaffected by an increased spread of the gradient (LaBerge & Brown, 1986). This conflict might be resolved if the gradient and the adjustable size of attention represent two separate stages of processing. LaBerge and Brown (1989) proposed that the earliest stages of selective processing are automatically deployed around the attended location, creating an expectancy gradient. A later stage of processing then selects a specific region within the expectancy gradient for further processing, adjusting the size of this region as required by the task.

Because responses are necessarily recorded after all processing stages are complete, it is difficult to differentiate whether the gradient of attention and the

adjustable size of attention occur at a single stage, or at separate stages of selection. Further, if selection occurs at multiple stages, it is difficult to determine which experimental manipulations impact the distribution of the gradient, and which impact adjustments to the size of the attended area similar to a zoom lens model.

Event-Related Potentials

The behavioral data effectively demonstrate that selective attention directed to a location in the visual field improves performance for stimuli presented at that location. The use of event-related potentials (ERPs) adds to the behavioral data by providing information about the time course of processing prior to the response. This temporal information can be used to help differentiate between attention based effects at separate stages of processing. In addition, ERPs can be used to measure activity evoked by stimuli that do not require a behavioral response, and so can be used to demonstrate processing advantages independent of response planning.

Event-related potentials are the end product of a specific type of analysis of electroencephalogram (EEG) data. Participants in an EEG study are fitted with a cap of several to over a hundred electrodes. EEG takes advantage of the fact that neural activity in response to stimuli evokes electrical potentials measurable at the scalp. The magnitude of these electrical potentials is often too small to be seen in the raw EEG data. In order to isolate the signals of interest, the same stimulus is presented several times and an average is created from a number of segments of EEG data time locked to those presentations. This process of averaging EEG segments reduces the noise from electrical potentials generated by unrelated neural activity, and isolates the potentials evoked by the event of interest. The resulting measurement of electrical amplitude in response to an event is the

ERP waveform.

An ERP waveform consists of a series of positive and negative deflections. The positive and negative deflections that are reliably seen in response to stimuli or task conditions across experiments are labeled as specific components. Components are defined based on whether they are positive or negative deflections, and based on the time window at which they occur relative to an event of interest, such as the onset of a visual display. The onset of visual stimuli consistently evokes several components. The earliest components of interest are the C1, occurring at 50-60ms (which is observed as a positive or negative deflection depending on the location of the visual stimulus), the first major positive component (P1) occurring at ~80-120 ms, and the first major negative component (N1) occurring at ~150-200ms. These components are often referred to as visual evoked potentials (VEPs). Additional amplitude deflections may be evoked depending on the nature of the visual stimulus and the task. A P2 deflection and an N2 deflection are often observed following the N1. Lastly, a positive deflection, the P3 or P300, is often observed beginning at around 300 ms. The amplitude of the P3 is increased in response to targets, and is also larger in response to rare stimuli. Luck (2005) provides a thorough guide and review of the details of ERP studies and components.

In spatial attention studies, the amplitude of components evoked by stimuli appearing at an attended location are compared to components evoked by the exact same stimulus when attention is directed elsewhere. Differences in amplitude between these two conditions within a specified time window reflect differences in processing due to attention. ERP studies of selective attention have mainly focused on the earliest visual

evoked potentials as measures of attentional modulation of visual processing. The earliest effects of visual spatial attention are typically observed as larger amplitude across the first positive (P1) and first negative (N1) deflections. This early portion of the waveform, indexing primarily perceptual processing of both target and non-target stimuli, is modulated by the orienting attention to a location in the visual field (Luck, Hillyard, Mouloua, & Woldorff, 1994). The effect of attention on early ERP time windows has been reliably reproduced in many studies (Gonzalez, Clark, Fan, Luck, &Hillyard, 1994; Hillyard, Teder-Sälejärvia, & Münte, 1998; Mangun, 1995; Luck, Woodman, & Vogel, 2000; Hopfinger, Luck, & Hillyard, 2004).

In comparing the results of ERP studies with those of behavioral studies, it should be noted that many ERP studies use a sustained attention paradigm, in which the same location is attended for a block of trials. The use of a sustained attention paradigm eliminates the overlap between the potentials evoked by the cue stimuli and those of the event of interest. Similar effects on the P1 and N1 have been found with sustained and transient attention studies, suggesting that these time windows index the same processing demonstrated in behavioral cuing studies (Mangun & Hillyard, 1991). Another characteristic of ERP studies that makes them ideal for investigating the distribution of attention is that the ERP measurements index the processing of distractors that are completely ignored. Thus, while participants in RT experiments must respond to stimuli at cued and uncued locations, participants in ERP experiments can be instructed to respond only to target stimuli at the cued location(s). This is advantageous in that a response is never required for stimuli at uncued locations, reducing the motivation to occasionally attend to uncued locations, or split attention between cued and uncued

locations. Thus, any processing advantages at uncued locations can be attributed to a spread of attention, and not a strategic monitoring of low probability target locations.

Following the P1 and N1, amplitude in several later time windows is also affected by attention, particularly the second negative (N2) and third positive (P3) deflections. The deflections in both of these time windows are observed primarily across posterior electrodes. Differences in the N2 time window have been linked to shifts of attention and filtering of distractor information (N2pc; Luck & Hillyard, 1994a; Luck & Hillyard, 1994b; Woodman & Luck, 1999; Woodman & Luck, 2003), selection of non-spatial features (selection negativity, SN; Hillyard & Münte ,1984; Eimer, 1995; Anllo-Vento & Hillyard, 1996; Eimer, 1997; Schoenfeld, et al., 2007; McGinnis & Keil, 2011), and even visual awareness (VAN; Railo, Koivisto, & Revonsuo, 2011). Of the deflections described in the N2 time window, the selection negativity (SN) is of particular interest in the current studies. The SN is a larger amplitude negative deflection observed in response to the onset of images that include an attended feature such as color, shape, orientation, spatial frequency, and motion. Hillyard and Münte (1984) proposed that the SN reflects a second stage of processing following spatial selection in the P1/N1 time range. Finally, the P3 time window is thought to reflect the updating of working memory to facilitate stimulus processing (See Polich, 2007 for a review), and is an index of one of the last stages of processing prior to planning a response.

One advantage of the temporal resolution of ERP studies is that separate stages of processing can be measured relatively independently of one another. An example of this is the differentiation between amplification of processing at attended locations and inhibition of processing at unattended locations. That amplification and inhibition may

involve separable mechanisms was demonstrated in a study using three cue conditions; valid cues, invalid cues, and neutral cues (Luck et al., 1994). ERPs were time locked to a mask presented a short time after the target, and at the same location as the target. On invalid trials, P1 amplitude in response to the mask was reduced compared to neutral trials. On the valid trials, there was no change in P1 amplitude, and N1 amplitude was increased compared to the neutral trials. Luck (1995) proposed that the P1 indexes the inhibition of processing at unattended locations while the N1 indexes enhanced processing at attended locations. The electrophysiological data provided the temporal information necessary to differentiate between these two stages of selection.

Electrophysiological studies have provided supporting evidence for models of the distribution of spatial attention, including the gradient model. Mangun and Hillyard (1988) demonstrated a gradient of attentional effects such that amplitudes in the P1 and N1 time windows decreased with the distance of the stimulus from a cued location. This pattern suggests that the attentional processing indexed by these early time windows has a graded distribution, and is not focused exclusively on the cued location. A graded distribution of attention in the N1 time window is also found in transient attention tasks, where attention is relocated on every trial (Eimer, 1997). The electrophysiological evidence also indicates that the distribution of attention may be more complicated than a simple gradient of facilitation. When the distance between items in a display is reduced, reduced amplitude in the N1 time window for locations just beyond the gradient of facilitation demonstrates a border of inhibition (Hopf, et al., 2006). The inhibition of amplitude in the N1 is localized to a specific distance from the target location, consistent with the Mexican hat distribution proposed by Müller et al. (2005). Interestingly, the

effects of inhibition in the Hopf et al. (2006) study are seen in the N1 time window, which seems to contradict the findings by Luck et al. (2004) that N1 attention effects are driven primarily by facilitation. Several methodological differences may have lead to these disparate findings, including distance between attended and unattended locations, and the perceptual load of the display. All of these studies suggest that for the N1 time window, and in certain circumstances the P1 time window, there is a distribution of the effects of attention that extends beyond the cued area. The results of Experiment 1 provide further information about the distribution of the gradient of spatial selection, particularly whether the gradient is symmetric around the monitored location.

Electrophysiological measures have also been used to demonstrate the effect of the size of the cued area on the distribution of spatial attention, but the results have been somewhat inconsistent. Studies using search displays preceded by variable cue sizes have found cue size dependent modulations in the P1 and N1 time windows (Luo, Greenwood, & Parasuraman, 2001; Fu, Caggiano, Greenwood, & Parasuraman, 2005). While cue size modulates amplitude in P1 and N1 time windows in response to search arrays, there is some indication that when stimuli are presented in isolation, the effects of the cue size may not be seen until the later N2 time window (Mangun & Hillyard, 1988; Eimer, 1999).

Using a sustained attention paradigm, Mangun and Hillyard (1988) demonstrated that attention based modulation of amplitude in the P1 and N1 time windows has a gradient distribution, indicating that the selective processing advantages expand beyond the cued area. The same study found attention based modulation in the N2 time window only at cued locations, suggesting that the N2 may represent a stage of processing that

selects only the cued area. However, it is difficult to determine from this study the sensitivity of the N2 to cue range. The size of the cued area was not varied, leaving open the possibility that the N2 simply indexes a smaller region of selection around the center of the cued location that would not be expanded when monitoring larger areas. Another study found that the N2 was the first time window affected by attention to a ring defined by degrees of eccentricity around fixation, with no change in P1 or N1 amplitude (Eimer, 1999). These amplitude differences in the N2 time window likely index a later stage of perceptual processing, as cuing studies have found that the posterior N2 is modulated by attention across scalp locations similar to the N1 (Shedden & Nordgaard, 2001). The evidence from these studies suggest the posterior N2 as a candidate index of a stage of processing dissociable from earlier stages in its sensitivity to the size of the attended area, but they do not definitively dissociate the N2 from the earlier time windows in terms of the spread of attention across peripheral locations. Experiment 2 was designed to further define the time windows sensitive to size adjustments of the attended area for stimuli presented in isolation.

There is an apparent discrepancy between the results of search studies that suggest the effects of adjusting the size of the attended area modulates the P1 and N1, and the results of studies in which stimuli are presented in isolation that suggest cue size effects are indexed by the N2. One reason for this discrepancy may be that changing the size of the attended region in search tasks changes the number of items presented within the attended region. As the attended region gets larger, the number of items that fall within this region increases. Differences in the number of items within the attended area may lead to differences in early processing stages due to the competition between stimuli

within the attended range. Conversely, for the studies in which only a single item is presented at a time, there is not the same need to resolve competition between concurrent stimuli. A full understanding of the effects of changing the size of the cued area will need to address this difference between the amplitude differences in search tasks and in sustained attention paradigms.

Attention Based on Objects

The literature reviewed thus far clearly indicates that spatial regions of the visual field can be attended. There is also evidence that the presence of object boundaries can affect the distribution of spatial attention. Evidence for object-based selection was presented by Duncan (1984) in a study in which judgments about two features of a single object were more accurate than judgments about the features of two separate objects. This was true even though both objects occupied an overlapping spatial region. Baylis and Driver (1993) extended these findings by showing that, even with physically identical displays, the object-based advantage relied upon whether the display was interpreted as a single object or multiple objects. These studies demonstrate that there is an advantage for single objects compared to multiple objects in terms of processing object features, but they do not confirm the effect of object boundaries on the distribution of spatial attention.

The effect of object boundaries on the distribution of spatial attention was demonstrated by Egly, Driver and Rafal (1994) with two rectangles flanking fixation and a cue indicating the likely occurrence of a target at one end of one of the rectangles. The critical targets were those presented at an equal distance from the cued location, at both the uncued side of the rectangle containing the cued location, and within the rectangle

that did not contain the cued location. Response times were faster to targets presented on the uncued side of the cued rectangle compared to targets presented within the other rectangle. The response time advantage for stimuli presented at an uncued location within a cued object suggests the distribution of spatial attention is altered such that it spreads more within the boundaries of a cued object than to equally distant uncued objects.

There is an alternative to the guided spread of attention explanation for the object-based response time advantage; there may be a preference to search within a cued object before searching within other objects. Support for this alternative explanation comes from Shomstein and Yantis' (2002) finding that object-based attention effects depend on whether the location of the target is held constant or varied. The displays used in this study consisted of a central long rectangle and two shorter rectangles arranged to form a cross. In one set of experiments the target always appeared in the center of the long rectangle, and high interference flanker stimuli were presented either on the same object as the target, or at an equal distance from the target on the two adjacent objects. In another experiment the target could appear at one of four locations surrounding fixation, and the location of the target was not known prior to presentation. They found object based attention effects when the location of the target was varied across trials, but not when the target location was held constant. These studies support the view of object-based selection as a search preference rather than a perceptual advantage for locations within the same object as the cue. However, Chen and Cave (2006) argued that the arrangement of objects in the Shomstein and Yantis (2002) study was such that they may have been perceived as a single object rather than as separate objects. Using similar

stimuli they showed that object based attention effects were present in the flanker paradigm when filler trials were inserted that encouraged viewing the display as a collection of separate objects. It is also possible that Shomstein and Yantis (2002) did not find object based effects because the letter stimuli were viewed as separate from the objects. Richard, Lee, and Vecera (2008) demonstrated object based modulation of the flanker effect using rectangular bars with different shaped bites cut out at three locations. Using stimuli defined by bites in the rectangle encouraged viewing both the target and the flankers as parts of the object. Responses were always made to bites in the center of the rectangle, so the target location was held constant as in Shomstein and Yantis (2002). They found that when all three bites appeared on the same rectangle, there was a stronger flanker effect than when the bites occurred on separate rectangles, suggesting there is a spread of attention within objects to features that are perceived as part of the object.

Further evidence for object-based attention comes from studies demonstrating that the distribution of attention is automatically adjusted to fit the size of presented objects. One study presented variable size squares centered on fixation followed by a target stimulus (Maringelli & Umilta, 1998). All targets were presented at fixation, ensuring that the square was not informative as to the location of the target. Response times to the target were faster following small squares compared to large squares, suggesting the attended window was adjusted to fit the square object boundaries. A more recent study found that when two objects were presented in succession, the focus of attention adjusted to the size of the second object (Turatto et al., 2000). Further support for the effect of objects on the distribution of spatial attention comes from the finding that there is a gradient of attentional facilitation that spreads within objects, and is weaker across object

boundaries (Hollingworth, Maxcey-Richard, & Vecera, 2008). These studies suggest that fitting the window of attention to the object boundaries occurs regardless of whether the object provides spatial information useful for performing the task.

ERP studies have been used to determine the stage of processing affected by the presence of object boundaries. Modulation of early ERP components, particularly in the N1 time window, has been reliably used to index the effects of spatial attention on perceptual processing, so modulation of these time windows based on object boundaries would provide supporting evidence that object based attention is occurring at a similar processing stage as spatial attention. Using a modified version of the paradigm from Egly, Driver and Rafal (1994), Martinez et al. (2006) found that stimuli presented within an attended object evoked larger amplitude in the N1 time window compared to stimuli presented within an unattended object. Object based modulation of the N1 time window was also demonstrated with cues presented peripherally rather than centrally; however in this case there was a topographical difference between space based and object based effects in the N1 time window, with spatial effects more anterior at central electrode sites and object based effects more posterior across temporal and occipital electrode sites (He, et al. 2004). Greater N1 amplitude has also been found for probes presented within an illusory object containing a cued location compared to when the cue is the same distance from the probes but no illusory object is present (Martinez, Teder-Salejarvi, & Hillyard, 2007). As the N1 has been previously associated with perceptual processing differences in spatial attention tasks, amplitude differences in the N1 time window in object based attention tasks provide evidence that selection is occurring at the perceptual stage of processing, and suggest that this selection is achieved by altering the distribution of

spatial attention.

The evidence reviewed here suggests that the distribution of spatial attention is affected by the presence of object boundaries. Specifically, if one part of an object is cued, the effects of attention can be shown at locations throughout the object. Further, the electrophysiological evidence supports the theory that this spread of attention provides a processing advantage to stimuli presented within the attended object's boundaries. What is not yet clear is how object based attention relates to the gradient and zoom lens models of the distribution of spatial selection. Do the boundaries of the object prevent a gradient of spatial attention from spreading outside its bounds? The size of the attended area seems to be adjusted to fit the area of an object, but can task demands narrow the focus to only part of the object? If the gradient and zoom lens models represent a single stage of processing, there would be no distinction between object based attention effects on these distributions. However, if the gradient and the adjustable region of attention occur at two separate stages of selection, then object boundaries may only impact one stage of attention. Experiment 3 was designed to investigate the interaction between the size of the cued area and the size of objects in the display on the distribution of attention.

Attention Based on Color

Thus far the discussion has focused on the selection of stimuli based on location within the visual field. However, selection also occurs based on other task relevant features of the stimuli. Returning to the example of searching for your car in a parking lot, you might first look for cars with a similar color to yours. Selecting by color in this way narrows down the number of cars that need to be further examined to determine if

they are in fact your car. Selection on the basis of color has been demonstrated using a visual search task (Treisman & Gelade, 1980). In this study, if the target was defined by both color and shape, then increasing the number of items that matched the target color resulted in increased search times. However, if the target had a unique color compared to all the other items in the display, search times did not increase as the number of items increased. One model proposed to explain these results suggests that color is not selected for directly, but instead guides the allocation of spatial attention (Wolfe, Cave, & Franzel, 1989). This model explains the data from search studies that require shifting attention between items in an array of items. However, it leaves open the question of whether objects with attended features such as color receive selective processing when location is held constant, such as when a stream of stimuli are presented at fixation.

Electrophysiological measures have shown that attention to color affects ERP amplitude when location is controlled. Time windows sensitive to attention to color are well described in a study measuring the ERP waveform time-locked to the onset of red or blue check patterns (Anllo-Vento, Luck, & Hillyard, 1998). ERPs time-locked to the presentation of an unattended color were subtracted from the response to a cued color. Attention to color was found to modulate amplitude in three time windows: an early posterior positive deflection (PD130) from 100-140 ms, a posterior selection negativity (SN) from 160-350 ms, and an anterior selection positivity (SP) from 180-230 ms. Attention based modulations in similar time windows have been demonstrated using a sustained attention task in which the effects of cuing location and color were separable (Hillyard & Münte, 1984). For non-target items, attending to the location of an item resulted in modulation of early visual components (P1, N1, P2). Attention to the color of

the item resulted in amplitude modulation in the SN and SP time windows beginning about 150 ms after stimulus onset. A similar study used transient attention conditions in which location and color were cued preceding each trial with a short delay before stimulus onset (Eimer, 1995). This study found modulation for items in the attended color in the SN time window, beginning about 200 ms after stimulus onset. The difference in SN onset latency between the two studies may have been the result of using a sustained compared to a transient attention task. These studies demonstrate that attention based on color results in measurable ERP amplitude differences. In all studies the effects of color selection were larger for stimuli at attended compared to unattended locations, suggesting that selection by location may be a prerequisite for selection by color.

Selection based on color has also been demonstrated when location uncertainty was removed entirely from the task (Vierck & Miller, 2005). This study employed a rapid serial visual presentation (RSVP) task at the center of the visual field. In an RSVP task, stimuli are presented with a very short stimulus onset asynchrony (SOA) such that there is not enough time to fully process all of the stimuli. This is essentially a search display spread out over time rather than space, and encourages the use of attention to filter out irrelevant stimuli in the stream. The task was to report whether a target letter was presented in an upper or lower case font. The streams were preceded by a cue indicating with 80% validity the color of the target letter. Responses were faster and more accurate for targets that appeared in the cued color, demonstrating that attention to color provided a processing advantage. A more recent study used the same task while collecting ERP data (Vierck & Miller, 2008). They found amplitude differences in the

SP and P3 time windows for validly compared to invalidly cued targets. These studies provide evidence for selection based on color for stimuli at a constant spatial location.

One open question concerning color-based attention is whether color can be selected directly or if color is indirectly selected based on the location of spatial selection. The indirect selection argument suggests that color guides the orienting of spatial attention, and all differences in performance based on cued colors are actually spatial attention effects mediated by color guidance (Cave & Pashler, 1995). The argument for direct selection relies upon findings that cued colors are facilitated when they are presented at known locations, and therefore no spatial attention is needed (Hillyard & Münte, 1984; Andersen, Müller, & Hillyard, 2009). The theory that has gained favor in much of the ERP research falls somewhat between these two ideas, and suggests that direct selection of color is possible, but only at spatially attended locations. Support for this theory comes from evidence that color-based attentional modulation in the SN time window is prominent for stimuli presented at attended locations, and largely absent at unattended locations (Hillyard & Münte, 1984; Lange, Wijers, Mulder, & Mulder, 1998). More recently, it has been suggested that features can be selected prior to location when there is sufficient competition between items in the display, and during simple visual search tasks (Zhang & Luck, 2009, Hopf et al., 2004). Clearly color can play an early role in selection, as color can effectively be used to guide the allocation of spatial attention and saccades in a search array. In addition, some degree of post-spatial color selection seems to be occurring in tasks that require responding to items of a specific color at a known attended location. What is not yet clear is to what extent the pre-spatial and post-spatial color selection rely on the same neural mechanism. Comparing the

results of Experiment 4 to search studies on color selection will hopefully clarify whether these two types of color selection have similar selection profiles.

There is convincing evidence for selection based on color when a single color is cued, but few studies have explored whether attention to a color results in a gradient of attention spreading to similar colors, and whether a range of colors can be attended. One study addressed this question using a visual search task in which two colors of varying similarity were cued on each trial (Stroud, Menneer, Cave, & Donnelly, 2012). Eye movements were tracked during search to determine color selectivity. The number of fixations to items of each color was used to determine whether participants were fixating only items of the two cued colors, or if they were fixating all items within a range that included the cued colors. The eye tracking data demonstrated that the more dissimilar an item was from a target color, the less likely it was to be fixated, suggesting a gradient of color selectivity. As the distance between the target colors increased, color selectivity suffered, such that larger differences between the two target colors led to more fixations to items dissimilar to either target. Further, when the two target colors were similar to one another, items with an intermediate color between the two target colors were fixated at a rate that was similar to the fixations for the target colors.

One explanation proposed for the eye tracking results is that each cued color forms an attentional gradient in color space, causing similar colors to be fixated more frequently. When the two cued colors are close to each other in feature space, the gradients of the two colors overlap, and if the gradients are additive, items with a color between the cued colors receive more fixations than items similar to only one of the cues. Another possibility is that a single range is selected with edges defined by the cued colors

that includes intermediate colors. Some modeling of the eye tracking data suggests that additive gradients provide the most parsimonious explanation of the data from all of the search conditions (Stroud, Menneer, Cave, & Donnelly, 2012). There have not been many studies exploring selection of multiple colors and more research is needed to determine whether it is possible to select for a range of colors, and whether there are costs associated with attending to larger color ranges. Further studies using items in a dense color space are also needed to confirm that the gradient of fixations seen in visual search tasks is due to a gradient of selective processing. Electrophysiological measures provide a means to measure the response to non-target items with colors of varying similarity from the cues, and thus establish whether color based attention has a graded distribution similar to that seen in spatial attention. In addition, the ability to measure the response to non-target items provides an effective comparison between larger and smaller ranges of attended colors.

Attention Based on Size

While color is a salient and useful feature in distinguishing stimuli, it is not the only feature that can be used to guide selection. Another critical feature is the size of the stimuli. Larsen and Bundesen (1978) first reported that participants were slower at responding to the orientation of a character if it appeared at an unexpected size. They found that as the disparity between the expected and actual size of the target character increased, response times also increased. Slowed response time to stimuli appearing at an unexpected size has also been demonstrated when two overlapping objects are presented (Cave & Kosslyn, 1989). This effect was greatest when the presented objects had an expected shape. One explanation for these results is that the visual system is

prepared to match the target representation with a stimulus of a particular size, and when it differs from the expected size, either the stimulus or the representation must be scaled to establish a match. The larger the difference between the expected and the actual size, the longer the scaling takes to complete, accounting for the response time differences. An alternative explanation for these results is that participants are attending to the feature of stimulus size with a graded distribution. This explanation posits that stimuli with sizes close to that of the attended size receive some selective advantage and can be processed more rapidly.

One of the primary roles of attention is the reduction of interference from distracting stimuli. Directing attention with a cue indicating the target size should aid in the discrimination of target stimuli, and reduce interference from stimuli of other sizes. Size cues do provide a benefit in an RSVP task (Poder, 2001). In this study, characters appeared at 2 different sizes, either small or large, and the scale difference between the sizes was varied between blocks. Participants were cued to monitor either small or large characters for targets. They found that when participants monitored either large or small characters, performance was better than when both sizes were monitored. This improved performance suggests that size information can be used in the filtering of distractor items.

There have also been electrophysiological studies addressing the effect of selection for stimuli of a specific size using a global/local paradigm (Heinze, Hinrichs, Scholz, Burchert, & Mangun, 1998; Rijpkema, Aalderen, Schwarzbach, & Verstraten, 2007). In the display for these studies, a single large item is made up of constituent smaller items; for instance, a set of small letters arranged to form one large letter. The ERPs evoked by the display can then be compared between conditions in which

participants attend to either the large or small scale. Heinze et al. (1998) found that there were amplitude differences in the P1 and N2 time windows when participants attended to either the small or the large scale compared to when they passively viewed the stimuli. They also compared the response to targets occurring at different scales when both sizes were monitored. They found an asymmetry in the distribution of the N2 deflection, with greater amplitude over the right hemisphere for global targets, and over the left hemisphere for local targets. These differences could be interpreted as either the effect of attending to different sizes, or the effect of attending to global compared to local features. A functional magnetic resonance imaging (fMRI) study used a similar paradigm to demonstrate that attention to the local scale resulted in greater activation in cortical areas around fixation in V1, while attending to the global scale resulted in a larger area of activation including cortical areas representing the periphery of the visual field (Rijpkema et al., 2007). These results suggest that when the local level is being attended, stimuli in the periphery are inhibited, supporting the theory that attention to size is being used to perform the global/local task.

Size based attention has not been studied as thoroughly as color-based attention. Because of this, the timing of the electrophysiological response will provide useful clues as to the stage of processing impacted by attending to a target size. One possibility is that attention to any feature, color, size, orientation, etc., will be handled by a general feature based selection mechanism. Particularly interesting is the relationship between selection of objects based on their size and adjustments of the area of spatial attention. Presenting objects of variable sizes can cause an automatic adjustment of the attended window (Marengelli & Umilta, 1998; Turatto et al., 2000). This automatic adjustment of the

attended area could be the result of the same mechanism that allows for the selective processing of stimuli of a given size. If attention to size does operate via an adjustment of the window of visual attention, then it may have different characteristics from attention to color. In order to differentiate between these explanations, a better characterization of the electrophysiological effects of attention to size is needed. Further, as in the case of color, it would be useful to know whether the distribution of attention in the dimension of size has the same characteristics of a graded distribution and attention to a range of sizes as seen in spatial attention.

Current Studies

Two experiments are presented demonstrating the effects of separate stages of spatial selection; an earlier stage with a gradient distribution and a later stage in which attention is focused to a more specific area. Three further experiments extend these findings to object and feature-based selection. Experiment 1 demonstrates an early gradient of attention indexed by the N1 that is stronger below compared to above the cued location. The second experiment uses a similar task to demonstrate a later focusing or "zoom lens" of attention indexed by the N2. Experiment 3 addresses the effect of object boundaries on the distribution of attention, and in particular the interaction between the size of the cued area and the presence of object boundaries in the display. Experiments 4 and 5 address the question of whether the gradient and zooming stages of attention are restricted to the spatial domain, or are also used in selecting based on the features of color and size. Comparing the results of Experiments 4 and 5 also informs our understanding of whether attention to size and color share a general feature based attention mechanism. Taken together, these studies provide evidence about the stages of

attention across a number of feature dimensions when selecting visual information for further processing.

CHAPTER II

EXPERIMENT 1: SPATIAL GRADIENT

Introduction

The goal of the first two studies was to further define the distribution of spatially selective processing based on the location and size of the cued area. The first experiment investigated the gradient of facilitation around a cued location. Using numerous locations surrounding fixation also allowed measurements of any asymmetries in the spread of the gradient in the horizontal or vertical directions. The second experiment investigated changes in the size of the cued area. By keeping the center of the cue constant, and modulating the scope of locations cued, the stages of processing sensitive to the size of the attended area were determined. In both of these experiments, ERPs were used to measure facilitation based on attention at different locations in the visual field. This provided evidence for a differentiation of stages of selection based on the time window of modulation in the ERP waveform. In particular, these studies addressed whether the effects of the gradient of facilitation in Experiment 1 appear within the same time windows as changes in the size of attention in Experiment 2. While previous studies suggest that these factors modulate separate ERP time windows, direct comparisons are difficult as the studies differ significantly in their design. By using paradigms that were identical except for the cues presented at the beginning of each block, direct comparisons could be made between the timing of the gradient effects against the timing of the effects of the cued area size.

Experiment 1 investigated the characteristics of the gradient of spatial attention by measuring how far it extended and whether there were any asymmetries in its

distribution. A sustained attention paradigm was used in which participants monitored one of 12 squares arranged on an imaginary circle around fixation and responded to targets appearing within a cued square. Images were presented rapidly to discourage shifting attention between stimulus presentations. This paradigm allowed us to examine several aspects of the distribution of attention. First, by presenting stimuli at a relatively large number of locations, the spread of attention could be measured across larger areas. The gradient model would suggest that, particularly when a small area is cued, locations adjacent to the cued area would receive some attentional modulation, but it is unclear how far this spread of attention would reach. In addition, the large number of locations made it possible to compare stimuli presented above/below or to the left/right of the cue to determine if there were asymmetries in the distribution of the gradient.

Method

Participants

Data from eighteen participants (8 female, mean age: 24.5 years, SD: 7.2) were included in the final analyses. Each participant completed two 2.5 hour sessions; the second session was within 10 days of the first. Twenty-four participants were initially included in at least some portion of the experiment; data from 4 participants were excluded because of an insufficient number (< 80) of artifact free trials in some conditions (artifacts included blinks, eye movements, and electrodes showing excessive noise). Data from an additional 2 participants were excluded due to technical problems. All participants were right handed, and reported having normal or corrected to normal vision. All participants provided written informed consent prior to the study, and were paid for their participation.

Stimuli

The display consisted of a black background with 12 grey outlined squares marking the possible locations at which stimuli could appear (Figure 1). These squares were arranged equidistant from each other on an imaginary circle surrounding a fixation cross. Square locations will be referred to with numbers indicating position on a 12-hour analog clock face, with location 12 at the top and labeled sequentially from 1-11 around the circle in a clockwise direction. Each square occupied 0.3° by 0.3° of visual angle. The squares were centered on points 1.2° from the fixation cross and 0.66° from one another. The cue consisted of changing the color of one square from grey to red and doubling the line thickness. Each location around the circle was cued in separate blocks, resulting in 12 cue conditions. Stimulus letters were presented in white and each was either a standard (O) or a deviant (X) occupying 0.25° by 0.25° of visual angle. The letters appeared one at a time, each within one of the locations marked by grey squares, with 80% being standards and 20% deviants.

Procedure

Participants were seated in a comfortable chair and instructed to keep their eyes focused on a fixation cross and to press a button when a deviant appeared at the location that was previously cued for that block (a target). The cue was presented at the beginning of each block for 2000 ms. The first stimulus letter appeared 1000 ms after the cue disappeared. Stimulus letters were presented in rapid succession for 72 ms each with a random interstimulus interval (ISI) between 200-600 ms. Stimuli were presented with equal frequency at all twelve squares.

A block lasted approximately 2 minutes, during which 240 stimuli were

presented, with 4 deviants and 16 standards at each of the 12 locations. There were 72 blocks total, with 6 blocks of each cue condition in random order, resulting in 24 deviants and 96 standards at each location for each condition. Prior to beginning the experimental trials, all participants were given a ten minute introduction and practice block, which included practice on the discrimination between standards and deviants, as well as the task of responding to deviants at cued locations. A button press was considered correct if it occurred between 250 and 1000 ms after the onset of a target. If more than one response occurred between 250 and 1000 ms after a target, time windows were used to determine which response would be associated with the target (primary time bin 500-749 ms, secondary 250-499 ms, tertiary 750-1000 ms). All button presses that did not occur between 250 and 1000 ms after a target were classified as false alarms. Due to the rapid presentation and frequency of standards, it was impossible to determine with certainty which stimulus onset was associated with each false alarm.

ERP Procedure and Comparisons

Participants viewed stimuli while EEG was recorded from a 128-channel electrode net (EGI, Eugene Oregon). EEG recorded from all electrodes was amplified with 0.01-100 Hz bandpass and sampled at 250 Hz. Impedances were maintained under 50 kΩ throughout the experiment. The vertex electrode was used as a reference for all other electrodes during recording. Data were segmented into epochs from 100 ms prior to 500 ms after onset of standards. Electrodes located above and below each eye were used to detect eye blinks, and electrodes at the outer canthi were used for detecting horizontal eye movements. The resulting epochs were subjected to artifact rejection algorithms and human visual inspection to discard segments containing artifacts.

Artifacts were defined as epochs containing eye blinks or eye movements, or for which electrodes showed excessive noise. Following artifact rejection, data were re-referenced to the average of the mastoid electrodes. Scalp potentials evoked by standards presented at each location and in each attention condition were averaged for each individual separately. ERPs elicited by deviants were not analyzed due to the limited number of trials in which they appeared. All ERP segments were baseline corrected to the 100 ms pre-stimulus interval.

Mean amplitude was measured around each peak typically observed in visual evoked potentials. The time windows were determined by visual inspection and guided by previously published studies. For posterior components, mean amplitude was measured during the P1 (70 to 120 ms), N1 (150 to 200 ms), N2 (230 to 270 ms), and P3 (300 to 450 ms) time windows. The P2 amplitude was not analyzed since the positive deflection contralateral to the stimulus presentation in the time window associated with the P2 overlapped temporally and spatially with both the N1 and N2. Groups of electrodes were chosen for measurement in each time window guided by the distributions commonly found in previous research. Twenty-seven electrodes placed over posterior regions were divided into three groups of 9 electrodes over the left-hemisphere, medial regions, and the right-hemisphere (Figure 2). For the P1, N1, and N2 measurements, attention effects for standards presented at lateral locations (1-5 and 7-11) were measured at the group of 9 posterior electrodes contralateral to standard presentation, and for standards presented at the midline (6 and 12) were measured at the 9 posterior medial electrodes. Measurements in the P3 time window were taken across all 27 posterior electrodes. The remaining factors in the analyses were presentation Location of the

standards and Attention condition. Standards occurred in one of seven attention conditions defined by the number of squares separating the standard presentation location and the cued location: at the cued location (C0), 1,2,3,4, or 5 squares away from the cued location (C1, C2, C3, C4, C5), or the square opposite the cued location (C6). All comparisons including a factor with more than two levels used the Greenhouse-Geisser correction.

Three sets of comparisons were performed for mean amplitude measurements in each time window. To determine the effect of orienting attention, comparisons were made between the responses to standards when the standard's location was cued against when the opposite side of the display was cued. To determine the effect of a gradient distribution of selection a second set of comparisons measured the effect of varying cue distances from the standard. Finally, to determine if there were asymmetries in the gradient of selection comparisons were made between the response to standards for cues that appeared above vs. below the standard. A similar analysis was performed for cues that appeared to the left vs. right of the standard. The analysis for asymmetries in attention was restricted to time windows that showed a gradient distribution of attention in earlier comparisons.

Results

Behavioral Results

To determine if there were differences in the behavioral responses across locations, separate analyses were performed for the hit rate, false alarm rate, and response time by cued location (summarized in Table 1). There was not a significant effect of location on either false alarm rate or response time (FA: $F(11,187) = 1.6$, $p = .202$; RT:

$F(11,187) = .7$, $p = .684$). However there was a significant effect of cued location on hit rate ($F(11,187) = 2.3$, $p < .05$). A larger percentage of the targets at locations near the horizontal midline were identified compared to locations near the vertical midline. These results suggest that participants were somewhat more effective at discriminating standards from deviants at positions horizontal to fixation than those vertical to fixation.

ERP Results

An initial set of tests investigated the effect of attention on the visual evoked potentials across all of the presentation locations. Mean amplitude from trials in which the cue was at same location as the standard (C0) was compared against trials in which the cue was on the opposite side of the display, or 180 degrees around the circle, from the standard (C6). For instance, for a standard presented at the 2 o'clock position, C0 indicates that the square at 2 o'clock was cued, and C6 indicates that the square at 8 o'clock was cued. Averaged ERP waveforms evoked at each location are shown in Figure 2. For simplicity, in the results section standards are referred to as presented on the cued/uncued side. However, in all cases the comparisons are between standards at the same location in the visual field under different cue conditions to ensure that all differences in ERP response can be attributed to the allocation of spatial attention and not to physical differences in presentation location. Attention effects were measured with standard location as a factor, and significant effects were explored further with specific contrasts.

For the mean amplitude measurements during the P1 time window there was no main effect of attention ($F(1,17) = .3$, $p = .609$) and no interaction between attention and standard presentation location ($F(11,187) = 1.0$, $p = .432$). There was also no main effect

of attention at ipsilateral electrodes in the P1 time window ($F(1,17) = 2.3$, $p = .149$) and no interaction with presentation location ($F(11,187) = .7$, $p = .682$). It is unlikely that the lack of an attention effect in the P1 time range was due to a lack of power as there was little difference in the means between standards in the cued and uncued conditions, and there was a strong attention effect for other time windows commonly associated with spatial attention. The lack of modulation in the P1 time window may indicate either that there was no preferential processing, or that with the particular display used the evoked P1 was of too low amplitude to register modulation based on attention. These possibilities are explored further in the discussion.

Mean amplitude in the N1, N2, and P3 time windows all showed a significant main effect of attention (N1: $F(1,17) = 26.7$, $p < .001$; N2: $F(1,17) = 12.6$, $p < .005$; P3: $F(1,17) = 54.0$, $p < .001$). Consistent with previous studies, cued standards elicited more negative mean amplitude relative to uncued standards in the N1 and N2 time windows, and more positive mean amplitude relative to uncued standards in the P3 time window. For the N1 time window, there was also a significant interaction between attention and location of standard presentation ($F(11,187) = 2.5$, $p < .05$). Separate analyses for each presentation location revealed an effect of attention for standards presented at all locations except the 12 o'clock position, with cued standards eliciting a larger negativity than uncued standards (all p's $< .05$). At the 12 o'clock location there was no significant modulation of amplitude based on attention ($F(1,17) = .3$, $p = .603$). The lack of modulation at the 12 o'clock position was likely due to reduced amplitude of the component evoked by standards presented at that region of the screen, and not a difficulty in monitoring the location. There was not a significant interaction of attention by

location of standard presentation for the N2 or P3 (N2: $F(11,187) = 1.1$, $p = .394$; P3: $F(11,187) = .7$, $p > .667$). The first set of comparisons confirms that the time windows commonly associated with spatially selective attention were modulated in the current paradigm. In addition, the modulation seen for every time window across all standard presentation locations (with the exception of the N1 at the 12 o'clock location) confirms that the time windows and electrode groups selected capture the attention effects within components of interest.

A second set of comparisons was made to determine if there was a gradient in the distribution of attention. Attention effects were analyzed for standards based on their distance from the cued location (C0, C1, C2, C3, C4, C5, C6), with C0 indicating that the standard's location was cued, and C6 indicating that the square opposite the standard's location was cued. For time windows demonstrating main effects of cue distance, further contrasts were done to determine which cue conditions differed significantly from the cue opposite condition (C6). Differences from cue opposite are interpreted as attentional facilitation for standards at that distance from the cued square. Where more than one cue condition differed from cue opposite, further contrasts were performed to determine if there was a gradient of facilitation such that attention based modulation dropped off with increasing distance from the cue. The P1 time window was excluded from this analysis as it did not show an amplitude difference between the C0 and C6 conditions. This comparison also collapsed across standard location, as there were limited differences between standard locations in the effects of orienting attention. Averaged ERP waveforms at differing cue distances are shown in Figure 3a, and mean amplitude in the N1 and N2 time windows is shown in Figure 4.

For the N1 time window there was a main effect of cue distance on mean amplitude ($F(6,102) = 19.1$, $p < .001$), and contrast measurements indicated that the C0, C1, and C2 conditions were significantly more negative than the C6 condition (C0 vs. C6: $F(1,17) = 26.7$, $p < .001$; C1 vs. C6: $F(1,17) = 22.8$, $p < .001$; C2 vs. C6: $F(1,17) = 6.7$, $p < .05$). For standards in the C3-C5 conditions there were no differences from the C6 condition (p's > .05). Additional contrasts revealed that the C0 condition was significantly more negative than the C1 condition ($F(1,17) = 8.3$, $p < .05$), and that the C1 condition was significantly more negative than the C2 condition ($F(1,17) = 16.4$, $p < .005$). These results indicate that for the N1 time window there was attentional facilitation for locations up to 2 squares away from the cued locations. Further, this facilitation was distributed as a gradient, with the cued location receiving the greatest facilitation, and attention dropping off with distance from the cued location. For 3 squares away from the cue and further, any facilitation was not strong enough to reach significance.

There was also a main effect of cue distance for mean amplitude in the N2 time window ($F(6,102) = 11.3$, $p < .001$), but individual contrasts revealed that only the C0 condition was significantly more negative than the C6 condition ($F(1,17) = 12.6$, $p < .001$). None of the other cue distances differed significantly from the C6 condition (p's > .05). This suggests that for the N2, unlike the N1, there was no facilitation of locations adjacent to the cued location. There are at least two possible interpretations of the lack of modulation for neighboring locations in the N2 time window. One is that there is a gradient of facilitation for this time window, but it is smaller than that indexed by the N1, and the locations used in this study were far enough apart that the nearest neighbors

exceeded the edge of the gradient. A second possibility is that the N2 time window indexes a stage of selection that is modulated only for locations that fall within the cued region. The second of these possibilities is further investigated in Experiment 2. Under either interpretation, the attentional effects in the N2 time window appear more precisely localized than in the N1 window when a small spatial area is cued. To further investigate the differences in the spread of facilitation between the N1 and N2 time windows, a post-hoc comparison was performed that included time window and cue distance as factors. Two comparisons were performed with two levels of cue distance each, cue opposite and either C1 or C2. These cue distances were chosen because they demonstrated an attention effect in the N1, but not the N2 time windows. There was a significant interaction for both comparisons (C1: $F(1,17) = 9.3$, $p < .01$; C2 $F(1,17) = 14.2$, $p < .005$), such that there was a difference in amplitude between when the cued location was near the standard (C1,C2) and when it was further away (cue opposite) for the N1, but not for the N2. This supports that the facilitation indexed by the N1 time window spread to locations further from the cue compared to facilitation indexed by the N2 time window.

For the P3 time window there was a main effect of cue distance ($F(6,102) = 37.5$, $p < .001$), and both the C0 and the C1 conditions were significantly more positive than the cue opposite condition (C0 vs. C6: $F(1,17) = 54.0$, $p < .001$; C1 vs. C6: $F(1,17) = 9.2$, $p < .01$). None of the other cue distances differed significantly from the cue opposite condition (p's > .1). The C0 condition was also more positive than the C1 condition (C0 vs. C1: $F(1,17) = 53.3$, $p < .001$). Thus, there is evidence for a gradient of attention in the P3 time window that is tightly focused around the cued location.

The cue range analysis showed that there was a gradient in attention based modulation for the N1 such that locations up to 2 squares away from the cue received facilitation. Further, the modulation of the N1 decreased as a function of the distance from the cued square, indicating that this spread of facilitation had a gradient distribution. A similar gradient was observed for the P3 time window, but with a spread of facilitation only to the squares adjacent to the cue. For the N2 only the cued square received attention based modulation. Of the time windows commonly associated with perceptual processing benefits, only the N1 showed a gradient distribution of attention. While the N2 may also index perceptual processing differences, this facilitation is limited to the cued area.

A final set of comparisons addressed whether the gradient of attention had a symmetric distribution around the cued location, or whether the distribution was asymmetric. Tests for asymmetries were performed for both the vertical and horizontal directions. The circular layout of standard presentation locations did not allow for a comparison of standards presented directly above, below, or to the left or right of the cue. However, by reducing the analyses to only some of the presentation locations, asymmetries could be assessed based on cue locations that were generally above/below or to the left/right of the standard. Standard locations that could have cues appear 1 and 2 positions above/below them (i.e. the 2, 3, and 4 o'clock positions in the right visual field and the 10, 9, 8 o'clock positions in the left visual field) were compared in four new conditions that described the cue location relative to the standard: cue 1 step above the standard (A1), cue 2 steps above (A2), cue 1 step below (B1), and cue 2 steps below (B2). Standard locations that could have cues appear 1 and 2 positions to the left/right of

them (i.e. the 11, 12, and 1 o'clock positions in the upper visual field and the 5, 6, and 7 o'clock positions in the lower visual field) were also compared in four conditions: cue 1 step left (L1), cue 2 steps left (L2), cue 1 step right (R1), and cue 2 steps right (R2). This analysis was limited to the N1 and P3, as these were the only time windows that showed a gradient distribution of facilitation.

For standards presented one square away from the cued location, mean amplitude in the N1 time window was significantly more negative for the A1 condition compared to the B1 condition (Figure 3b) ($F(1,17) = 15.1$, $p < .005$). The same pattern held for squares two locations away, with the A2 condition evoking more negative mean amplitude than the B2 condition ($F(1,17) = 11.8$, $p < .005$). There was no difference in the allocation left or right of the cued location at either cue distance (Figure 3c) (L1 vs. R1: $F(1,17) = .003$, $p = .958$; L2 vs. R2: $F(1,17) = .3$, $p < .573$). These results indicate that the gradient of selection indexed by the N1 is not distributed evenly around the cued location. While there was no difference in the spread of attention left or right of the cue, there was a greater spread of attention below compared to above the cue.

For the P3 time window there was no difference between cues one square above/below, or left/right of the standard location (A1 vs. B1: $F(1,17) = .002$, $p = .964$; L1 vs. R1: $F(1,17) = 2.4$, $p = .139$). In this time window the locations 2 away from the cue were not analyzed, as there was no evidence for a gradient of attention at that distance from the cue. There was no evidence of an asymmetry in the spread of facilitation for the P3 time window.

Discussion

There were three major analyses for Experiment 1. First, attention effects (cue same vs. cue opposite) were compared for standards appearing at all presentation locations. No significant effects of attention were observed in the P1 time window. There was attention-based modulation of N1, N2, and P3 amplitude that did not vary across most of the presentation locations. These findings are consistent with previous electrophysiological studies of visual attention and indicate that the locations of electrodes and time windows for mean amplitude measurements fully capture the attention effects. In addition, this analysis shows that attention effects are consistent across the presentation locations employed in the current study such that collapsing across presentation location for subsequent analyses is warranted. The only exception was a lack of an effect in the N1 time window at the upper most, or 12 o' clock, position. This null result may reflect the absence of an N1 in the waveforms for both attended and unattended standards presented at this location.

There was no effect of attention on P1 amplitude either contralateral or ipsilateral to the stimulus. There are several differences in the current experiment and previous studies that may explain why attention based modulation was not found in this early time window. Specifically, physical characteristics of the display (e.g., the eccentricity and size of the stimuli) may have affected the distribution or amplitude of the P1 in such a way that modulations of this portion of the waveform could not be detected. In addition, including the square boundaries to demarcate stimulus locations may have reduced the impact of the small visual onsets in a manner that reduced the overall amplitude of the P1 as well as its sensitivity to where attention was allocated. It has also been suggested that

amplitude in the P1 time window indexes inhibition of processing for images presented at unattended locations while amplitude in the N1 time window indexes facilitation for images presented at attended locations (Luck, 1995). Under this account, the lack of attention effects on P1 amplitude could be explained by participants not inhibiting standards at unattended locations in the current study.

The primary goal of Experiment 1 was to determine the timing with which a gradient of selective attention around the cued location affects visual processing. Attentional facilitation extended to nearby locations as indexed by mean amplitude in both the N1 and the P3 time windows. Amplitude in the N1 time window was larger for standards presented up to 2 locations away from the cue compared to when the cue was on the opposite side of fixation. Further, the size of the N1 attention effect decreased with distance from the cued location. This pattern of facilitation is consistent with a gradient model of attention and, as was true of previous studies, suggests gradients of spatial selection modulate visual processing within the first 200 ms after onset (Gonzalez et al., 1994; Mangun & Hillyard, 1998; Mangun, 1995). Effects of attention on processing images that appeared in locations other than the cued square were also evident on P3 amplitude. However, the selection gradient was more tightly focused for processing by 300 ms after onset such that facilitation extended only to the locations nearest the cued square. In contrast, there was no evidence of facilitation for images presented beyond the cued square on processing as measured with N2 amplitude, which falls between the N1 and P3 temporally.

Observing a gradient in some time windows and not others provides evidence against the argument that varying amounts of facilitation can be fully explained by

allocating attention to different locations on a trial-by-trial basis within the same condition. Graded effects observed on measurements that have been averaged across trials, including ERPs, could reflect a probabilistic distribution of attention. In the majority of trials viewers allocate attention to the cued location, but on some trials they instead allocate attention to a nearby location, and on an even lower proportion of trials they allocate attention to distant locations. After averaging across trials, attention effects would appear to be larger for the location where attention was most frequently focused (i.e., the cued location) and to decrease in strength with increased distance. The final measured distribution would be the result of the probability of attending to a specific location on each trial, rather than a gradient of attention that is consistent for every trial. However, since attention is maintained at one location within each trial, graded effects should be evident in every time window in which attention effects are observed. Probabilistic allocation of attention that differs from trial to trial cannot explain the pattern of results in the current study: graded attention effects in some time windows (N1 and P3) and attention effects for images presented exactly at the cued location in other time windows (N2).

A third set of analyses suggests that the distribution of the gradient of attention around the cued location is not symmetric. Attention effects were compared for images presented at locations that could have cues 1 or 2 squares above and below them. Attentional facilitation in the N1 time window was greater for standards appearing below the cued location than for standards appearing above the cued location. This novel finding of a strong asymmetry in the allocation of the gradient suggests more work is needed to determine the functional significance of preferentially processing locations

below the focus of attention. There was no asymmetry between the left and right side of the cued location, and no evidence of asymmetries in any direction for the P3 time window.

While the findings of Experiment 1 support a gradient model of attention, they do not address how the distribution of attention changes when different sized areas are cued. Selective processing was observed in the early N1 and later P3 time windows for nearby locations, even though images at these locations were irrelevant to performing the task. This pattern suggests that the attentional facilitation of visual processing indexed by N1 amplitude spreads beyond the cued location. However, later visual processing indexed by N2 amplitude was only modulated for images presented at cued locations. Experiment 2 was designed to determine whether the range of locations receiving selective processing can be adjusted based on task demands. Specifically, can the scope of the gradient of attention be adjusted based on the size of the area being monitored in a manner that affects visual processing in the first 200 ms after onset? Is the attentional facilitation observed on later visual processing indexed by N2 amplitude necessarily limited to images within a small region of space or can it be extended across a broader region based on the demands of the task?

CHAPTER III

EXPERIMENT 2: SPATIAL SCALE

Introduction

Experiment 2 followed the same procedures as Experiment 1 with the exception of the cue types used. In this experiment the size of the monitored area was manipulated by cuing 1, 3, or 5 adjacent locations in each block. In order to keep the number of trials reasonable with the addition of the new cue ranges, the center of the monitored area was restricted to the squares directly to the left and right of fixation, the 3 o'clock and 9 o'clock squares respectively. This paradigm allowed us to examine how different stages of visual processing were affected by changes in the size of the cued area. If changing the size of the cued area impacted the same stage of processing as the gradient demonstrated in Experiment 1, then the predicted differences would be between cue ranges in the N1 and P3 time windows. If, however, a separate stage of processing is associated with processing only the attended area, then the predicted modulation based on cue range would occur at the N2 time window.

Experiment 2 also allowed us to determine whether there was a fixed amount of attentional resources distributed across the cued region. The zoom lens model predicts that when the size of the attended region increases, there will be a lower level of resources allocated to each location, and thus less attentional facilitation at each location. If the amplitude of perceptual components in response to stimuli at the center of the cued area was unaffected by the cue size, this would suggest that the behavioral responses which led to the zoom lens hypothesis were not the result of resource limitations at the stage of perceptual selection, but instead were the result of a later processing bottleneck.

Method

Participants

Data from seventeen participants (8 female, mean age: 25 years, SD: 5.28) were included in the final analyses. Twenty-five participants were initially included in at least some portion of the experiment; data from 7 participants were excluded because of an insufficient number (< 80) of artifact free trials in some conditions. Artifacts included blinks, eye movements, and electrodes showing excessive noise. Data from one participant was excluded due to poor performance on the task (greater than 2:1 false alarm to hit ratio). All participants were right handed, and reported having normal or corrected to normal vision. All participants provided written informed consent prior to the study, and were paid for their participation.

Stimuli

The display was identical to that used in Experiment 1 except for the cue conditions (Figure 1). For Experiment 2, the cued region was centered directly to the left or right of fixation and contained 1 (small cue), 3 (medium cue), or 5 (large cue) adjacent squares, resulting in 6 cue conditions. The cue consisted of changing the color of the cued square from grey to red and doubling the line thickness. As in Experiment 1, stimulus letters were presented one at a time, each within one of the squares, with 80% being standards and 20% deviants.

Procedure

The task was the same as for Experiment 1. Participants were instructed to keep their eyes focused on a fixation cross and to press a button when a deviant letter (X) appeared at a previously cued location (a target). Standards (O) were ignored. The cue

was presented at the beginning of each block for 2000 ms. Stimuli began appearing 1000 ms after the cue disappeared. Stimuli were presented in rapid succession for 72 ms each with a random interstimulus interval (ISI) between 200-600 ms. Stimuli were presented with equal frequency at all twelve squares. A block lasted approximately 2 minutes, during which 240 stimuli were presented. Each cue condition was repeated for 8 blocks, resulting in 32 deviants and 128 standards at each of the twelve squares for each condition.

Prior to beginning the experimental trials, all participants were given a 10 minute introduction and practice block, which included practice on the discrimination between standards and deviants, as well as the task of responding to deviants at cued locations. This practice included short blocks of both the large and small cue conditions. A button press was considered correct if it occurred between 250 and 1000 ms after the onset of a target. If more than one response occurred between 250 and 1000 ms after a target, time windows were used to determine which response would be associated with the target (primary time bin 500-749 ms, secondary 250-499 ms, tertiary 750-1000 ms). All button presses that did not occur between 250 and 1000 ms after a target were classified as false alarms. Due to the rapid presentation and frequency of standards, it was impossible to determine with certainty which stimulus onset was associated with each false alarm.

ERP Procedure and Comparisons

ERP analyses followed the same procedures as for Experiment 1, with the exception of the conditions being compared. There were six cue conditions used for analysis in Experiment 2, each defined by the range of locations cued and by the side of the cue relative to the standard presentation location. There were three cue range

conditions on the same side as the standard presentation, cue small (CS), cue medium (CM), and cue large (CL), as well as three cue range conditions on the side opposite standard presentation, uncued small (US), uncued medium (UM), and uncued large (UL). Note that the term "cued side" simply means that the standard appeared on the same side of the display as the cued location(s), not necessarily within the cued area. When comparisons were made collapsed across cue side, only the three cue range conditions were analyzed; small (S), medium (M), and large (L). All comparisons of more than two levels used the Greenhouse-Geisser correction.

Results

Behavioral Results

Response data were collapsed across targets appearing to the left/right side of the screen and above/below the midline locations. For all of the behavioral analyses, only responses to stimuli presented at cued locations were analyzed, as stimuli at locations that were not cued did not require a response. Hit rate and response time were compared for targets (i.e., deviants at one of the cued locations) appearing at different locations in the same cue condition. These comparisons were only made for the medium and large cue conditions, because in the small cue condition there was only one location at which targets could appear. In the medium cue condition, there were more hits for targets presented at the midline compared to those presented 1 square away ($F(1,16) = 20.2$, $p < 0.001$). Response times were also faster to targets at the midline than to targets 1 square away from the midline ($F(1,16) = 10.7$, $p < 0.005$). In the large cue condition, the hit rate was higher for targets presented at the midline compared to 1 or 2 squares away (mid vs 1-away: $F(1,16) = 20.7$, $p < 0.001$; mid vs 2-away: $F(1,16) = 43.8$, $p < 0.001$), and higher

for targets presented 1 square away compared to 2 squares away ($F(1,16) = 33.6$, $p < 0.001$). Target location also affected response time in the large cue condition ($F(2,32) = 21.5$, $p < 0.001$), such that responses were slower when the target was presented 2 squares away from the midline compared to the midline ($F(1,16) = 29.1$, $p < 0.001$) or 1 square away ($F(1,16) = 108.5$, $p < 0.001$). There was not a significant difference in response time between targets presented at the midline and those presented 1 square away ($p > .05$). The faster and more accurate responses for the center of the cued area suggest a gradient of behavioral performance that drops off gradually with distance from the center.

Hit rate and reaction times were also examined under different cue range conditions for targets presented at the horizontal midline and 1 square above and below the midline. Cue range did not affect hit or false alarm rates, summarized with the other behavioral results in Table 2 (*p's* > .05). However, cue range did affect response times, such that responses were generally slower for stimuli at the edge of the cued region. The left side of Figure 5 shows the effect of cue range on response time to the targets at midline locations ($F(2,32) = 3.5$, $p = .06$). For these targets, responses in the small cue condition were slower than in the medium or large cue conditions (CS vs CM: $F(1,16) = 5.4$, $p < .05$; CS vs CL: $F(1,16) = 3.8$, $p = .069$; CM vs CL: $F(1,16) = .3$, $p = .599$). For targets presented 1 square away from the midline, response times were slower for the medium compared to the large cue condition ($F(1,16) = 20.1$, $p < .001$). Comparisons across cue conditions showed a slower response for stimuli at the edge of the cued area, and did not show the faster responses for smaller cue sizes that would be predicted by resource constraints within a zoom lens model.

ERP Results

Effects of orienting attention

The first comparisons were performed to confirm that there was attention-based modulation dependent on the cued side relative to the side of standard presentation. For standards at each location, mean evoked amplitude for trials in which the cued region was on the same side of fixation as the standard was compared to trials in which the cued region was on the opposite side of fixation. For each square location these comparisons were limited to cue ranges that encompassed that square, so the midline condition included all three cue ranges, the 1-away condition included the medium and large cue ranges, and the 2-away location included only the large cue range. The most consistent modulation of amplitude was found for the N1 and N2 time windows, so the results related to these time windows are presented first, followed by the P1 and P3 results. Averaged ERP waveforms are shown in Figure 6, and mean amplitudes for the N1 and N2 time windows are shown in Figure 7.

For standards presented at midline, one square away from the midline, and two squares away from the midline, there were main effects of cued side for both the N1 and N2 time windows (N1 midline: $F(1,16) = 32.3$, $p < .001$; N1 1-away: $F(1,16) = 35.1$, $p < .001$; N1 2-away: $F(1,16) = 8.7$, $p < .01$; N2 midline: $F(1,16) = 18.8$, $p < .001$; N2 1-away: $F(1,16) = 24.1$, $p < .001$; N2 2-away: $F(1,16) = 9.4$, $p < .01$), such that standards appearing on the cued side of the display evoked more negative mean amplitude than when the side opposite the standards was cued. This confirms spatial attention based modulation for both the N1 and N2 time windows at all locations of interest, and motivates further analyses of cue range effects for these time windows.

The second set of analyses tested for a spread of facilitated processing to locations outside of the cued area, similar to the gradient of facilitation demonstrated in Experiment 1. For instance, standards at the 1-away locations never fell within the small cue range. Similarly the 2-away locations were outside both the small and medium cue ranges. Modulation of amplitude at these locations based on cued side indicates that the area of facilitation spread beyond the cued range. For the N1 time window there was modulation based on cued side at both the 1-away and 2-away locations when a small region was cued (1-away: $F(1,16) = 25.5$, $p < .001$, 2-away:$F(1,16) = 4.9$, $p < .05$), such that standards presented outside of the cued range on the cued side evoked greater mean negative amplitude than when the opposite side was cued. These results suggest a spread of facilitation in the N1 time window on the cued side of fixation, similar to the gradient of facilitation in Experiment 1. There was not a significant difference in N1 amplitude based on cued side for the 2-away location preceded by the medium cue ($F(1,16) = 3.0$, $p = .1$), but the difference between the means was consistent with a spread of attention in this condition as well.

For the N2 time window there was limited evidence for a spread of perceptual processing facilitation beyond the cued region for the small cue range. There was only a trend towards significant modulation based on cued side at the 1-away location, and no effect at the 2-away location (1-away: $F(1,16) = 3.8$, $p = .069$; 2-away: $F(1,16) = 0.3$, $p = .581$). However, when a medium range was cued there was a difference based on cued side for standards presented at 2-away locations ($F(1,16) = 4.8$, $p < .05$), such that standards on the cued side evoked greater mean negative amplitude compared to standards on the uncued side. These results suggest that the N2 indexes facilitated

processing that has a limited spread to adjacent locations for both the small and medium cue range conditions. To further investigate the difference in the spread of facilitation between the N1 and N2 time windows, a post-hoc comparison was performed for standards presented at the 2-away location in the small cue range condition. There was a significant interaction between cue side and time window ($F(1,16) = 5.4$, $p < .05$) indicating that, similar to Experiment 1, when a single location was cued facilitation spread further beyond the cued region in the N1 compared to the N2 time window.

Effect of cue size on the allocation of attention

The third set of analyses of visually evoked potentials directly compared the three cue range conditions when standards were presented on either the cued side of fixation (CS, CM, CL), or the uncued side of fixation (US, UM, UL). Differences on the cued side indicate that the size of the attended area was widened and narrowed to match the size of the cued area. Differences on the uncued side indicate that processing for distant locations in the visual field was impacted by the size of the cued area. Both analyses provided information about the time windows for which amplitude was modulated by differences in the extent of the spread of attention.

For standards presented on the cued side at midline locations, there was no main effect of cue range on mean amplitude of either the N1 or the N2 time windows (N1: $F(2,32) = 1.2$, $p = .299$; N2: $F(2,32) = 1.6$, $p = .216$). There was a main effect of cue range for both N1 and N2 time windows on the uncued side (N1: $F(2,32) = 4.5$, $p > .05$; N2: $F(2,32) = 3.5$, $p < .05$). Individual contrasts on the uncued side of fixation revealed that there was more negative mean N1 amplitude evoked in response to standards for the small and medium cue conditions compared to large cue condition (US vs. UL: $F(1,16) =$

5.7, $p > .05$; UM vs. UL: $F(1,16) = 9.8$, $p < .01$; US vs UM: $F(1,16) = .3$, $p = .605$). The same pattern was observed in the N2 time window (US vs. UL: $F(1,16) = 5.5$, $p > .05$; UM vs. UL: $F(1,16) = 6.0$, $p < .05$; US vs UM: $F(1,16) = .1$, $p = .938$). The diminished amplitude in the large cue condition when standards were presented on the uncued side suggests that enlarging the cued area reduced the processing resources available for distant locations in the visual field.

For standards 1 square away from the midline on the cued side there was a main effect of cue range in the N1 time window and a trend towards a main effect in the N2 time window (N1: $F(2,32) = 4.8$, $p < .05$; N2: $F(2,32) = 3.1$, $p = .076$), and no main effect of range on the uncued side (N1: $F(2,32) = .8$, $p = .422$; N2: $F(2,32) = 1.6$, $p = .224$). Individual contrasts on the cued side of fixation revealed that the amplitude of the N1 was larger in the medium compared to the large cue condition even though the standards fell within the cued range for both of these conditions, and cue small was not significantly different from either of the larger cue sizes even though 1-square away from midline was not within the cued region for the cue small condition (CS vs. CM: $F(1,16) = 1.1$, $p = .317$; CM vs. CL: $F(1,16) = 15.9$, $p < .005$; CS vs CL: $F(1,16) = 2.9$, $p = .110$). This same pattern was repeated in the N2 time window, and similarly only the difference between medium and large cues reached significance (CS vs. CM: $F(1,16) = 3.1$, $p = .099$; CM vs. CL: $F(1,16) = 12$, $p < .005$; CS vs CL: $F(1,16) = .8$, $p = .857$). The effects 1 square away from the midline suggest that for the N1 and N2 time windows processing within the cued region was reduced when a large range of locations was monitored.

For standards presented 2 squares away from the midline there was a main effect of cue size for both the N1 and N2 time windows for standards presented on the cued side

(N1: $F(2,32) = 4.2$, $p < .05$; N2: $F(2,32) = 8.4$, $p < .005$), but not on the uncued side of fixation (N1: $F(2,32) = 1.2$, $p = .314$; N2: $F(2,32) = .1$, $p = .907$). For both time windows mean negative amplitude was greatest in the large cue condition, reduced in the medium cue condition, and smallest in the small cue condition. In the N1 time window only the difference between the large and small cues reached significance (CS vs. CM: $F(1,16) = 2.3$, $p < .149$; CS vs. CL: $F(1,16) = 7.5$, $p < .05$; CM vs. CL: $F(1,16) = 2.2$, $p = .155$). For the N2 time window both the medium and large cues evoked significantly greater mean negative amplitude compared to the small cue (CS vs. CM: $F(1,16) = 11.3$, $p < .005$; CS vs. CL: $F(1,16) = 11.4$, $p < .005$; CM vs. CL: $F(1,16) = 1.7$, $p = .210$). Amplitude in both the N1 and N2 time windows was greater in response to standards presented in the large cue conditions, the only condition for which the 2-away location was within the cued range, suggesting that selective processing indexed by these time windows is sensitive to changes in the size of the cued area. That the medium cue condition was not significantly different from the large cue condition is probably indicative of the spread of selective processing to nearby locations.

For both the N1 and N2 time windows, there was evidence of sensitivity to the size of the cued area for all presentation locations. However, the results did not indicate that facilitation was limited to just the cued area, as would be predicted by a zoom lens of attention that could be precisely fit to the cued region. The pattern of facilitation suggests a gradient of attention that becomes slightly broader with increasing cue size. The impact of cue size was most apparent at locations 2 squares away from the midline, where relative to small cues, the area of facilitation for the large and medium cues spread to include the 2-away locations on the cued side of the display. For the large cue condition,

this spread incurred a cost in attentional resources such that there was reduced processing for locations 1-away from the midline on the cued side and midline locations on the uncued side of the display. While the N1 and N2 results were largely similar, there were some differences in the distributions of attention effects. The N1 results are consistent with a gradient of facilitation similar to that demonstrated in Experiment 1, and suggest that the spread of this gradient is coarsely adjusted based on cue size. The spread of this gradient of facilitation appears to extend beyond the cued region for all cue sizes. For the N2 time window, a similar spread of selection and sensitivity to cue size was observed, but for this time window the gradient did not spread as far as for the N1.

For the P1 and P3 time windows, the effects of cue condition were less consistent across standard presentation locations. For standards presented at all locations, there were no significant differences in contralateral or ipsilateral P1 amplitude based on the side of attention (p's > .1). The same was true in the P3 time window for standards presented 1 or 2 squares away from fixation. For standards at the horizontal midline, there was an effect of cue side such that standards on the attended side evoked larger mean positive amplitude in the P3 time window than those on the unattended side ($F(1,16) = 19.4$, $p < .001$). For standards presented at the midline, there was also an effect of cue range in the P3 time window on the cued side of fixation ($F(2,32) = 11.5$, $p < .001$). The same difference was not observed for standards presented on the uncued side ($F(2,32) = 1.2$, $p = .313$). For standards presented on the cued side of fixation, mean P3 amplitude was greater in the small compared to the medium and large cue conditions (CS vs. CM: $F(1,16) = 16.2$, $p < .001$; CS vs. CL: $F(1,16) = 14.1$, $p < .005$; CM vs. CL: $F(1,16) = 1.7$, $p = .212$). The P3 time window showed a pattern of modulation consistent

with reduced processing resources under larger cue size conditions predicted by a the zoom lens theory of attention. However, this result would also be consistent with P3 modulation based on differences in the frequency with which standards were presented within the cued range.

Discussion

Experiment 2 demonstrated that there was sensitivity to the range of cued locations in the N1, N2, and P3 time windows. The finding of modulation in the N1 time window is consistent with previous studies using ERP techniques to examine differences in the spatial scale of attention that found modulation within the early P1 and N1 time windows (Lou et al., 2001; Fu et al., 2005). The present study extends upon these results by demonstrating modulation in the N1 time window for stimuli presented in isolation rather than in a search array. The pattern of amplitude differences fit two predictions of an adjustable area of selection. First, for locations that were within the range of the large cued area, and outside the range of the small cue area, there was greater negativity in the N1 following the large compared to the small cue. This indicates that the size of the gradient of perceptual facilitation was expanded for the largest cue range. Second, for locations adjacent to the center of the cued area, stimuli evoked greater amplitude when preceded by smaller compared to larger cues. This indicates a cost to increasing the size of the gradient over a larger area. This cost was not found for locations at the center of the cued area, suggesting spreading the gradient of selection may not impact the peak of the gradient. Differences based on cue size were also found on the uncued side of the display at midline locations, suggesting that when the gradient was expanded to fit a larger region, stimuli presented at distant locations in the visual field received less

processing compared to when a smaller region was attended. However, there are difficulties with this interpretation as this effect was only seen at midline locations.

One interesting and unexpected result was the enhanced facilitation across numerous stimulus locations on the cued side for the medium cue range condition. It is unclear exactly why this advantage occurred, but it suggests the medium cue condition may be closest to the optimally sized attended window for stimuli at the eccentricity used in this study.

The posterior N2 time window showed modulation based on the size of the attended area similar to that of the N1. That the N2 window was sensitive to cue size fits with the findings of other studies that the N2 is modulated by large changes in the area of peripheral cues. Eimer (1999) found that when rings of different eccentricities around fixation were cued, the N2 was larger when the cued ring encompassed the stimuli compared to when it did not. An earlier study using similar stimuli found that cuing quadrants of the visual field evoked larger amplitude in the P1 and N1, but not the N2 time window (Eimer, 1997), similar to the findings of Experiment 1. Together these findings suggest that there are two dissociable stages of selection for orienting the location of attention and adjusting the size of the attended area. The current study extends these findings by demonstrating both stages of processing in a single paradigm, and also by showing that modulation in the N2 time window indexes size difference in a simply shaped cue region, compared to the ring of eccentricity previously used. In contrast with other studies that used stimuli presented in isolation, Experiment 2 also demonstrated modulation of the N1 time window based on cue size. The earlier modulation of the N1 time window in the current study could reflect differences in

attending to different sized areas, as compared to rings around fixation. Alternatively, the differences in the N1 time window could be the result of an earlier onset of the same negativity indexed by the N2. This possibility is explored more thoroughly in the general discussion of Experiments 1 and 2.

There was no evidence of attention based modulation of the P1 time window in this experiment. The lack of P1 modulation is not surprising given that amplitude in this time window was also not modulated in Experiment 1. Experiment 2 was kept as similar as possible to Experiment 1, and does not provide further insight as to whether the configuration of the display or the spatial attention task led to the absence of P1 modulation. As with the previous experiment, it is possible that adjusting cue size does not involve early inhibition of the type indexed by the P1 time window. However it is impossible to confirm this with the current results in which no condition modified the P1. Further studies will be needed to demonstrate whether P1 attention effects differ under different sized cue conditions.

The P3 time window showed differences between the cue size conditions for stimuli presented in the center of the cued area. Differences in this time window may suggest a cost to extending the size of the attended area. This pattern is consistent with the processing limitation predicted by the zoom lens theory, which posits that attention is a limited resource, and that the wider attention is spread the less facilitation will be available at any one location. However, definitively linking the P3 results to the allocation of attention is problematic as this time window is also modulated by the frequency of target occurrence (Polich, 2007). Stimuli were presented at each location with equal frequency in all three cue sizes, so that more stimuli were presented within the

cued area for larger cue size conditions. Thus, from the present study it cannot be determined whether modulation of the P3 was driven by differences in the distribution of attention, or by differences in the frequency of stimuli in the cued area.

The most striking behavioral result was that the slowest responses occurred for targets near the edge of the cued area. For targets presented at the horizontal midline, the slowest responses were in the small cue condition, and for targets presented one square away from the midline the slowest responses were in the medium cue condition. Responses may have been slowest at these locations because location was a critical feature to determining if a deviant was a target. Thus there may have been less certainty as to whether deviants at the edge of the cued range could be classified as targets. A second possibility is that inhibition of locations just outside of the cued area may have extended to targets presented at the edge of the cued area (Cave & Zimmerman, 1997; Mounts, 2000; Müller, Mollenhauer, Rösler, & Kleinschmidt, 2005; Hopf et al., 2006).

Contrary to the initial predictions, increasing the size of the cued area did not result in slower response times. There are a few possible interpretations of why the response time results did not replicate the predictions of a zoom lens model. In previous studies in which larger cues were associated with longer response times, the target was presented in a multi-stimulus search display (Eriksen & St. James, 1986; Greenwood & Parasuraman, 1999). In these search tasks, smaller cue sizes provided specific information about the target location, allowing it to be located and/or distinguished from distractors more rapidly. In the current study, stimuli were always presented one at a time, so no search was necessary. This does not explain differences with Castiello and Umilta's (1990) study, which also used stimuli presented in isolation and found slower

response times following larger cues. The critical difference between that study and the current one may be the frequency of target occurrence. In the present study, in larger cue size conditions targets appear with greater frequency. Participants may have maintained a higher level of alertness when there was less down time between responses.

Experiments 1 and 2 General Discussion

Experiments 1 and 2 provide evidence for three temporally distinguishable stages of spatial selection: an early stage that selects a broad gradient around the center of the cued area, a second stage at which selection is limited to a smaller area determined by the size of the cued area, and finally a memory access stage that shows characteristics of both the gradient and scaling stages of selection. ERP Evidence for the early gradient stage of attention comes from the N1 time window that showed a gradual decrease in facilitation with increasing distances from the cued location in Experiment 1. This facilitation was symmetrically distributed to the left and right of the cue, but stronger below compared to above the cue. Unlike the N1, the N2 time window showed no gradient of selection in Experiment 1, and a more limited spread of selection outside of the cued area in Experiment 2. Experiment 2 demonstrated that the gradient of facilitation indexed by the N1 was coarsely adjusted based on the size of the cue. Adjusting the size of the cued area also revealed a second stage of processing, indexed by greater negativity in the N2 time window for standards that were within or just beyond the cued area. This second stage of processing had a tighter focus to the cued area, and was highly sensitive to adjustments in cue size. A final stage of processing, indexed by the P3 time window, showed both a gradient of selection and sensitivity to the size of the cued area. All three time windows showed modulation consistent with a tradeoff between attentional strength

and size of the attended area as predicted by a zoom lens model of attention. However, in the case of the P3 time window this difference may be the result of differences in the frequency of items falling within the cued region, rather than differences in the allocation of processing resources. The same frequency account cannot explain the differences in the N1 and N2 based on cue size, as there were not significant differences at the center of the cued region for these time windows. Finally, the behavioral responses revealed slower response times when a target appears at the edge of the cued area, suggesting uncertainty about the target's location or perhaps an inhibition of stimuli at the edge of the attended region.

The clearest evidence for the gradient stage of selection comes from Experiment 1, demonstrating selection that drops off gradually with distance from the cued location. This gradient of selection was indexed by modulation of the N1 time window, consistent with previous studies (Gonzalez et al., 1994; Mangun & Hillyard, 1998; Mangun, 1995). There was no motivation to attend in a graded manner in the current task, suggesting that the gradient of selection around the cued location is relatively automatic. The N1 time window also showed modulation on the basis of cue size in Experiment 2. This indicates that the spread of the gradient stage of selection is variable based on the size of the cued region. This interpretation is supported by LaBerge and Brown's (1986) finding that the spread of the gradient can be adjusted based on differences in the display.

There was an asymmetry in the distribution of selection indexed by the N1, such that the gradient of selection was stronger for locations below than above the cue. This asymmetry was unexpected, as there is very little literature addressing asymmetries in the distribution of attention. There is evidence of an advantage in attending to the lower

visual field, as well as increased visual acuity in the lower visual field (He, Cavanagh, & Intriligator, 1996; Talgar & Carrasco, 2002). It has also been posited that the upper visual field may be primarily tuned to process distant information, while the lower visual field is tuned to process nearby and action relevant information (Previc, 1990). However, differences in the upper and lower visual field cannot explain the asymmetry in the spread of attention, as in the current study the stimuli for each comparison all appeared at the same location in the visual field, and only the cue location varied. It is possible that this asymmetry is ecologically motivated, preferentially biasing selection towards aspects of the environments in which useful information is likely to occur. For instance, navigating around an environment may benefit from a bias towards spreading attention to lower regions of the visual field. While focal attention may primarily be directed towards objects on the horizontal midline, there is also a need to monitor the ground level for obstacles and terrain changes. This explanation receives some support from studies indicating there is a bias towards processing ground surface information over ceiling surface information (McCarley & He, 2000; Bian & Andersen, 2010). While the results of Experiment 1 cannot specifically confirm any of these roles for an asymmetric gradient, it does suggest that further research into the asymmetry is needed to fully understand the distribution of attention.

The second stage of processing is indexed by the N2 time window. This stage of processing does not show the same graded distribution of selection as seen in the N1, but does show a sensitivity to cue size. While other studies have found differences in attention-based modulation between the N1 and the N2, this difference is not frequently a point of emphasis (Hillyard, 1988, Eimer, 1999). One reason for this is that the N2 is

more difficult to interpret as an index of selective attention than earlier time windows such as the P1 and the N1. Previous literature on the N2 time window has predominantly focused on the anterior N2, which has been linked to cognitive control tasks such as go/no-go and flanker paradigms (see Folstein, 2008 for a review). However, the observation that the size of the cued area affects attention-based modulation at posterior electrode sites within the N2 time window suggests that it indexes a stage of perceptual processing enhanced by spatial attention. Studies using functional magnetic resonance imaging (fMRI) have found that changing the size of the attended area results in changes in the magnitude and extent of BOLD activation in areas V1, V2, VP, and V4 (Müller, Bartelt, Donner, Villringer, & Brandt, 2003). Similar differences in activation in visual cortical areas have been observed when comparing responses to the same stimuli when focusing on the local compared to global features, suggesting that local/global adjustments may rely on mechanisms that also adjust the scale of the attended area (Rijpkema, van Aalderen, Schwarzbach, & Verstraten, 2008). One possibility is that the N2 indexes activity from the same cortical visual areas as the N1 at a later stage of processing. In the present study the N2 had a posterior distribution very similar to that of the N1, and similar to the distribution of the N2 in other studies demonstrating selective visual processing in the N2 time range (Eimer, 1999, Shedden & Nordgaard, 2001). The distribution is also similar to the N2b, which is associated with target detection in search tasks, and has been linked to attention-based modulation in the visual cortex (Hopf et al., 2006). This suggests that the N2 in the present study is indexing a second stage of selective processing that is related to that indexed by the N1 time window, but is not automatically spread over as large an area of the visual field

The idea of attention requiring multiple passes through the visual system is consistent with evidence that the earliest activation of the striate cortex is not modulated by attention, but that activity in the same cortical area is modulated 100 ms later, presumably through recurrent connections from extrastriate regions (Martinez, et al., 1999; Martinez, et al., 2001; Di Russo, Martínez, & Hillyard, 2003; Noesselt et al., 2002). Disruption of the processing mediated by these recurrent projections can also interfere with object perception as measured by both behavioral response and evoked electrophysiological potentials (Fahrenfort, Sholte, & Lamme, 2007). Theories of perception based on backward masking characteristics and search times have come to similar conclusions about the importance of recurrent processing in visual perception, and attention in particular (Di Lollo, Enns, & Rensink, 2000; Hochstein & Ahissar, 2004). In the present study, the N1 may index an early pass through this system, which filters based on a gradient centered on the cued location, while the N2 might index a later pass that further filters visual input more selectively based on the size of the cued area.

Thus far the N2 modulation on the basis of the size of the cued area has been discussed as a second stage of spatial selection, similar to that indexed by the N1 but with a tighter spatial distribution. However there is an alternate explanation, that the N2 time window indexes a more general mechanism that selects items with a target defining feature for further processing. This time range has been previously associated with selection of non-spatial features such as shape, color, orientation, and spatial frequency, which has been labeled the selection negativity (SN) (Hillyard & Münte ,1984; Eimer, 1995; Anllo-Vento & Hillyard, 1996; Eimer, 1997; Schoenfeld, et al., 2007; McGinnis & Keil, 2011). The SN is frequently observed within the time ranges overlapping those

observed in the present study, extending from the mid to late N1 (~160ms) to the N2 (~ 300ms), and it indexes selective processing of stimuli that have a feature in common with the target. In the present study, targets are defined by a conjunction of shape and spatial location. Because of this, spatial location is a target defining feature of the visual items. Whether the N2 indexes spatial or feature-based selection impacts predictions about what types of stimuli show attention-based modulation in this time window. If the N2 indexes spatial attention similar to the N1, one would predict that all stimuli falling within the area of selection would receive attentional facilitation. On the other hand, if the N2 indexes feature-based attention, only stimuli that are similar enough to the target to require further processing may show modulation in this time window. While beyond the scope of the current findings, determining whether the N2 indexes spatial or feature-based attention will be important for a full understanding of this stage of visual selection.

A final stage of selective processing is indexed by activation in the P3 time window. This stage of selection showed both a graded response in Experiment 1, though with a smaller distribution than the earlier N1, and a sensitivity to the size of the cued area in Experiment 2. The predominant characteristic of the P3 response was a reduction in amplitude as the size of the cued area increased. The P3 time window is difficult to interpret as both the allocation of attention and the rate of presentation of potential targets have been shown to modulate amplitude in this time window (Polich, 2007). The rapid presentation of targets could have led to a bottleneck at the site of memory encoding with more stimuli competing for resources in the larger cue size conditions. Alternatively, the differences in the P3 response could simply indicate greater processing of infrequent stimuli.

The results of these experiments support a model of visual spatial attention in which there is a separation between the gradient stage of selection and the stage of selection that is adjusted to closely fit the size of the cued area. The two stages of selection demonstrated in this experiment are in contrast to models of attention such as that proposed by Luo et al. (2001) that combine the gradient and the size adjustment of the attended area into a single stage of selection. The pattern of results is most in line with the predictions of the model proposed by Laberge and Brown (1989) in which an anticipatory gradient precedes a more selective stage of processing. The ERP data indicate that this dissociation is between the early N1 time window and the later N2 time window. The dissociation of early and later attention effects with different filtering qualities highlights the importance of considering attention as a multi-stage process, and raises some very interesting issues. For instance, there is evidence that attending to one location within an object increases selective processing for all locations within that object (Egly, Driver, & Rafal, 1994; Martinez et al., 2006; Martinez et al., 2007). However it is not known whether this object based selection is due to a spread of the attentional gradient within object boundaries or an adjustment of the attended area to match the object, or perhaps both. Further, the two stage method of selection may be a more general strategy that is also employed in attention to features such as color and size.

CHAPTER IV

EXPERIMENT 3: SPREAD OF VISUAL ATTENTION WITHIN, BETWEEN, AND IN THE ABSENCE OF OBJECTS

Introduction

Experiments 1 and 2 presented evidence supporting a two-stage model of attention, with an early broad gradient of attention and a later stage more narrowly fit to the attended area. Experiment 3 examined to what extent one or both stages of processing are impacted by the presence of object boundaries in the visual field. Understanding the effects of objects on the distribution of visual attention is vital, as the environment in which we use attention is full of complex objects and features. Previous studies have demonstrated selective enhancement for stimuli presented within the borders of an attended object (Egly, Driver, & Rafal, 1994; Duncan, 1984; Rock & Guttman, 1981). Experiment 3 tested the extent to which both the initial gradient of attention and the subsequent focusing of attention are affected by object boundaries. The time course of attention-based effects in the evoked ERPs was used to differentiate these two stages of selection.

Previous electrophysiological studies of object-based attention have used modified versions of the paradigm developed by Egly, Driver and Rafal (1994). In this type of study probes were presented at an equal distance from the cued location, at both the uncued side of the object containing the cued location, and at a similar location on an uncued object. ERP studies using this paradigm have demonstrated modulation in the N1 time window for probes presented on the uncued side of the cued object, suggesting object boundaries affect the distribution of the gradient stage of processing (Martinez et

al., 2007; Valdes-Sosa, Bobes, Rodriguez, & Pinilla, 1998). However, changing the size of an attended object may also impact the size of the attended region. Maringelli and Umilta (1998) demonstrated that response times to targets at fixation were faster following the presentation of a small square than after the presentation of a large square, suggesting the attended window was adjusted to fit the boundaries of the object that preceded the stimulus. The goal of Experiment 3 was to determine whether object-based facilitation occurs in the time frame of the gradient of selection or the time frame of adjusting attention to fit an explicit cue.

Experiment 3 also investigated the effect of varying the size of the cued region to encompass all of an object or only part of an object. While previous studies have cued one part of an object and looked for a spread of attention within the boundaries of that object (Egly, Driver, & Rafal, 1994), the current experiment differentiated between cuing a portion of the total area covered by an object, cuing an entire object, or cuing a region extending across objects. These object boundary conditions were also compared against a condition with no objects present, in which the distribution of attention was unconstrained. The results of Experiment 2 suggest that the N2 may index a stage of selection that is sensitive to task relevant locations. If the presence of object boundaries adjusts the distribution of attention at a stage of selection separate from cue size, then the N2 time window would be predicted to index changes in cue size irrespective of object condition. Alternatively, the effects of object boundaries may automatically induce adjustments to the scope of attention in the same time range as cue size. Experiment 3 will provide insight into both the effect of object boundaries on the distribution of attention, and the characteristics of the gradient and adjustable focus stages of selection.

If there are object based effects on the distribution of the initial gradient stage of processing, they should be seen in the N1 time window, while any object based effects on the size of the attended area should be seen in the N2 time window.

Method

Participants

Data from eighteen participants (12 female, mean age: 23.1 years, SD: 4.391) were included in the final analyses. Twenty-five participants were initially included in at least some portion of the experiment; data from 7 participants were excluded because of an insufficient number (< 40) of artifact free trials in some conditions. Artifacts included blinks, eye movements, and electrodes showing excessive noise. All participants were right handed, and reported having normal or corrected to normal vision. All participants provided written informed consent prior to the study, and were paid for their participation.

Stimuli

The display consisted of 6 presentation locations in two columns on either side of fixation (Figure 8). Each column had three vertically aligned locations: one on the horizontal midline, and two more peripheral locations above and below the midline. The center of the presentation locations were separated by 1.2° visual angle within columns, and 2.4° between columns. Locations were cued by a red rectangle indicating the area to be monitored. There were 4 cue conditions. The cues varied in the side of presentation, appearing equally often on either the left or right of fixation. The cues also varied in size, with the small cue containing only the midline location, and the large cue containing a full column of presentation locations. Stimuli consisted of standards (O, 80%) and

deviants (X, 20%) each occupying 0.25° by 0.25° of visual angle, and each appearing within one of the six presentation locations. Three object conditions were used. In the big objects condition two grey rectangles were present throughout the block, one to the left and one to the right of fixation, which encompassed the two columns of presentation locations. In the small objects condition six grey squares were present, one surrounding each presentation location. In the no object condition there was no permanent demarcation of the presentation locations.

Procedure

The conditions were split into 24 blocks (2 blocks of each condition, 2 levels of cue side, 2 levels of cue range, 3 levels of object boundaries, 2x2x2x3 = 24). The blocks occurred in random order and each contained 240 trials. Trials began with a fixation cross displayed for 1000 ms, along with the large or small objects in the appropriate conditions. At the offset of the fixation cross, a cue appeared for 2000 ms. Approximately 500 ms after the offset of the cue, the presentation of stimuli began. Stimuli were displayed for 72 ms with an ISI of 250-750 ms. Stimuli appeared with equal frequency at each presentation location. At the beginning of each block, participants were cued to monitor either one of the midline locations, or all three locations in one of the columns. The task was to press a button when a deviant appeared within the cued area. Each block provided 32 standards and 8 deviants at each location. For the whole experiment, this provided 64 standards and 16 deviants at each location in each condition. Blocks were approximately 2 minutes long, and presenting all 24 blocks took approximately 48 minutes. Total time for the session that included setup, practice, and breaks was approximately 2 hours.

Prior to beginning the experimental trials, all participants were given a ~10 minute introduction and practice block, which included practice on the discrimination between standards and deviants, as well as the task of responding to deviants at cued locations. Short practice blocks included examples of all three object conditions, as well as both the small and large cue conditions. A button press was considered correct if it occurred between 250 and 1000 ms after the onset of a target. If more than one response occurred between 250 and 1000 ms after a target, time windows were used to determine which response would be associated with the target (primary time bin 500-749 ms, secondary 250-499 ms, tertiary 750-1000 ms). All button presses that did not occur between 250 and 1000 ms after a target were classified as false alarms. Due to the rapid presentation and frequency of standards, it was impossible to determine with certainty which stimulus onset was associated with each false alarm.

ERP Procedure and Comparisons

Scalp potentials evoked by standards presented at each location and in each attention condition were averaged for each individual separately. Effects of attention on ERP amplitude were assessed across the same set of posterior electrodes used in Experiments 1 and 2, and time windows of interest included the P1, N1, N2, and P3. The conditions were separated across three variables; cued side relative to the stimulus (cued, uncued), large or small cued size (LC, SC), and type of object boundary (big objects, BO; small objects, SO; no objects, NO). Behavioral and ERP responses were analyzed separately for stimuli at the center column location (midline), and stimuli at the upper and lower column locations (peripheral). It was anticipated that there would not be a significant effect of stimulus side on attention, so data points were collapsed across

stimulus side when analyzing the other factors.

Four main comparisons were performed. First, to determine the effect of orienting attention, the responses to standards were compared when the cue directed attention to the same side of fixation as the standard versus the opposite side of fixation. Second, the effect of cue size on the allocation of attention was considered by comparing the two cue size conditions when standards were presented on either the cued side of fixation or the uncued side of fixation. Third, the interaction between object type and cue side were analyzed to determine the time windows in the ERP waveform affected by the presence of object boundaries. Lastly, the impact of object boundaries on cue-based adjustments in the size of the attended area was investigated using interactions between cued size and type of object boundaries

Results

Behavioral Results

Separate comparisons were made to determine the impact of object type and cue size on the behavioral responses. The hit rates (HR) and response time (RT) results are summarized in Figure 9. The first set of comparisons tested for differences in HR and RT based on cue size and object type. This comparison was limited to the midline locations, as these were the only locations that could contain a target in both the small and large cue conditions. For targets presented at the midline there was an effect of cue size on hit rate ($F(1,17) = 7.1$, $p < .05$), such that more targets were correctly identified in the small cue compared to the large cue condition, although performance in both conditions was near ceiling. This pattern fits the predictions of a zoom lens model of attention, with better performance when attention is focused on a smaller area. There was

no effect of cue size on response time at central presentation locations ($F(1,17) = .01$, $p = .913$).

There was also a main effect of object type for both hit rate and response time at midline locations (HR: $F(2,34) = 6.5$, $p < .005$; RT: $F(2,34) = 8.0$, $p < .005$), although the pattern of results was different between these two measures. For hit rate, a greater number of targets were recognized in the big object condition compared to the small and no object conditions (BO vs. SO: $F(1,17) = 5.8$, $p < .05$; BO vs. NO: $F(1,17) = 15.7$, $p < .005$; SO vs. NO: $F(1,17) = .7$, $p = .403$). For response time, responses were faster in the big and small object conditions compared to the no object condition (BO vs. SO: $F(1,17) = .8$, $p = .374$; BO vs. NO: $F(1,17) = 14.7$, $p < .005$; SO vs. NO: $F(1,17) = 7.0$, $p < .05$). There was no interaction between cue size and object condition for either hit rate or response time (HR: $F(2,34) = .3$, $p = .744$; RT: $F(2,34) = .1$, $p = .849$). Overall the responses at midline locations suggest a performance advantage for the big object condition, with intermediate performance in the small object condition, and relatively reduced performance in the no object condition.

A second set of comparisons tested for differences between object conditions for targets presented at the peripheral locations. These comparison were limited to the large cue condition blocks, as these were the only blocks in which these locations contained targets. For peripheral locations, there was a main effect of object on both hit rate and response time (HR: $F(2,34) = 22.2$, $p < .001$; RT: $F(2,34) = 11.0$, $p < .001$), such that in the small object condition responses were both slower and fewer targets were recognized compared to the big and no object conditions (HR BO vs. SO: $F(1,17) = 39.7$, $p < .001$; HR SO vs. NO: $F(1,17) = 20.8$, $p < .001$; RT BO vs. SO: $F(1,17) = 19.3$, $p < .001$; RT

BO vs. SO: $F(1,17) = 10.1$, $p < .01$). There were no differences in either response time or hit rate between the big and no object conditions (HR: $F(1,17) = 2.0$, $p = .173$; RT: $F(1,17) = 1.1$, $p = .318$). There was a significant performance disadvantage in the small object condition relative to the big and no object conditions at these locations. This could be due to either difficulty in attending to multiple objects at once, or perhaps difficulty in discriminating the more peripheral targets with object boundaries close to their presentation location.

A third set of comparisons tested for differences across presentation locations, and was limited to the large cue condition, as the small cue condition did not provide targets at the peripheral locations. There was a main effect of location such that more targets were recognized and responses were faster at the midline compared to the peripheral locations (HR: $F(1,17) = 39.3$, $p < .001$; RT: $F(1,17) = 262.7$, $p < .001$). This is consistent with a gradient model and with Experiment 1. There was also an interaction between target location and object, such that the difference between midline and peripheral response times and hit rates was greatest in the small object condition (HR: $F(2,34) = 18.2$, $p < .001$; RT: $F(2,34) = 13.3$, $p < .001$). This interaction suggests a reduced spread of the gradient in the small object condition relative to the big and no object conditions.

False alarm rates were also measured, but due to the rapid presentation rate these responses could not be associated with specific locations (Figure 10). Comparisons between false alarm rates across all presentation locations revealed a main effect of object ($F(2,34) = 12.1$, $p < .005$), such that there were more false alarms in the no object condition than in either of the two object conditions (BO vs. SO: $F(1,17) = 1.4$, $p = .259$;

BO vs. NO: $F(1,17) = 16.5$, $p < .005$; SO vs. NO: $F(1,17) = 12.5$, $p < .005$). There was also an effect of cue condition ($F(1,17) = 4.8$, $p < .05$), such that there were more false alarms in the large compared to small cue condition. The object and cue size effects interacted, such that the difference between small and large cue conditions was greatest in the no object condition ($F(2,34) = 5.0$, $p < .05$). The false alarm results suggest that participants made the most mistakes in identifying whether a stimulus within the cued range was a deviant or a standard. If the majority of false alarms had been due to uncertainty about the location of deviants, this would have resulted in greater false alarms in the small cue condition where there was closer proximity between cued and uncued locations. Further, that the majority of these errors were made in the no object boundary condition suggests there was not significant interference from the presence of object boundaries in the small and big object conditions. This indicates that the response time differences at peripheral locations in the small object condition were likely driven by the distribution of attention, and not interference from object boundaries surrounding the presentation location.

The behavioral results suggest that both the cue size and object boundaries had an impact on performance. Cue size effects at midline locations followed the predicted pattern of improved performance at midline locations for small cue sizes. The most apparent object boundary effect was that the small object condition showed reduced performance at the more peripheral locations, impacting both response time and hit rate at those locations. This is likely due to a difficulty in expanding the scope of attentional facilitation to include multiple objects in the small object condition, as the small cue condition did not show greater false alarm rates as would be predicted if object

boundaries were interfering with the ability to discriminate the standard from the deviant. At midline locations, the no object condition showed the slowest response times, and this did not interact with cue size. This suggests a general difficulty directing attention precisely to the location of stimulus presentation when no objects were present.

ERP Results

The effect of object type and cue condition on mean amplitude evoked by standards was examined in four time windows, the P1, N1, N2 and P3. Separate ANOVAs were performed for midline and peripheral locations and for each time window with cue size and object condition as factors. The results of these comparisons were split into effects of orienting attention, cue size, object condition, interactions between object condition and orienting attention, and interactions between object condition and cue size. This division of the comparisons is meant to address specific questions about the distribution of spatial attention and the impact of object boundaries on that distribution.

Effects of orienting attention

In order to determine the effects of orienting attention, comparisons were made of mean amplitude within all time windows between standards presented in the cued visual hemifield and those presented in the uncued hemifield (Figure 11). For the midline location in both large and small cue conditions, and at the peripheral location in the large cue condition, this comparison indicates the impact of a standard appearing within the cued range. For peripheral locations in the small cue condition, differences based on cue size indicate that the facilitation of processing spreads outside of the cued area, as standards at these locations on the cued side are beyond the scope of the cued range. This preliminary analysis did not include differences between object boundaries. The effects

of cue side were fairly consistent across locations and cue conditions. For midline locations there was modulation based on cued side for the N1 and P3 amplitude in the small cue range condition (N1: $F(1,17) = 14.0$, $p < .005$; P3: $F(1,17) = 41.4$, $p < .001$), and P1, N1 and P3 amplitude were modulated in the cue large condition (P1: $F(1,17) = 4.7$, $p < .05$; N1: $F(1,17) = 10.1$, $p < .01$; P3: $F(1,17) = 14.5$, $p < .005$). At peripheral locations, P1 and N1 amplitude were modulated by cue side for both cue large condition (P1: $F(1,17) = 19.4$, $p < .001$; N1: $F(1,17) = 29.7$, $p < .001$), and the cue small condition (P1: $F(1,17) = 9.0$, $p < .01$; N1: $F(1,17) = 43.9$, $p < .001$), even though in the small cue range condition these locations did not fall within the cued area. In all measurements that showed significant modulation, amplitudes in the P1 and P3 time windows were more positive when standards appeared on the cued compared to the uncued side. Amplitude in the N1 time window was more negative for the cued side. There was not a main effect of attention for the P1 at midline locations following the small cue, for the P3 at peripheral locations under any cue condition, or in the N2 time window at any location for any cue size condition (p's > .1). Overall these effects suggest that there was a sensitivity to the orientation of attention in the P1 and N1 time windows. Further, this processing advantage spread beyond the cued area to the peripheral locations for the small cue condition for each of these time windows. For the P3 time window, this processing advantage was localized to the midline presentation location for both cue ranges.

The lack of a significant main effect of attention in the N2 time window is surprising given the results of Experiments 1 and 2. One possibility is that since the number of presentation locations was reduced for Experiment 3, the rate of items

appearing at each location was increased. The N2 time window can be enhanced in response to rare stimuli (Bruin & Wijers, 2002), and the relative increase in frequency in the current study may have reduced the N2 response. However the N2 attention effect was not completely eliminated, as will be discussed in the cue size analysis.

Effect of cue size on the allocation of attention

The effect of cue size on selection was determined by looking at main effects of cue size on both the cued and uncued sides of fixation (Figure 12). Effects of cue size for standards appearing at locations on the same side as the cue indicate adjustments of the range of locations receiving attention based facilitation. The most pronounced effects were anticipated at peripheral locations, which could be either within or outside of the cued region depending on the cue size. Main effects of cued size at the center location on the cued side would arise if attending to a larger area decreased the perceptual processing advantage at the midline location, and this pattern could arise from a limitation on attentional resources. Main effects of cue size for standards presented on the uncued side of fixation would indicate that the effects of attending to a larger or smaller area extend to relatively distant areas of the visual field.

On the cued side of fixation, different time windows were sensitive to cue size at the midline and peripheral presentation locations. At the midline location, both the P1 and the N1 time windows showed a trend towards an effect of cue size (P1: $F(1,17) = 4.3$, $p = .054$; N1: $F(1,17) = 3.5$, $p = .08$). For both of these time windows, mean amplitude was more negative in the small compared to the large cue condition. That the difference in both of these time windows had the same polarity makes the effect challenging to interpret. Typically, selective attention results in a larger positivity in the P1 time

window and a larger negativity in the N1 time window. That both time windows showed a greater negativity for cued standards suggests that they may index a single negative deflection, likely an increased N1 in the small compared to the large cue condition. The differences in both time windows only trended towards significance, so the pattern should be interpreted cautiously.

There was also an effect of cue size in the P3 time window for standards presented at the midline on the cued side of fixation ($F(1,17) = 19.0$, $p < .001$), such that the amplitude of the P3 was greater for standards presented in the small compared to the large cue size. As in Experiment 2 the P3 time window showed the same sensitivity to cue size as the N1 at the midline location. The P3 results likely indicate facilitation of access to working memory through the perceptual processing advantage indexed by the N1. There was no effect of cue size at midline cued locations for the N2 time window ($p > .1$).

The peripheral target location on the cued side was the most likely to indicate changes in the distribution of perceptual processing facilitation based on the size of the cued area. This is because this location only appeared within the cued area in the large cue condition. The only time window that was sensitive to the size of the cued area at this location was the N2 ($F(1,17) = 10.9$, $p < .005$). Mean N2 amplitude was more negative in the large cue condition compared to the small cue condition. This supports the findings of Experiment 2 that the N2 time window indexes differences in the allocation of selection based on the size of the cue. While amplitude in the N2 time window was modulated based on the size of the cued range for standards on the cued side, as previously noted there was not a significant effect of cue side at these locations.

Instead, the cue large on the same side of fixation condition was slightly more negative than cue large opposite, and the cue small on the same side condition was slightly more positive than cue small opposite, with neither difference reaching significance. This suggests that processing indexed by the N2 may be enhanced for monitored locations and inhibited for locations near the cued region that are not monitored.

On the uncued side of fixation there was no effect of cue size at either midline or peripheral locations for any of the measured time window (p's > 0.1). This suggests that the size of the attended area did not impact the processing of distant stimuli. This is somewhat surprising given the results of Experiment 2 demonstrating that cue size modulated the response to stimuli on the uncued side in the N1 time window. The lack of cue size effects in the uncued hemi-field in Experiment 3 may be due to the fact that a maximum of 3 locations were monitored, compared to a maximum of 5 locations in Experiment 2. Monitoring 3 locations may not have created sufficient competition for resources to impact the processing of standards on the uncued side.

The impact of cue size on the amplitude of ERP time windows was slightly different from that seen in Experiment 2. Specifically, the N1 did not show differences at peripheral locations that would indicate adjustments to the size of the selected area based on cue size, and showed only limited differences at midline locations. This suggests that the gradient of selection indexed by the N1 was automatically spread such that no adjustment was needed for the larger cue range in Experiment 3. In contrast, the N2 time window showed a clear difference between the small and large cue ranges in facilitation for peripheral stimuli, suggesting this time window is highly sensitive to the size of the cued range. However, these differences were not enough to create a significant

difference compared to when the opposite side of fixation was cued. While these findings are not entirely in line with those of Experiment 2, they do further suggest that the N1 and N2 represent separable stages of processing, with the N1 indexing a broadly focused relatively automatic gradient of selection, and the N2 indexing selection that is sensitive to the range of cued locations.

Effect of object boundaries on allocating attention

The impact of the presence of object boundaries on the allocation of attention was determined by looking at interactions between the object type and cued/uncued hemifield (Figure 13). Main effects of object condition were not considered as they are based on direct comparisons between different physical displays. Comparisons were made for standards presented at both the midline and peripheral locations. Interactions between object and cue side at the midline locations indicate differences in the ability to orient attention to a location based on the surrounding object type. Differences at the upper and lower presentation locations indicate a difference in the spread of the gradient of attention based on the presence of object boundaries. Of particular interest were interactions in the N1 and N2 time windows, the means of which are shown in Figure 14.

In the P1 time window there were no interactions between object type and attention effects for standards at the midline or peripheral locations (p's > .1). The attention effects seen in comparisons of the cued and the uncued side were not modulated by the presence of object boundaries. For the N1 time window there was an interaction between object and cue side for standards presented at the midline in the small cue condition ($F(2,34) = 4.9$, $p < .05$), such that the attention effect was strongest for the no object compared to the small and big object conditions. However, there was not a

significant interaction between cue side and object condition for the large cue range ($F(2,34) = 1.1$, $p = .35$). It is unclear why there would be a stronger impact of cue side when there were no object boundaries in the small but not the large cue range conditions. For standards at peripheral locations there was no interaction between attention and object for either cue range (p's > .1).

In the N2 time window there was an interaction between object and attention for standards at the midline in the small cue condition ($F(2,34) = 4.9$, $p < .05$), such that standards on the cued side evoked more negative amplitude compared to the uncued side for the big and no object conditions, and no difference in the small object condition. This difference appears to have been driven by an earlier onset of the P3 in the small object condition compared to the big and no object conditions. There was no interaction between object condition and cued side for the large cue range at midline locations, or for either cue range at peripheral locations (p's > .1), indicating that the lack of attention effects based on cued side was consistent across object boundary conditions.

For the P3 time window, for standards presented at midline locations there was a slight trend towards an interaction between object and cue side for the large cue range ($F(2,34) = 2.6$, $p = .095$), such that the attention effect was slightly greater in the small object condition. This could indicate more high level processing of the stimuli in this condition, but the marginal nature of this effect makes it difficult to provide a strong interpretation. There was no difference in the small cue range condition ($F(2,34) = 1.1$, $p = .347$). There was no attention by object interaction at the peripheral locations (p's > .1). Overall, the P3 time window did not show major differences based on object condition.

Modulation of cue size effects by object boundaries

The final analysis sought to determine if the scaling of the selected area based on cue size was impacted by the presence of object boundaries. This was tested with interactions between the effects of cue size and the effects of object boundaries. Similar to the main effects for cue size, these interactions were separately analyzed on both the cued and the uncued sides of fixation. There were no interactions between cue size and object condition for standards at any location in the P1, N1, N2, or P3 time windows (*p*'s > .1). Importantly, for the N2 time window at peripheral locations where there was a main effect of cue size, there was no interaction between cue size and object condition ($F(2,34) = 0.9$, $p = .421$). This suggests that the presence and type of object boundaries did not impact the scaling of selection based on the size of the cued area.

Discussion

The primary goal of Experiment 3 was to determine whether the distribution of attention based on object boundaries has a shared perceptual mechanism with the distribution of attention based on cue size. There is extensive evidence that there is a facilitation advantage for items presented within the boundaries of an object that includes an attended location (Egly, Driver, & Rafal, 1994; Duncan, 1984; Rock & Guttman, 1981, Martinez et al., 2007; Valdes-Sosa, Bobes, Rodriguez, & Pinilla, 1998). However, there is little information about the stage of processing impacted by object based selection. Experiments 1 and 2 found evidence for two separate stages of selection, an earlier stage that showed a gradient of selection around the center of the cued area, and a later stage that was sensitive to the scope of the attended area. The goal of Experiment 3 was to determine which stage of processing is impacted by the presence of object

boundaries. Specifically, how does the automatic spread of attention based on boundaries present in the scene interact with the top down spread of selection based on task demands? There was little evidence to suggest that the presence of object boundaries impacts the ability to select varying sized areas. This suggests that the mechanism for the bottom up spread of attention based on the object n a visual scene happens at a separate level from the top down allocation of attention based on task demands.

The first comparison considered the effect of orienting attention to one side of the display, independent of cue size and object type. There was evidence for attention-based facilitation on the cued side of the display in the P1, N1, and P3 time windows. Differences in these time windows confirm that the present paradigm is indexing attention-based facilitation of perceptual processing and the updating of working memory. There was no evidence for attention-based facilitation in the N2 time window, as was seen in Experiments 1 and 2. As will be discussed later, there was an interaction between cue size and cued side at peripheral locations, suggesting that processing indexed in this time window was sensitive to cue size. One possible reason for the lack of an attention effect is that the N2 is sensitive to the frequency of stimuli; more precisely, the N2 is larger in response to rare items (Bruins & Wijers, 2002). As a smaller range of locations was used in the present study compared to Experiments 1 and 2, the frequency of an item appearing at any given location was greater than in the first two studies. This may have reduced the N2 amplitude across all cue conditions and thus reduced the measurable attention based modulation of amplitude in the N2 time window.

The presence and type of object boundaries had a limited impact on the ability to orient attention to the cued side of the display in the present study. Differences in the

object condition primarily impacted the N1 time window. Specifically, differences based on orienting attention were strongest in the absence of object boundaries. There was greater facilitation at midline locations for the no object compared to the two object conditions, but only when the smaller region encompassing just the midline location was cued. Surprisingly, there was no impact of object boundaries on the allocation of selective processing to the peripheral locations. Based on previous research showing a spread of the gradient of selection within object boundaries, the prediction was that these peripheral locations would show the greatest differences. Modulation of N1 amplitude based on object condition is supported by previous studies demonstrating object-based selection. Greater amplitude in the N1 time window has been demonstrated for standards presented within the same object as a cued location compared to an equally distant location on an uncued object (He et al., 2004; Martinez et al., 2006), as well as for locations that fall within illusory objects that share a cued location with the standard (Martinez et al., 2007). Based upon these studies, the expectation was that modulation at peripheral locations would be greater for the big object condition compared to the small or no object conditions.

The difference between previous object based attention studies and the present one may be the location of the cue relative to the center of the objects. In previous demonstrations of object-based attention, rectangles were used similarly to the big object condition in the present study. The cued locations were then one of the ends of the rectangle, and the uncued end was the reference for relative selective processing. One interpretation of these results is that object boundaries primarily act by shifting the center of the gradient of selection. There is supporting evidence that one of the impacts of

object boundaries on the allocation of attention is that objects pull spatial attention towards the center of mass of the cued object (Alvarez & Scholl, 2005: Kravitz & Behrmann, 2008). This re-centering of the gradient would have the effect of moving the gradient closer to the uncued end of the cued rectangle, leading to the object-based attention effects seen in these types of studies. A similar mechanism would explain the selective processing advantage for same object locations in illusory object studies; when the illusory object is present it pulls the center of the gradient closer to the same object uncued location (Martinez et al., 2007). However for the present study, the center of mass of the object is always the center of the cued region. Because of this, the presence or type of object boundary never changed the center point of the gradient of attention. This interpretation suggests that the attentional gradient is not shaped to fill a cued object, but that objects have an impact on the location of spatial selection, pulling the center of the gradient of selection towards the center of mass of the object.

One of the primary debates concerning object-based selection centers on whether object selection shares the same processing mechanism as space-based selection. The critical question is whether spatial attention is enhanced for all locations within the objects boundaries, or whether locations within an attended object are given search priority over other objects. The N1 sensitivity to object boundaries in previous studies supports the hypothesis that object based attention is driven by shaping the allocation of spatial attention. The N1 is a time window reliably modulated by spatial attention, and processing in this time window has been localized using fMRI and source modeling procedures to the lateral occipital cortex (LOC) and V4 areas of the visual cortex in both space based and object based attention conditions (Martinez et al., 2006). The timing and

localization information strongly suggest that object based attention recruits a network of activation at least partially overlapping with spatial attention. This is also supported by findings of gradients of selection extending within objects centered on cued locations (Hollingworth et al., 2001), similar to the gradients in N1 modulation demonstrated for spatial attention tasks like Experiment 1 and other ERP studies (Hillyard et al., 1998). Taken together, these studies present compelling evidence that the root of object based selection occurs within the N1 time window, and shares a network of neural activation with space based selection in the same time window.

Another question addressed by Experiment 3 was whether the gradient of selection indexed by the N1 was extended when a larger cue range was used. There was not sufficient evidence to suggest that the N1 was sensitive to the size of the cued area, with only a marginal difference in amplitude at midline locations that did not interact with object type. There were no differences based on cue size at the peripheral locations. This difference is in contrast to Experiment 2, in which the gradient of facilitation indexed by the N1 was expanded to cover a larger area for larger cue ranges. This difference may be due to the range of locations cued, as the greatest differences in the spread of selection in Experiment 2 were observed when one location was cued compared to when five locations were cued, and in the present study the maximum cued range was three locations. Adjustments of the range of selection may only occur when the area to be attended extends beyond the normal automatic distribution of the gradient of selection, and Experiment 3 may not have exceeded the standard gradient with the cue ranges used. The minimal differences for stimuli presented at the midline locations combined with the

lack of differences for stimuli at the peripheral locations suggest that cue size did not impact the distribution of selective processing in the N1 time window.

The N2 time window showed the clearest effect of scope of attention with an effect of cue size on the cued side of fixation, such that for peripheral locations the N2 amplitude was greater when the cued region extended to include that location compared to when only the midline was cued. Thus the N2 was the only time window to show the anticipated impact of cue size. Surprisingly, as previously noted, though there were differences based on cue size there was no effect of cued side. However, at peripheral locations the modulation of N2 amplitude matched the predictions for the impact of cue size, which supports that this time window is sensitive to the scope of the cued area. This is in agreement with the findings of Experiment 2, and supports a differentiation between the stage of selection sensitive to orienting attention, and the stage sensitive to the scale of selection.

There was no difference in facilitation of the N2 time window based on object boundaries, suggesting this time window is not sensitive to the presence of objects. In addition, there was no interaction between the size of the attended area and the object condition. Under the interpretation that the N2 indexes adjusting the size of the attended area to fit task demands, this suggests that object boundaries do not impact this stage of processing. This is particularly interesting as adjusting the scope of selection is the most intuitive means of selecting the area covered by the object. However, the N2 showed no modulation based on object condition. This suggests that the processing reflected in the N2 represents a top down allocation of facilitation over the task relevant area that is relatively unaffected by boundaries present in the scene.

The distinction between adjustments to the distribution of attention based on object boundaries and distributions based on top down mechanisms is particularly interesting as it suggests a different explanation may be needed for some patterns of behavioral data that have been interpreted to indicate that the same mechanism mediates the spread of facilitation based on object boundaries and cue size. For instance, in Eriksen and St. James' (1986) study on the zoom lens of attention, they used either a large or small square object as a cue. This square then remained on the screen for the remainder of the experiment. While this study has been interpreted as indexing the same mechanism as variable sized cues, the ERP evidence suggests that in fact cue size is independent of object boundaries. Sustained attention to a larger region of the visual field impacts a stage of processing indexed by the N2, and is relatively invariant with respect to the presence of object boundaries.

Taken together the findings of the present study present an interesting insight into the time course and interaction of two factors that impact the distribution of attention. Previous behavioral studies have shown that attention spreads within the confines of an object presented on a screen, and that cue size has an impact on behavioral performance (Egly, Driver, & Rafal, 1994; Duncan, 1984; Rock & Guttman, 1981). The most parsimonious explanation would be that these two factors modulate a common attentional process, and impact a similar stage of visual processing. However the current study suggests that this is not the case. The current findings, along with those of Experiments 1 and 2, point to a multiple stage model of selection. There is evidence for a very early stage of selection indexed by the P1, which is sensitive to the orientation of attention, and is not impacted by either object boundaries or the size of the cued area. The N1, shown

previously to index a gradient stage of selection, indicates adjustment such that the center of the gradient is located near the center of the attended object. The N1 also showed limited sensitivity to the size of the cued area in Experiment 2, though this impact is observed primarily when the attended area extended to cover a larger number of locations. The N2 represents a stage almost solely modulated by the size of the attended area, and is unaffected by object boundaries.

Experiment 3 was designed to investigate the impact of object boundaries on the allocation of visual selection, and determine if there are interactions between the presence of object boundaries and the scale of visual attention. The anticipated interaction was between the size of the area of sustained attention and the presence of object boundaries, suggesting a shared attention mechanism between these two factors. There was no evidence of an interaction between the presence of object boundaries and the scale of selection on either N1 or N2 amplitude. While the null result does not definitively show that object boundaries do not affect the scaling of the attended area, it certainly suggests that cue size and object boundaries operate independently on the distribution of spatial attention. Further studies will be needed to definitively establish whether object boundaries and sustained selection of different sized areas rely on entirely independent processes.

CHAPTER V

EXPERIMENT 4: COLOR SELECTION, GRADIENT AND RANGE

Introduction

Attentional selection based on color affects search times (Tresiman & Gelade, 1980), response times to single targets (Vierck & Miller, 2005), and the amplitude of ERP components (Hillyard & Münte, 1984; Vierck & Miller, 2008, Anllo-Vento, Luck, & Hillyard, 1998). The majority of studies investigating color selection have used a single cued color and very simple color discriminations (ie. red vs. blue). However, when a wide range of colors is present in a search array, the probability that a particular color is fixated increases steadily with its similarity to the target color (Stroud, Menneer, Cave, & Donnelly, 2012). This steady increase suggests that there may be a gradient of selection when discriminating items from a dense color space. In addition, when there are two target colors that are similar, items with colors in between the target colors are searched more frequently than items that are similar to only one of the cues (Stroud, Menneer, Cave, & Donnelly, 2012). This suggests that, in addition to a gradient of color selection, it may be possible to maintain a range of selected colors that includes the two cued colors as well as the intervening color space. The current experiment will examine whether these properties of a gradient and range of color selection that are seen in visual search are also found when a single stimulus is presented. Experiment 4 will address this question by presenting stimuli at a single location and using ERPs to measure differences in selective processing. In addition, this experiment will expand upon the current electrophysiological knowledge on feature selection by determining the time course of the gradient and range of color selection.

Experiment 1 demonstrated that attention to a cued location enhanced amplitude in the N1 time window, and Experiment 2 showed that adjusting the size of the cued area impacted the range of stimulus locations for which there was enhanced negative amplitude in the later N2 time window. Experiment 4 addresses whether attention to color shares this characteristic of two distinct stages of processing. The paradigm was similar to that used in Experiments 1 and 2, but all of the stimuli were presented at fixation to avoid confounds with spatial selection, and the target was defined by color rather than by location. In addition, a slightly more difficult discrimination task was used (between symmetric T's and slightly offset T's), as the X/O discrimination used in the previous experiments may be too easy to require sufficient attention at fixation. If color selection shows separate processing stages for the color gradient and the color range, it would suggest that this is a general selection strategy employed in both spatial and feature based attention. Also of interest is determining the distribution of attention at the gradient stage of selection. This will be examined by comparing the amplitude of attention effects for probes at varying distances from the cue in the color spectrum. This experiment will demonstrate the extent to which the gradient and adjustable range factors determining the distribution of spatial selection are also present for feature-based selection.

Method

Participants

Data from sixteen participants (9 female, mean age: 21.625 years, SD: 3.16) were included in the final analyses. Twenty-one participants were initially included in at least some portion of the experiment; data from 5 participants were excluded because of an

insufficient number (< 40) of artifact free trials in some conditions. Artifacts included blinks, eye movements, and electrodes showing excessive noise. All participants were right handed, and reported having normal or corrected to normal visual acuity, and normal color perception. All participants provided written informed consent prior to the study, and were paid for their participation.

Stimuli

The design for Experiment 3 is shown in Figure 15. Stimuli were presented one at a time at the center of the screen against a black background, and consisted of symmetric T's (deviants, 25%) and slightly offset T's (standards, 75%). Stimuli were presented in a range of 16 possible colors (from Menneer, Stroud, Cave, & Donnelly, 2009). The colors were distributed such that all pairs of neighboring colors were approximately equally separated in CIE xyY color space. Three cue conditions were used: cue 1 color, cue 3 adjacent colors, and cue 5 adjacent colors. The cue consisted of 1, 3, or 5 color patches presented at fixation in the colors to be monitored for that block.

Procedure

The study was split into 15 blocks (5 blocks of each cue range condition) each containing 320 trials. Each participant performed blocks of all three cue ranges. The centers of the cue ranges were spread in color space such that the cue ranges any one participant saw did not overlap. The centers of the cue ranges were also different for each participant, such that every color was the center of every cue range for exactly one of the participants. In order to improve memory for the cued colors, blocks of the same cue range were performed consecutively. In addition, a practice session was performed before each new cue range providing feedback on discriminating the cued colors from the

other possible item colors. In these practice session the cue for the upcoming blocks was presented, followed by a deviant in a color randomly chosen from the set of 16 colors. The participant responded whether the deviant was within the cued color range or not. Following the response, they were given feedback as to whether they had correctly classified the color as within or not within the range, and shown an example of the cued color range for comparison. Cue range order was balanced across participants. Trials began with a fixation cross displayed for 1000 ms. At the offset of the fixation cross, a cue appeared for 2000 ms. Approximately 500 ms after the offset of the cue, the presentation of stimuli began. Each stimulus was displayed by itself for 72 ms with an ISI of 250-750 ms. Stimuli were presented in each of the 16 colors with equal frequency. The task was to press a button when a symmetric T (a deviant) appeared in the cued color range. Each block provided 16 standards and 4 deviants for each color. For the whole experiment, this provided 80 standards and 20 deviants at each color distance relative to the center of the cue. Blocks were about 3 minutes long, and all 15 blocks took about 45 minutes. Total running time for the study, with setup, practice, and breaks was approximately 2 hours.

Prior to beginning the experimental trials, all participants were given a 10 minute introduction and practice block, which included practice on the discrimination between standards and deviants, as well as the task of responding to deviants within the cued color range. Short practice blocks included all three cue range conditions. A button press was considered to be a response to a deviant if it occurred between 250 and 1000 ms after the onset of a deviant. If more than one deviant occurred between 250 and 1000 ms prior to a response, time windows were used to determine which deviant would be associated

with the response (primary time bin 500-749 ms, secondary 250-499 ms, tertiary 750-1000 ms). All button presses that did not occur between 250 and 1000 ms after a deviant were classified as responses to standards. Due to the rapid presentation and frequency of standards, it was impossible to determine with certainty which standard onset was associated with each response.

ERP Procedures and Comparisons

The ERP analysis for Experiment 4 differed from the previous experiments in several facets. First, the analysis included time windows specific to both spatial and feature based selection. The time windows in which amplitude is modulated by attention to color have been well described in Anllo-Vento, Luck and Hillyard (1998), the most reliable of which is the selection negativity (SN), which has been found in time ranges from ~160-350 ms. These previous studies as well as a visual inspection of the waveforms were used to determine two time windows for measuring the SN, the early SN from 200-250 ms, and the late SN from 250-300 ms. Two separate time windows were used as some studies have found the early and late SN to be functionally distinct (Anllo-Vento, Luck, & Hillyard, 1998; Lange, Wijers, Mulder, & Mulder, 1998). The SN is most often found across posterior electrode sites across the back of the head. Measurements were analyzed from the full posterior array of 27 electrodes used in Experiments 1, 2, and 3. In addition to the SN, the P1, N1, and P3 time windows were also measured. These measurements used the same set of 27 posterior electrodes. The N2 time window was not analyzed as it overlapped with the SN time window. The other major difference was that Experiment 4 used an average reference, as compared to the averaged mastoid reference in Experiments 1, 2, and 3. An average reference was used

because the broad distribution of the SN across lateral sites meant SN signal was substantial at the mastoid electrode sites. If a mastoid reference had been used, the SN could not have been detected signal at the other electrodes, compared to the reference. For this reason, average amplitude across all electrode sites was used as a reference was determined to provide a more accurate measure of SN amplitude across posterior electrode sites. The average reference has been used successfully in previous studies of color-based selection (Keil & Müller, 2009). All other ERP analysis steps, including averaging and artifact rejection, were performed as in Experiments 1, 2, and 3.

Analysis was performed across two main factors; distance in color steps of separation between the standard and the center cued color (D0, D1, D2,…., D8), and range of colors cued (C1, C3, C5). It should be noted that for Experiments 4 and 5, whenever the term "distance" is used, it refers to distance, or separation, in the feature dimension of interest, and not spatial distance in the visual field. There were three main sets of comparisons. To determine the extent of the gradient of color selection the response to standards at varying color distances for the cue were compared to the unattended condition (D8). Where the response to stimuli at multiple color distances differed from D8, individual contrasts were used to characterize the distribution of facilitation. Interactions between color distance and cue range were used to explore differences in spread of the distribution of selection based on cue range. The final analysis compared the ERPs to stimuli under different cue ranges collapsed across color distance. Main effects of cue range would indicate differences in visual processing based on the general task demands, separate from color selection.

Results

Behavioral Results

Analysis of the behavioral data included response rate and response time to deviants, and response rate to standards in each of the three cue conditions.

For response rate to deviants, there was a main effect of distance collapsed across cue range, such that the number of deviants that received responses decreased with distance from the center of the cued area ($F(8,120) = 260.4$, $p < .001$). There was also a main effect of cue range, such that the larger the range of cued colors the more responses were recorded ($F(2,30) = 32.6$, $p < .001$), which is appropriate given that more targets occurred for larger cue ranges. Most interesting was an interaction between cue range and cue distance ($F(16,240) = 13.0$, $p < .001$). Individual contrast at each cue distance revealed there was a main effect of cue range at distances 1-6, and a trend towards an effect at D7 (D1: $F(2,30) = 25.1$, $p < .001$; D2: $F(2,30) = 38.7$, $p < .001$; D3: $F(2,30) = 14.8$, $p < .001$; D4: $F(2,30) = 5.5$, $p < .05$; D5: $F(2,30) = 3.9$, $p < .05$; D6: $F(2,30) = 7.7$, $p < .005$; D7: $F(2,30) = 3.1$, $p = .088$). The differences across all color distances indicated response rate increased with larger cue ranges, as can be seen in Figure 16a. There was no difference in hit rate at the central cued color, indicating there was no cost in attending to a larger cue range ($F(2,30) = 1.0$, $p = .358$). It was not possible to compare cue ranges at the furthest distance from the cue, as the small cue condition received no responses at this distance. However, response rate for the other two cue ranges were near floor, suggesting no major differences for this color distance.

More specific contrasts were performed at distances of one and two colors from the central cued color to determine the impact of deviants falling inside versus outside the

cued range. For deviants one color away from the central cued color, there was no difference between the cue 5 and cue 3 conditions, and both received more responses than in the cue 1 condition (C1 vs. C3: $F(1,15) = 32.8$, $p < .001$; C1 vs. C5: $F(1,15) = 27.2$, $p < .001$; C3 vs. C5: $F(1,15) = 0.007$, $p = .935$). For deviants that were two colors distant from the central cued color, deviants in the cue five condition received more responses than in the cue 3 condition, which in turn received more responses than deviants in the cue 1 condition (C1 vs. C3: $F(1,15) = 83.2$, $p < .001$; C1 vs. C5: $F(1,15) = 24.2$, $p < .001$; C3 vs. C5: $F(1,15) = 13.1$, $p > .005$). These results indicate that participants were able to use color information to respond more frequently when a color fell within the cued range compared to outside of the cued range.

Further inspection of the data revealed that the critical determinant in the response rate might be the distance from the edge rather than the center of the cued range. A second analysis was performed comparing the response rate based on distance from the color at the edge of the cued range. When deviants were defined based on their distance from the edge of the cued range, there was still an interaction between cue range and color distance ($F(16,240) = 13.0$, $p < .001$). However, individual contrasts revealed that the only significant differences based on cue range were for cued colors at the edge of the cued range ($F(2,30) = 7.7$, $p < .005$), and the color 6 steps away from the edge of the cued range ($F(2,30) = 4.4$, $p < .05$). All other color distances did not differ based on cue range (p's $> .05$). This suggests that the slope of response rates was highly dependent upon distance from the edge of the cued range. This can be seen in figure 16b.

Response times were analyzed only for target items, as these were the only items that received consistent responses for all participants. Response times to targets of the

central cue color were compared between each of the three cue ranges (Figure 16c). There was no difference in response time at the central cue color, and no difference between the cue 3 and cue 5 conditions at one color distance from the center of the cued range, further suggesting no cost in expanding the cued range (D0: $F(2,30) = 1.5$, $p = .234$; D1: $F(1,15) = .3$, $p = .574$). There was also no difference between the response times at different distances within the cued range for either the cue 3 or the cue 5 conditions (C3: $F(1,15) = .1$, $p = .715$; C5: $F(2,30) = 2.6$, $p = .111$). This does not strongly refute or support a gradient distribution of selection within the cued range, as the RTs were consistent with a gradient distribution but the limited number of targets made it impossible to establish a definitive pattern.

There was a main effect of cue range on response rate to standards ($F(2,30) = 5.3$, $p < .05$), such that the greatest number of responses occurred in the cue 5 condition, followed by the cue 3 condition, and the least in the cue 1 condition (Figure 16d). Increased response rate to standards in the larger cue ranges indicates more of the non-target shapes were considered, and incorrectly identified, as targets.

ERP Results

Three main comparisons were made in each time window of the evoked waveforms. Comparisons were made based on the amplitude evoked by standards at varying color distances from the central cued color (Figure 17), between the three separate cued ranges collapsed across standards at all color distances (Figure 18), and interaction between cue range and color distance (Figure 19). The results are divided into time windows of analysis.

In the P1 time window (75-120 ms) there were no differences based on cue color distance from the standard ($F(8,120) = .7$, $p = .627$). This indicates that there was no selection based on color in this time window. There was also no main effect of cue range ($F(2,30) = .4$, $p = .670$), and no interaction between cue range and distance for the P1 time window ($F(16,240) = .6$, $p = .741$). These results are not surprising as the P1 time window has previously been associated with space based, but not feature based attention.

For the N1 time window (150-200 ms), there was also no main effect of color distance and no interaction between distance and cue range (Distance: $F(8,120) = 1.3$, $p = .289$; Distance vs. Range: $F(16,240) = .6$, $p = .790$). However, there was a main effect of cue range ($F(2,30) = 3.9$, $p < .05$), such that the N1 amplitude was more negative in the cue 1 compared to the 3 and 5 colors cued conditions (C1 vs. C3: $F(1,15) = 7.4$, $p < .05$; C1 vs. C5: $F(1,15) = 10.6$, $p < .01$; C3 vs. C5: $F(1,15) = 0.1$, $p = .725$). One interpretation of this difference is that the N1 indexes the earliest stages of the SN deflection, and that the SN is evoked earlier for standards in the cue 1 condition relative to the larger cue ranges. This interpretation is unlikely given that the difference in N1 amplitude did not interact with cue distance, and therefore does not seem to be color selective. More likely, the N1 time window is indexing spatial attention differences between the cue ranges. Spatial attention would affect processing of all standards equally, as is indicated by the main effect of cue range. Greater negativity in the N1 in the small cue condition suggests spatial attention was more focused in this condition, possibly due to the low frequency of targets when only one color is cued. Regardless of the mechanism underlying N1 modulation based on cue range, the lack of an interaction

with color distance from the central cued color indicates that this time window is not sensitive to color selection.

Amplitude modulation consistent with color-based attention was seen primarily in the early and late SN time windows, as was predicted (Figure 20). For the early SN time window (200-250 ms) there was a main effect of color distance ($F(8,120) = 9.2$, $p < .001$). This effect was in the form of increased negativity for colors near the center of the cued range compared to more distant colors. This indicates color selective processing is occurring within the early SN time window. There was no main effect of cue range, and no interaction between cue range and cue distance for the early SN (Range: $F(2,30) = .8$, $p = .452$; Range vs. Distance: $F(16,240) = .7$, $p = .684$). This suggests that the early SN was modulated based on the attended color for all cue ranges tested. Further tests were conducted specifically to detect differences between cue ranges for the D0, D1, and D2 color distances, as these colors fell within some cue ranges and outside of others. Specific comparisons at these color distances revealed no significant differences in amplitude between the cue ranges (p's > .1). This further reinforces that the effects of distance from the center of the cued range were consistent across cue ranges, and not determined by whether a standard fell within or outside of the cued range.

Comparisons between standards at varying distances from the central cued color were performed to determine the distribution of selective processing. Contrasts revealed that the differences in amplitude based on color distance showed a spread of facilitation up to two hue steps around the central cued color. There was not a significant difference in amplitude between D0, D1, and D2 (D0 vs. D1: $F(1,15) = 1.7$, $p = .213$; D1 vs. D2: $F(1,15) = .1$, $p = .765$). Mean amplitude was more negative for standards at D2

compared to D3 (D2 vs. D3: $F(1,15) = 8.6$, $p < .05$). Finally, all hues at D3 through D7 evoked similar mean amplitude, and were all more negative than D8 (D3 vs. D4: $F(1,15) = .1$, $p = .733$; D4 vs. D5: $F(1,15) = .8$, $p = .372$; D5 vs. D6: $F(1,15) = .1$, $p = .989$; D6 vs. D7: $F(1,15) = .6$, $p = .439$; D7 vs. D8: $F(1,15) = 8.8$, $p < .01$). These findings suggest that color-based attention, as indexed by the early SN time window, has a relatively broad distribution around the central cued color, including hues up to two steps away in the current study's palate of colors.

There was also a main effect of cue distance in the latter half of the SN time window (250-300 ms) ($F(8,120) = 12.3$, $p < .001$). This effect was in the form of increased negativity for colors near the center of the cued range compared to more distant colors. This indicates color selective processing is occurring within the late SN time window. There was no main effect of cue range, and no interaction between cue range and cue distance for the late SN (Late SN Range: $F(2,30) = 1.2$, $p = .319$; Late SN Range vs. Distance: $F(16,240) = 1.0$, $p = .441$). Similar to the early SN, the late SN showed attention to color based modulation for all cue ranges tested. Further tests looked specifically for differences between cue ranges for the D0, D1, and D2 color ranges, as these fell within some cue ranges and outside of others. Specific comparisons between the three cue ranges at these color distances revealed a trend towards standards at the D0 distance evoking greater SN amplitude in the cue 1 range compared to the cue 5 range ($F(1,15) = 3.7$, $p = .073$), suggesting there may have been a more focused allocation of selection to the center of the cued area in the smaller cue range. However, the cue 1 range was also more negative than the cue 3 range at the D1 distance ($F(1,15) = 4.7$, $p < .05$), which does not support a tighter focus of attention in the small cue range. There

were no other significant differences in amplitude between the cue ranges at these distances (p's > .1). Together with the overall lack of interaction between cue range and color distance, these comparisons are consistent with the interpretation that the effects of distance from the center of the cued range were similar across cue ranges, and not determined by whether a standard fell within or outside of the cued range.

The differences in amplitude in the late SN based on color distance showed a similar spread of selection to the early SN, but demonstrated a clearer gradient of facilitation. Mean amplitude was more negative for standards at the central cued color compared to standards one or more hues distant (D0 vs. D1: $F(1,15) = 5.5$, $p < .05$). There was no difference between one and two hues distant, but standards at both these hue distances evoked more negativity than standards 3 or more distant (D1 vs. D2: $F(1,15) = .1$, $p = .956$; D2 vs. D3: $F(1,15) = 18.6$, $p < .001$). There was no difference in amplitude between standards at D3-D8 (D3 vs. D4: $F(1,15) = .2$, $p = .658$; D4 vs. D5: $F(1,15) = .1$, $p = .739$; D5 vs. D6: $F(1,15) = 1.6$, $p = .225$; D6 vs. D7: $F(1,15) = .6$, $p = .453$; D7 vs. D8: $F(1,15) = 2.8$, $p = .118$). The primary differences between the late and the early SN were that there was a selective advantage for the D0 compared to the D1 and D2 standards, and that D8 did not differ from D3-D7. To determine the reliability of the differences between the early and late SN, a separate ANOVA was run including both time windows, resulting in a trend towards an interaction between time window and distance ($F(8,120) = 2.7$, $p = .059$). Despite this difference, the modulation based on color distance in the late SN time window was very similar to that seen in the early SN time window, and there is not sufficient evidence to suggest they index separate processes.

For the SN time window as a whole, there was evidence for selection based on perceptual distance from the central cued color. In addition, these differences were distributed as a gradient around the cued color. However, there was little evidence of the spread of attention differing based on the range of colors cued. All three cue ranges showed a very similar distribution of selective processing.

In the P3 time window there was a main effect of distance ($F(1,15) = 5.4$, $p < .001$); however individual contrasts revealed that only the D1 standards evoked mean amplitude that was significantly more positive than D8 standards (D1 vs. D8: $F(1,15) = 7.1$, $p < .05$; D0, D2-D7 vs. D8: all p's > .05). The pattern of means suggests an advantage of colors near the cued location compared to those on the opposite range of colors, but it is difficult determine the distribution of this facilitation. It is likely that there were limited differences based on color distance in the P3 time window due to overlap with late SN deflections. There was no main effect of cue range in the P3 time window, and no interaction between cue range and distance (Range: $F(2,30) = .8$, $p = .451$; Range vs. Distance: $F(16,240) = .5$, $p = .824$). Further tests looked specifically for differences between cue ranges for standards at the D0, D1, and D2 color distances, as these fell within some cue ranges and outside of others. Specific comparisons at these color distances revealed no significant differences in amplitude between the cue ranges (p's > .1). Consistent with earlier time windows, for the P3 the effects of distance from the central cued color were consistent across cue ranges, and not determined by whether a standard fell within or outside of a cued range.

Discussion

Experiment 4 addressed several questions about how selective processing is

distributed in color space. First, does color-based selection for stimuli presented in isolation at a known location have the same gradient of facilitation suggested by color-based search? There was evidence for a gradient distribution of color selection modulating amplitude in the SN time window. Second, can a range of colors be attended simultaneously, and is there a cost to this spread of selection over a range of colors? While the behavioral data indicated that cue range was effectively used to guide responses, there was no evidence that cue range impacted the extent of color space that was modulated in the SN time window. Third, are there separable stages of selection for color similar to those seen in spatial selection? There was not conclusive evidence for separate stages of color selection; only a single stage that showed a gradient distribution around the center cued color.

There was evidence of a graded distribution of selection across color space in both the behavioral and ERP data. For the behavioral data, response rate to deviant items was greatest within the cued range, and dropped off rapidly outside of the cued range. The determining factor in the number of responses was the hue distance from the edge of the cued region. This decline from the edge of the cued range was relatively constant regardless of the number of colors cued. Interestingly, there was no effect of cue range on hit rate for targets with a color at the center of the cued range. This suggests that there was no performance cost to expanding the selected range of colors from 1 color to 3 or 5 colors. This is notably different compared to attention to different sized spatial regions, where there is often a cost associated with attending to a larger area (Eriksen & St. James, 1986; Castiello & Umilta, 1990). It is also different from the pattern seen in search studies, in which searching for two separate colors produces a marked interference on

color selection (Stroud, Menneer, Cave, & Donnelly, 2012). Since the Stroud et al. study used a similar set of colors to test related questions on color-based attention, the difference between their results and the current results are particularly interesting, and will be discussed at greater length below.

In order to determine the time course of the gradient of color selection in perceptual processing, the timing of amplitude differences in the ERP waveform was examined. This examination began with the early P1 and N1 time windows associated with spatial selection (Gonzalez, Clark, Fan, & Luck, 1994; Hillyard, Teder-Sälejärvia, & Münte, 1998; Mangun, 1995; Luck, Woodman, & Vogel, 2000; Hopfinger, Luck, & Hillyard, 2004). Most previous studies have not found evidence of color-based selection in these early time windows, except when the task resulted in significant competition between concurrently displayed colors (Zhang & Luck, 2009). However, investigation of the P1 and N1 was necessary to rule out the possibility that color selection in the current task was mediated by rapidly switching spatial attention to or away from the foveal stream. These measurements were also analyzed to determine whether any of the cue conditions induced different levels of spatial selection of the stream. There was a distinct P1 deflection in response to all stimuli, but there was no indication of any modulation of this time window based on the cued condition or hue distance of the stimulus relative to the cue. The N1 was sensitive only to the scope of the cued color range; specifically items evoked a larger negativity when 1 color was cued compared to when 3 or 5 colors were cued. These differences were independent of the items' distance in color space from the central cued color, indicating that the N1 did not index color-based selection. Instead, this cue range effect suggests that when 1 color was cued, participants devoted

more spatial attention to the entire stream of items. It is unclear why the narrowest cue range would have induced greater spatial attention relative to the broader cue ranges, but participants may have been more vigilant when monitoring the small color range due to the relatively rare occurrence of targets in this condition.

The SN was the earliest time window to show modulation based on distance to the cued color. Amplitude in the early phase of the SN time window (200-250 ms) was more negative for items similar to the center of the cued color range compared to more distant colors. This facilitation spread up to two color steps away from the central cued color. Amplitude modulation in the latter half of the SN time window (250-300 ms) also showed facilitation over the same range of color distances. However, facilitation in the latter half of the SN was distinct in showing a roughly graded distribution, with the greatest selection at the center of the cued color range. While the gradient of selection was more defined in the latter phase of the SN, the differences between the early and late SN were not sufficient to provide compelling evidence that they represent separate stages of processing. The pattern of SN modulation is in keeping with previous findings that this time window is reliably sensitive to selection of feature-based information (Hillyard & Münte, 1984; Vierck & Miller, 2008, Anllo-Vento, Luck, & Hillyard, 1998). These earlier studies used a very limited range of colors, often two very dissimilar colors such as red and blue. Such clear-cut discriminations were used for the very good reason that it made the effects of color selection easy to distinguish. This was a necessary first step in defining the neural correlates of feature based selection, but it does not address the specific distribution of color selection. The current study extends upon these findings by demonstrating that selection of colors as indexed by the SN time

window spreads to nearby hues in a dense color space, and this spread has a roughly graded distribution.

The other question addressed with Experiment 4 was whether the distribution of color selection would vary based on the range of cued colors. Based on the evidence from color guided search tasks, it was predicted that expanding the range of monitored colors would increase the scope of color space that received attention-based facilitation (Stroud, Menneer, Cave, & Donnelly, 2012). It was anticipated that changes in the scope of the facilitated range of colors would impact amplitude in the SN time window. Indeed, the behavioral data from Experiment 4 seem to indicate that the distribution of color selection was adjusted based on cue range. Hit rates for all cue ranges decreased steadily with distance from the edge of the cued range, suggesting the range of attended colors was expanded to match the cue. However, cue range did not impact the amplitude of feature-based attention effects in the SN time window. This pattern indicates that color selection, at the level of perceptual processing indexed by the SN, is not sensitive to the range of cued locations. The result was unexpected, especially in light of the strong impact of cue range on hit rate. The contrast in the behavioral and ERP findings indicates that the processing which leads to cue range differences in the behavioral data must be driven by a stage of processing which was not identified in the ERP waveform.

The fact that the SN is later than space-based attention effects observed on the P1 and N1 raises the question of whether the SN indexes perceptual processing or decision-related processes. There is ample evidence that attention-based modulation of amplitude in the SN time window represents facilitation of perceptual processing. Previous studies utilizing both fMRI and source modeling of ERP data on the same task have localized

effects in the SN time window to activation in cortical region V4v, an area known to be involved in color processing (Anllo-Vento, Luck, & Hillyard, 1998, Schoenfeld et al. 2007). Our results are in line with interpretations of the SN as an index of perceptual processing. The main evidence for this is that selection is distributed as a gradient in color space, and in particular that the gradient is invariant with respect to cue size. If SN amplitude indexed decision making processes, one would predict that the pattern of modulation would parallel the hit rate data, changing dramatically based on the cue range. In fact, facilitation was observed in the SN time window for all items near the cued feature value. This result supports the conclusion that the SN indexes the effects of feature-based attention on perceptual processing, and that the determination of whether an item is within the target color range occurs at a later stage that is potentially more variable in time.

There are some interesting parallels between space-based and color-based attention raised by the current study. Chief among these is that both modes of selection show a gradient of facilitation extending from the center value of the cued feature. The graded facilitation of colors seen in the current study is similar to the graded facilitation of locations seen in Experiment 1, as well as several other spatial attention tasks (Downing & Pinker, 1985; LaBerge & Brown, 1986; Mangun & Hillyard, 1988). For both color selection in the SN time window and spatial selection in the N1 time window, this distribution around the cued value seems to be automatic and occurs even for very small cue ranges. However, unlike spatial selection there is no electrophysiological evidence of a second stage of color selection that is sensitive to the cued range. This suggests that for attention to color, tasks that require selecting precise cue ranges rely on

mechanisms that are not indexed in the ERP waveform. Overall, the similarities between the N1 modulations (Experiments 1 and 2) and the SN modulation (Experiment 4) suggest that an automatic gradient of selection may represent a general characteristic of attention.

One particularly interesting question is how these results relate to search tasks in which color is used to guide spatial attention. For instance, Stroud, Menneer, Cave, and Donnelly (2012) looked at the efficiency of search based on the number of target colors. They found a gradient of selection such that items with hues similar to the cued color were fixated more readily than distant hues. This finding mirrors the gradient of attention effects in the SN when attention is directed to a stream of items at fixation. A second finding of the Stroud et al. (2012) study was that searching for multiple colors interfered with color selection. This resulted in increasing the probability of fixating items of colors that were very different from the target. The current study found no indication of interference in color selection based on cue range. There were two major differences between the studies that could account for these seemingly incompatible results. First, in the Stroud et al. study the cued colors did not always fall adjacent to each other in the hue space, and when they were more disparate they could be separated by distractor colors. The current study used a number of contiguous colors that never had intervening distractors. However, a subsequent search study employing contiguous color cues similar to the present study showed that attending to a range of colors impairs color selectivity even more than attending to two separate colors (Stroud, Menneer, Kaplan, Cave, & Donnelly, 2011). Therefore it is more likely that the critical difference is that in the search studies color is used to guide spatial attention. Selecting based on color across the

whole visual field may rely on a different mechanism from selecting colors at a known spatial location. The relationship between pre-spatial color selection and post-spatial color selection is a fascinating one, and further investigations into the relationship between these two types of color selection will be needed to determine the cause of these differences.

The results of Experiment 4 provide insight into the distribution of selective visual processing based on color. The findings are consistent with those of previous studies in that there were perceptual processing differences between attended and unattended colors. Experiment 4 expanded upon these findings by showing that the allocation of color-based attention for items at fixation has a gradient distribution around the cued color. While a gradient of selection is seen in both the behavioral and SN measures of selection, only the gradient in response rate was sensitive to differences in the range of cued colors, suggesting an intermediary stage of selection not reflected in the ERP waveform.

CHAPTER VI

EXPERIMENT 5: SIZE SELECTION, GRADIENT AND RANGE

Introduction

Size based attention has been shown to affect response times to targets (Larsen & Bundesen, 1978; Cave & Kosslyn, 1989; Poder, 2001), sensitivity to different visual frequencies (Shulman & Wilson, 1987), and amplitude of ERPs in the N2 time window in a global/local task (Heinze, et al., 1998). While these studies have shown that having correct expectations concerning the size of a stimulus provides a processing advantage, the distribution of attention based on size has not been described. Experiment 5 addresses several questions about selection based on the size, including the similarities between size based and color based attention. It was designed to determine whether there is a gradient of size selection that explains the in response-time patterns reported in behavioral studies. Second, the results will demonstrate whether cuing a range of sizes impacts the distribution of perceptual facilitation. Lastly, this experiment will provide initial information about the timing of the effects of size-based attention on ERP waveforms. Comparing the timing of effects indexing size selection with those observed in Experiments 1-4 will provide insight into whether size-based attention relies on mechanisms more closely linked to spatial attention, or to feature based attention.

Experiment 5 has a similar design to Experiment 4 with single stimuli presented at fixation and cues differing in size rather than color. One difference between the features of size and color is that hue can be arranged in a circular feature space, whereas size is inherently linear. The design was adjusted for this difference by reducing the number of cue range conditions in Experiment 5; only the cue 1 and cue 5 conditions

were included. In addition only two sizes were used as the center of the cued range of sizes, one on the large side and one on the small side of the size spectrum. The prediction was that stimuli presented in the cued size would evoke greater amplitude at posterior electrode sites within the SN time window compared to stimuli at uncued sizes. Such an attention effect would suggest that attention based on size relies on a feature selection mechanism similar to that employed in attention based on color. A further prediction was that amplitude modulation in the time windows sensitive to size selection would show a gradient of facilitation around the cued size. Comparisons were also done to test for attention-based modulation in time windows sensitive to spatial attention, specifically the P1 and N1. Additional comparisons were made between the small and large ranges of cued sizes to determine if cue range impacted the distribution of attention. If attention based on size is achieved by a feature selection mechanism similar to attention to color, then there would be no anticipated difference in the distribution of selection between the cue 1 and cue 5 conditions.

Method

Participants

Data from twenty participants (13 female, mean age: 22.8 years, SD: 3.679) were included in the final analyses. Twenty-three participants were initially included in at least some portion of the experiment; data from 3 participants were excluded because of an insufficient number (< 40) of artifact free trials in some conditions. Artifacts included blinks, eye movements, and electrodes showing excessive noise. All participants were right handed, and reported having normal or corrected to normal vision. All participants provided written informed consent prior to the study, and were paid for their

participation.

Stimuli

Experiment 5 had the same basic structure as Experiment 4, with the following changes. Instead of being varied based on color, stimuli varied based on size. The design for Experiment 5 is shown in Figure 21. Sixteen different item sizes were used, from 0.5° visual angle to 8° visual angle. Each item size was 0.5° degrees of visual angle larger than the next smallest size. The cues consisted of square outlines that matched the sizes to be monitored for that block. Two cue ranges were used, indicating participants should monitor either 1 or 5 contiguous sizes. Unlike hue, size does not represent a circular feature space, so there was necessarily an upper and lower limit on the range of sizes used. The cuing structure was changed to accommodate this difference. The center of the cued range was limited to either the fifth smallest size (2.5°) or the fifth largest size (6°). Half of the participants received the cue 5 sizes range centered at 2.5°, and the cue 1 size range centered at 6°. The other half received the cue 5 sizes range centered at 6° and the cue 1 size range at 2.5°. Collapsing across participants allowed us to determine the impact of cue range independent of the physical size of the stimuli. As in Experiment 4, stimuli consisted of symmetric Ts (25%) and asymmetric Ts (75%).

Procedure

The study was split into 10 blocks (5 blocks of each cue range condition) each containing 320 trials. In order to improve memory for the cued sizes, blocks of the same cue range were performed consecutively. In addition, a practice session was included before each new cue range providing feedback on discriminating the cued sizes from the other possible item sizes. In these practice sessions the cue for the upcoming blocks was

presented, followed by a deviant in a size randomly chosen from the set of 16 sizes. The participant responded to indicate whether the deviant was within the cued size range or not. Following the response, they were given feedback as to whether they had correctly classified the size as within or not within the range, and shown an example of the cued size range for comparison. Cue range order was balanced across participants. Trials began with a fixation cross displayed for 1000 ms. At the offset of the fixation cross, a cue appeared for 2000 ms. Approximately 500 ms after the offset of the cue, the presentation of stimuli began. Each stimulus was displayed by itself for 72 ms with an ISI of 250-750 ms. Stimuli were presented in each of the 16 sizes with equal frequency. The task was to press a button when a symmetric T (a deviant) appeared in the cued size range. Each block provided 16 standards and 4 deviants for each size. For the whole experiment, this provided 80 standards and 20 deviants at each size. Blocks were ~3 minutes long, and all 10 blocks took approximately 30 minutes. Total running time for the study, with setup, practice, and breaks was approximately 1.5 hours.

Prior to beginning the experimental trials, all participants were given a 10 minute introduction and practice block, which included practice on the discrimination between standards and deviants, as well as the task of responding to deviants within the cued size range. A button press was considered to be in response to a deviant stimulus if it occurred between 250 and 1000 ms after the onset of a deviant. If more than one deviant occurred between 250 and 1000 ms prior to a response, time windows were used to determine which deviant would be associated with the response (primary time bin 500-749 ms, secondary 250-499 ms, tertiary 750-1000 ms). All button presses that did not occur between 250 and 1000 ms after a deviant were classified as responses to standards. Due

to the rapid presentation and frequency of standards, it was impossible to determine with certainty which standard onset was associated with each response.

ERP Procedure and Comparisons

There is little research on the electrophysiological correlates of attention to size, and therefore differences between attention conditions were tested in time windows modulated by spatial attention, the P1 and N1, as well as the SN time window, which is modulated by attention to features. The same set of comparisons were used for Experiment 5 as Experiment 4, with some important differences to account for the linearity of the feature space for size. To determine facilitation based on the size distance of the item from the central cued size, the 16 possible item sizes were split into two groups categorized based on whether the center cued size falls within the large or small half of the size range. For instance, if the cued range fell within the 8 smaller sizes, then those sizes constituted the cued half (CH) and the 8 larger sizes constituted the uncued half (UH). Conversely, when the cued range was within the 8 larger sizes then those sizes were the CH, and the smaller sizes were the UH. Within each group of 8 sizes items were defined based on their size difference from the edge of the set of possible sizes. For the condition in which the cue falls within smaller half of sizes, the items were labeled, from smallest to largest; C1, C2, C3, C4, C5, C6, C7, C8, U8, U7, U6, U5, U4, U3, U2, U1. When the cue was within the large set of sizes the same labels applied, but in reverse order of absolute size, such that C1 was the largest item size and U1 was the smallest. For all conditions, the cue is centered on C5. Most of the comparisons were between the same standard sizes when they occurred in the cued or uncued half of the set of possible sizes. For these comparisons, the sizes are referred to as S1, S2, S3, S4, S5,

S6, S7, and S8. In the results section, differences between sizes are referred to as distance for simplicity. However in all cases this refers to distance in the size feature space, and not spatial distance in the visual field. The remaining factor of comparison is cue range, which was a range of a single cued size (R1), or a range of five adjacent cued sizes (R5).

Results

Behavioral Results

Comparisons were made between the response rate and response time to deviants, and the response rate to standards (Figure 22) for the two cue ranges. For response rate to deviants there was a main effect of deviant size, such that the number of responses was greatest at the central cued size (C5) and decreased as size distance increased ($F(15,285) = 94.3$, $p < .001$). There was also a main effect of cue range, such that there were more responses in the R5 compared to the R1 condition ($F(1,19) = 54.0$, $p < .001$), and this response rate difference interacted with distance from the central cued size ($F(15,285) = 6.6$, $p < .001$). Individual contrast at each deviant size revealed there was a main effect of cue range for deviants at sizes C2 through U8 (C2: $F(1,19) = 11.6$, $p < .005$; C3: $F(1,19) = 27.4$, $p < .001$; C4: $F(1,19) = 25.8$, $p < .001$; C5: $F(1,19) = 15.7$, $p < .001$; C6: $F(1,19) = 17.4$, $p < .001$; C7: $F(1,19) = 18.5$, $p < .001$; C8: $F(1,19) = 18.2$, $p < .001$; U8: $F(1,19) = 9.3$, $p < .01$). There were no differences based on cue range at C1 or U7-U2 (p's > .1). That there were differences in response rate even for deviants at the central cue size (C5) indicates that participants responded more readily in the R5 compared to the R1 condition. The overall increase in response rate to deviants in the broader R5 condition suggests that participants were setting a lower threshold for categorizing deviants as

targets. There was also a difference between cue ranges at U1 showing similarly increased responses for R5 ($F(1,19) = 13.1$, $p < .005$). However this is difficult to interpret due to the lack of differences between cue ranges in the U7-U2 sizes, and may be a spurious result as both values were near floor.

Comparisons were made between the cue ranges for response times at the central cued size (C5), and between deviant sizes within the cued range in the R5 condition. There was a difference in response time to deviants at the central cue size ($F(1,19) = 10.4$, $p < .005$), such that responses in the R5 condition were faster than in the R1 condition. This further supports the conclusion that targets in the center of the cued range were identified more quickly when more sizes were cued. There was no difference between the response times and only a trend towards a difference in response rate at different distances within the cued range for the R5 condition (RT: $F(4,76) = 0.5$, $p = .676$, RR: $F(4,76) = 2.3$, $p = .098$), and thus no indication from the behavioral data of a gradient of attention within the cued range.

There was a main effect of cue range on responses to standards ($F(1,19) = 8.0$, $p < .05$), such that a greater number of responses occurred in the cue five condition compared to the cue one condition. This is reasonable as there was a larger range of cued sizes and thus a greater potential to misclassify standards as targets.

ERP Results

Three main comparisons were conducted on measurements taken in each time window of the evoked waveforms. Comparisons were made on the amplitude evoked by standards presented in the two cued ranges (Figure 23), standards at varying size distances from the central cued size (Figure 24), and the interaction between these two

factors. The results are divided into time windows in which ERP waveforms were measured.

To confirm that the planned collapse across the large and small halves of standard sizes was not problematic, a comparison was made of all 16 standard sizes based on whether cues fell in the small or large half of the range of sizes. In this analysis, subject group (whether subjects received the cue range of 1 in the small half and cue range of 5 in the large half, or the reverse) was a between-subjects factor. ERPs evoked by standards in each stimulus size for the two groups of participants are shown in Figure 25. For the P1, N1, early SN, late SN, and P3 there was an interaction between the standard size and whether the cue occurred in the small or large half of possible sizes (P1: $F(15,270) = 2.1$, $p < .05$; N1: $F(15,270) = 2.2$, $p < .05$; SN early: $F(15,270) = 5.3$, $p < .001$; SN late: $F(15,270) = 2.7$, $p < .01$; P3: $F(15,270) = 2.4$, $p < .05$). The clearest pattern of effects was for the early and late SN time windows, which showed greater negativity when the center of the cue was in the same half of item sizes compared to when the center of the cue was in the other half. This effect is analyzed in greater detail in the comparison after collapsing across subject groups. For the P1, N1, and P3 time windows the pattern of facilitation was less clear, but did not contradict the choice of collapsing over the halfway point of sizes. Further, the evoked potentials were not so drastically different based on stimuli size that they would preclude averaging across the two halves of sizes. The three way interaction between subject group, item size, and center of the cued range location was not significant for any of the tested time windows (p's > .1). These results support the planned collapse over the two subject groups to

allow the direct comparison between the cued and uncued halves of the item sizes for the remaining tests.

For the P1 time window there was a main effect of cue range ($F(1,19) = 5.2$, $p < .05$), such that greater positive amplitude was evoked in the R5 compared to the R1 condition. This cue range difference was present for all standards in the stream, as cue range effect did not interact with whether standard size were in the cued or uncued half ($F(1,19) = 1.4$, $p = .245$). Reduced P1 amplitude in the R1 condition suggests that the scale of spatial attention may be used to inhibit areas of the visual field that fall outside of the cued size, and that this inhibition may be more active when fewer sizes are being monitored. The main effect of whether standards were within the cued or uncued half was also considered. There was a trend towards an effect of cue half ($F(7,133) = 3.5$, $p = .077$), such that standards within the CH evoked a slightly more positive mean amplitude than in the UH. There was also an interaction between item size and cue half ($F(7,133) = 2.5$, $p < .05$), such that only standards at S2, S6, and S7 evoked a more positive mean amplitude in the CH than the same sized standards on the UH (S2: $F(1,19) = 9.5$, $p < .01$; S6: $F(1,19) = 7.1$, $p < .05$; S7: $F(1,19) = 7.3$, $p < .05$). All other item sizes did not show a significant difference (p's $> .1$). Due to the small amplitude differences and inconsistent pattern of facilitation, the P1 results are difficult to interpret.

For the N1 time window there was no main effect of cue range, and no interaction between cue range and cue half (Range: $F(1,19) = .7$, $p = .428$; Range vs. Half: $F(1,19) = 0.002$, $p = .969$). There was a trend towards an effect of cue half ($F(2,38) = 3.4$, $p = .081$), such that items within the CH evoked slightly greater negativity than those in the UH. This cuing effect did not interact with item size ($F(7,133) = 1.2$, $p = .324$). The N1

showed modulation for items similar to the cued size, but the limited magnitude of this effect makes it difficult to interpret. One possibility is that amplitude in the N1 time window reflected the onset of the SN, resulting in modulation that was too small to induce statistical significance.

The more consistent size-based attention effects were seen in the early and late SN time windows, shown in Figure 26. For the early SN time window (200-250 ms) there was a main effect of cue half such that standards within the CH evoked more negative amplitude than standards within the UH ($F(1,19) = 35.6$, $p < .001$). In addition, there was an interaction between cue half and standard size, indicating that not all standard sizes were modulated equally ($F(7,133) = 2.6$, $p < .05$). Individual contrasts revealed that mean amplitude was more negative on the CH compared to the UH for all sizes except S6 and S8 (S1: $F(1,19) = 10.4$, $p < .001$; S2: $F(1,19) = 6.7$, $p < .05$; S3: $F(1,19) = 18.1$, $p < .001$; S4: $F(1,19) = 21.7$, $p < .001$; S5: $F(1,19) = 13.7$, $p < .005$; S6: $F(1,19) = 0.1$, $p = .836$; S7: $F(1,19) = 4.0$, $p = .059$; S8: $F(1,19) < 0.1$, $p = .999$). This suggests a relatively broad area of facilitation that extended asymmetrically from the central cued size towards the edge of the set of sizes. It is difficult to determine whether this broad facilitation fits a gradient distribution model. There is no evidence of a dropoff in facilitation from the center of the cued area towards the edge of possible sizes, which suggests a gradient would not adequately describe the pattern of modulation. Instead, the difference between the sizes on the cued and uncued sides spread relatively uniformly towards the edge of the range of possible sizes. Conversely, as sizes get closer to the median of the size set (closest at S8) the size differences are reduced between the cued and uncued sides. Overall, the pattern of facilitation suggests a broad range of selection

around the cued size that spreads to all items with a large size disparity between cued and uncued sides.

For the later SN time window (250-300 ms) there was also a main effect of cue half and an interaction between cue half and standard size (Half: $F(1,19) = 6.5$, $p < .05$; Half vs. Size: $F(7,133) = 2.8$, $p < .05$). The extent of facilitation was more narrow than for the early SN, with an effect of cue side only at standard sizes S3, S4, and S5 (S1: $F(1,19) < 0.1$, $p = .932$; S2: $F(1,19) = 1.7$, $p = .205$; S3: $F(1,19) = 6.4$, $p < .05$; S4: $F(1,19) = 10.7$, $p < .005$; S5: $F(1,19) = 5.6$, $p < .05$; S6: $F(1,19) = 0.1$, $p = .767$; S7: $F(1,19) = 2.0$, $p = .178$; S8: $F(1,19) = 0.2$, $p = .625$). Similar size-based selection is occurring in the late SN as the early SN, but in the later SN the facilitated range of sizes is more narrowly focused on the sizes nearest the center cued size. This narrowing of selection is evident in reduced facilitation even for items with the greatest size disparity between the cued and uncued halves; namely S1 and S2. To determine the reliability of the differences between the early and late SN, a separate ANOVA was run including both time windows, resulting in a trend towards a three way interaction between time window, attended side, and item size ($F(7,133) = 2.6$, $p = .058$). It is unclear whether the differences between the early and late SN indicate two separate stages of processing, or a single stage of processing that concludes earlier sizes more distant from the cued size.

For both the early and late SN time windows there was no main effect of cue range, no interaction between cue range and cue half, and importantly no interaction between cue range, cue half, and standard size (p's > 0.1). The lack of a cue range effect in the SN time window suggests that perceptual facilitation is similarly distributed whether 1 or 5 sizes were cued.

For the P3 time window there was no effect of cue range, cue half, or interaction between the two (Range: $F(1,19) = .8$, $p = .360$; Half: $F(1,19) = .2$, $p = .656$; Range vs. Half: $F(1,19) = 1.8$, $p = .191$). The lack of P3 modulation is surprising, but may reflect the difficulty of discriminating sizes relative to shapes in this experiment. If shape (difference between standards and deviants) information was used as a filter for determining which standards received processing at the level indexed by amplitude in the P3 time window, this may have reduced P3 modulation based on cue size. In other words, perhaps none of the standards received appreciable levels of processing as indexed by the P3 since they had all been ruled out as potential targets based on shape.

Discussion

There were three main questions addressed with Experiment 5. First, for a discrimination task at a known location, would size based attention result in modulation of ERPs in time windows known to reflect perceptual processing differences? Second, would modulation occur in the P1 and N1 time windows indicative of space based selection, or in the SN time window indicative of feature based selection. The answers to these first two questions were clearly demonstrated in the ERP data; there was modulation based on the cued size(s) in both the early and late SN time windows, indicating feature-based selection similar to the color selection seen in Experiment 4. Finally Experiment 5 was designed to demonstrate the distribution of size-based attention, whether it is distributed as a gradient across items similar to the cued size(s), and whether the distribution of selection can be adjusted to match the range of cued sizes. There was evidence for a spread of selection to items whose sizes were close to the

central cued size, similar but not identical to a gradient distribution, but no evidence of an impact of the range of cued sizes.

The behavioral data indicated that participants were able to perform the task and could discriminate between the presented sizes. There was a gradient of response rate around the central cued size for both the large and small cue ranges. This parallels previous studies demonstrating a gradient of response time benefits for sizes near a cued size (Larsen & Bundesen, 1978; Cave & Kosslyn, 1989). There was also an effect of the range of cued sizes, such that there were more responses at all locations surrounding the cue in the large compared to the small cue condition. This reflects both the broader window of sizes classified as targets in the large cue condition, and the greater certainty of a target being of an appropriate size when it appeared in the center of the cued range.

One question was whether ERP modulation based on attention to size would occur in the P1 and N1 time windows indicative of spatial selection. The possibility of attention effects in this time window is particularly interesting given the finding by Heinze et al. (1998) of P1 modulation in a local/global attention task. While both the P1 and N1 time windows showed small amplitude modulation for sizes similar to the cue, there was not sufficient evidence to indicate that spatial attention was the primary mechanism of size selection. The data generally supports the theory posited by Heinze et al. (1998) to explain P1 modulation in a local/global task, that spatial attention may be recruited to assist in size selection. For instance, when monitoring the fixated stream for smaller items there may be some inhibition of the peripheral visual field to reduce the processing of larger items. Likewise, when monitoring a larger size attention may be shifted to the periphery and the foveal region inhibited. While these adjustments in the

distribution of spatial attention may help inhibit task irrelevant sizes to an extent, it seems the primary mechanism of attention to size does not occur this early in processing. The marginal and somewhat sporadic nature of the modulation of the P1 and N1 suggest that the later SN is the first time window clearly demonstrating selection based on size.

There was evidence for size-based selection in both the early and late phases of the SN time window. The timing of these differences suggests that size selection occurs at roughly the same stage of processing as other types of feature-based selection (Hillyard & Münte, 1984; Vierck & Miller, 2008, Anllo-Vento, Luck, & Hillyard, 1998). The early phase of the SN time window (200-250 ms) showed a sensitivity to size similar to that seen for color in Experiment 4. Specifically, a greater negativity was observed when the cue was at or near the presented item's size, compared to when the cue was much larger or smaller. There was not a clear gradient of selection around the central cued size as there was for color in Experiment 4. Instead, facilitation spread asymmetrically towards sizes close to the edge of the range of presented sizes and away from sizes in the middle of the range. The asymmetry in the spread of SN modulation is likely due to the size differences between the stimuli used in these comparisons. Near the edge of the range of presented sizes there was a greater disparity in size between items on the cued and uncued half of the attended range, while near the middle the size differences between the cued and uncued half were much smaller. This design was a necessary consequence of using only two central cued sizes, which allowed for the comparisons between cue ranges. However, it would be useful for future studies to systematically vary the size difference between the cue and standards, thus determining whether the spread of selection is more accurately characterized as a gradient or as a square wave distribution.

Selective processing indexed by the later phase of the SN time window (250-300 ms) was similar to the early phase, but with a narrower scope. Amplitude in this time window showed facilitation of stimuli with sizes similar to the cue, and an asymmetric spread of facilitation towards the edge of presented sizes. However, the range of facilitated sizes did not extend all the way to the edge of presented sizes as it did for the early SN. This suggests a more narrow feature selectivity in the later phase compared to the early phase of the SN, somewhat in parallel to the more defined gradient of color selection in the latter half of the SN in Experiment 4. The differences in the extent of selection between the two phases of the SN suggest a distribution of attention that becomes more precisely focused over time.

Previous studies have made a distinction between the early and late phases of the SN, suggesting that the early SN indexes perceptual processing specific to the attended feature, while the later SN indexes more feature independent processing (Lange, Wijers, Mulder & Mulder, 1998). Indeed, Harter and Previc (1978) found that attention to spatial frequency results in sharper feature tuning in the latter phase of the SN. It is tempting to interpret the early and late phases of the SN as representing separate stages of processing, but the SN in the current study may simply represent one processing stage that is sustained longer for items closer to the cued feature. Too little is currently known about the relative timing, distribution, and neural sources of different phases of the SN to make definitive claims about whether the early and late phases represent a single process or multiple processes.

One challenge to differentiating processing stages is that it is difficult to determine the neural locus of amplitude differences in the SN time window driven by

attention to size. Differences in a local/global task have been linked to differential activity in the extrastriate cortex (Rijpkema et al., 2008). Specifically, attending to the local level increases the intensity of neural activity in early visual areas, and thus limits the scope of activation to include only cortex representing a small part of the visual field. Conversely, attending to a global level spreads activation out over neurons representing more of the periphery of the visual field, and shows greater activation in higher visual areas with larger receptive fields such as V4. It seems likely that a similar pattern of activation is occurring in the current study during size selection, but it is unclear whether this is the activation responsible for differences in the SN time window. Certainly, the first activations of these early visual areas occur earlier than the observed SN modulation, suggesting that if the SN does index activity in these areas, it is through feedback from higher processing stages. Alternatively, the SN may index the activation of the higher cortical areas mediating activity in the visual cortex. In other words, it is unclear whether the SN represents activity from the source of attentional control or the site of processing facilitation. However, the prominence over posterior electrodes and the graded distribution of selection suggest that modulation of SN amplitude represents perceptual processing differences at the site of attention in the visual cortex.

Modulation of amplitude in the SN time window by size selection suggests interesting similarities between the current experiment and other paradigms that may also be mediated by size-based attention. For instance, in a local/global task, attending to either the local or global aspect of the stimuli resulted in greater amplitude in the SN time window compared to when both features were being monitored simultaneously (Rijpkema et al., 2008). Several studies of attention to spatial frequency show similar

modulation in the SN time window (Harter & Previc, 1978; Lange, Wijers, Mulder & Mulder, 1997). While explanations for the effects in these studies have been based on attention directed towards a spatial frequency or part versus whole, the fact that the timing of ERP effects is similar to cuing stimulus size suggests that a common mechanism may mediate selection in all three paradigms. This observation presents interesting topics for future research, including whether these tasks all modulate attention based on the same feature, and if so, whether attention to size provides the best description of how people are selecting stimuli for attentive processing.

Experiment 5 also addressed the effect of cuing a range of several contiguous sizes on the spread of facilitation. The results of Experiment 4 indicate that amplitude modulation in the SN time window is not sensitive to the range of cued colors. Experiment 5 extends this finding to size based attention. There was no electrophysiological evidence of a broader distribution of size selection when the cued range was increased from one size to five sizes. This was consistent across both the early and late phases of the SN time window. The only time window sensitive to the cue range was the P1, which showed greater positive amplitude for stimuli presented in the large cue range. However this cue range effect did not interact with size difference from the cue, and so cannot be interpreted as an adjustment of the extent of selected sizes. The behavioral data indicate that participants did adjust their responses based on cue range, as there were more responses to deviants at all sizes surrounding the cue in the large compared to the small cue range. Similar to color selection, cue range appears to impact processing later than the SN time window, and prior to the behavioral response. It is unclear when exactly this takes place, as there were no time windows in the ERP

waveform that indexed this stage of processing. It is also possible that fine grained size discriminations were only performed for items that possessed the target shape. However, there were not sufficient data to detect the electrophysiological correlates of shape discrimination, as too few deviants were presented in each condition to allow for meaningful comparisons.

It should be noted that there is an alternative explanation for the present results that does not rely on selection based on item size. Namely, it is possible that rather than selecting directly for item size, that items of differing sizes were perceived as occurring at different distances, or visual depths. There is evidence that attention can be directed to visual depth, incurring the same advantages in response time and mitigation of distractor as spatial attention to location in a two dimensional plane (Marrara & Moore, 2000; Andersen & Kramer, 1993; Theeuwes, Atchley, & Kramer, 1998). These studies have primarily investigated the effects of attention based on depth using stereoscopic depth displays. In the current study there were no stereoscopic depth cues, and no contextual depth cues indicating that items of different sizes occurred at differing distances from the viewer. In addition the random presentation of item sizes discouraged any induction of apparent motion in depth. It is therefore unlikely that participants perceived the stimuli in the current study as occurring at different depths. However, it is possible that some participants viewed the size differences as indicating similarly sized items at differing depths. In order to fully discount this possibility, further studies would be needed in which some conditions included contextual or stereoscopic depth cues to determine if this affects the nature or timing of the allocation of attention.

In summary, Experiment 5 demonstrated selection on the basis of the size of an item when it was presented at a known location. The effects of this size selection were evident in the SN time window, similar to what has been observed for selection based on other features such as color, orientation, and motion. Amplitude in the same time window is also modulated in local/global tasks and those requiring attention to a spatial frequency, suggesting that size may be the critical selection feature in all of these tasks. Size selection was found to spread to items with sizes close to the cued size(s), and this spread was most pronounced for items at the extreme large and small end of the set of sizes used. The extent of the spread of selection was similar for both a single cued size and a range of cued sizes, suggesting that the SN is not sensitive to adjustments in the range of cued sizes. Future studies will be needed to determine if the distribution of size selection can be adequately described by a gradient of selection, and to what extent the neural locus of size selection is shared with selection based other features such as color.

CHAPTER VII

GENERAL DISCUSSION

The goal of the current set of studies was to examine how attention is allocated across a number of salient visual features. The initial experiments presented evidence in favor of two stages of spatial attention. Experiment 1 demonstrated an automatic gradient of spatial selection around a cued location indexed by the N1. Experiment 2 showed that changing the scope of the attended area based on task demands occurs at a later stage of processing, most clearly indexed by amplitude of the N2. Experiment 3 addressed the impact of object boundaries on these two stages of spatial selection. Experiments 4 and 5 addressed whether feature-based attention also shows a gradient of selection and a sensitivity to cue range.

Experiment 3 investigated the impact of object boundaries on the distribution of spatial attention. Great strides have been made in describing the distribution of spatial attention; however we do not fully understand how a complex visual scene interacts with task demands to determine the distribution of attention. One important aspect of visual scenes that clearly impacts the distribution of attention is the presence of object boundaries. Research on object-based attention suggests that the attended area automatically scales to fit the size of a presented object (Egly, Driver, & Rafal, 1994; Chen & Cave, 2006; Martinez et al., 2006). This scaling provides a processing advantage for stimuli within an object if part of that object is attended. However it is still unclear to what extent top-down mechanisms can control the size of the attended area when task demands do not match the size of a presented object; for instance when a part of an object is cued compared to the entire object.

The aim of Experiment 3 was to leverage knowledge of the two stages of spatial attention indexed by the N1 and N2 time windows to determine the effect of object boundaries on the gradient distribution and zooming of attention. Neither the type of object boundary or the range of locations cued impacted amplitude in the N1 time window. Experiment 3 did not provide sufficient evidence to determine whether object boundaries shaped the distribution of the gradient of attention, but the lack of effects in the N1 time window suggests that the center of the gradient of selection is reoriented to the center of mass of an attended object. This is supported by studies demonstrating an enhanced allocation of attention based N1 modulation toward the uncued end of a cued object (He et al., 2004, Martinez et al., 2006; Martinez et al., 2007). Preferential processing for stimuli at locations within the cued size impacted the later N2 time window. This cue size effect did not interact with object boundaries, and suggests that the N2 time window indexes a stage of processing that is sensitive to whether the stimulus falls within a possible target location, and is independent of the object information in the scene. These findings further reinforce the proposition from Experiments 1 and 2 that spatial attention has two stages of selection, an early automatic gradient of selection, and a later stage that is adjusted to match task demands.

One aim of Experiment 4 was to determine whether the gradient and adjustable range properties of spatial selection are also seen in attention based on color. While a wealth of research has addressed the distribution of spatial attention under a broad range of conditions, not as much is known about the distribution of attention on the basis of nonspatial features, such as color. Attention based on color has predominantly been investigated in situations in which the stimuli are drawn from a limited color gamut

(Hillyard & Münte, 1984; Anllo-Vento, Luck, & Hillyard, 1998; Vierck & Miller, 2005; Vierck & Miller, 2008). Within these sparsely probed color spaces, it has not been possible to establish whether there is a gradient of facilitated processing for items similar to the attended color, or if a range of colors can effectively be selected. A study by Stroud, Menneer, Cave, and Donnelly (2012) used a dense color gamut of items in a search task to demonstrate a gradient in fixation probability to colors similar to the target color. Experiment 4 addressed whether this gradient in fixations during search is driven by perceptual processing differences, and if a similar gradient of selection is present when stimuli appear at a known location.

The goal of Experiment 4 was to determine the distribution of attention to color, both when a single color is cued and when a range of colors is cued. The first test addressed whether there is a gradient of color selection for stimuli presented at fixation. There was evidence of a gradient of color selection that was indexed by amplitude difference in the SN time window. The second test addressed whether a range of colors can be effectively selected, and if selecting a large range of colors impairs color selectivity. While the behavioral data indicated that participants were able to use the range of cued colors to guide their responses, the range of cued colors did not affect amplitude in the SN time window. This suggests that the distribution of the gradient of color selection was relatively automatic, and was not adjusted to fit the cued range. The SN data for Experiment 3 paralleled the N1 results of Experiment 1, suggesting both spatial and color selection are distributed in a relatively automatic gradient.

Experiment 5 addressed whether attention to size would show the same distribution of selection as attention based on color. As with color, many of the studies

investigating attending based on the feature of size have included a limited set of sizes, often just two or three different item sizes (Poder, 2001; Heinze, Hinrichs, Scholz, Burchert, & Mangun, 1998; Rijpkema, Aalderen, Schwarzbach, & Verstraten, 2007). Larsen and Bundesen (1978) used a denser set of item sizes to demonstrate that response times increased with the difference between the expected and actual size of a presented item, and postulated that this was due to the time needed to rescale attention to fit the size of the new object. In addition, while attention to local/global features and spatial frequency have been shown to modulate the SN time window, very little is known about the timing of direct selection based on stimulus size.

Attention based on size, like attention based on color, modulated amplitude in the SN time window. This modulation showed a spread of selection to similar sizes. While the distribution of selection was not definitively graded, it was otherwise very similar to the distributions found for color and spatial selection. Also similar to Experiment 4, the spread of size-based selection in the SN time window was not affected by cued range. The behavioral data indicated that cue range was effectively used to guide responses, suggesting the neural processing necessary for determining whether a stimulus fell within the cued range occurred later than the SN. The overall pattern of results suggests that selection based on size is performed in a similar time frame to other feature based attention tasks.

Comparing the results of all five studies presented here indicates there are some interesting similarities in the distribution of selection across very different visual features. Most prominently, when a small spatial area or a small range of feature values was cued, there was a spread of selection beyond the cued range for all cue types tested. For spatial

attention, this spread was apparent as a gradient of modulation in the N1 time window. A similar gradient of facilitation was observed for attention to color, but was indexed by later modulation of the SN time window. For size based selection there was not a clearly identifiable gradient of selection, but there was a very similar spread of facilitation to nearby sizes indexed by the SN time window. None of these observed gradients of selection were strongly impacted by the range of the cued area. This suggests that the range of the gradient of facilitation was relatively automatic, and was not adjusted to optimally fit the task. Taken together, these studies suggest that an automatic spread of attention is a common property of facilitation across several visual features. While gradients in N1 amplitude for spatial attention have been previously reported, this is to our knowledge the first electrophysiological evidence of modulation in the SN time window indexing a gradient of preferential processing for items with features similar to the cued feature.

A gradient of facilitation could have a number of advantages when attention is used in the wild. In a real scene, there is a significant amount of noise and variability inherent to visual information. For instance, though you may know the color of a particular item you are searching for, the actual color you perceive will be dependent upon the current light source. Similarly, though you may know the size of an item, the visual angle encompassed by the item will vary based on your current distance from the item. If you know roughly the distance you are likely to be from an item you can estimate this size, but a spread of attention to nearby sizes would improve your chances of selecting the right size. The same can be said of spatial selection; while locating a specific area of the visual field for processing may in general be easier than in the cases

of color and size, there is no guarantee that the scene will remain static for very long. If an item shifts after you decide to shift attention but before attention arrives to aid processing, it would be beneficial to still gain some perceptual advantage for the, now recently moved, item. The distribution of attention across all visual features tested appears tuned to account for the noise and variability that is present in the world.

Taking the findings of the current studies together with previous electrophysiological work on visual attention, an interesting picture begins to emerge of the time course of visual selection. Space-based attention seems to have a special place in this hierarchy, as the earliest effects of visual attention are seen for orienting attention to a location in space, in the P1 and N1 time windows. There is some evidence that these two time windows can be further split in terms of their processing, with the P1 indexing inhibition of interfering or unattended locations, while the N1 indexes the facilitation of attended location (Luck et al., 1994). The first two experiments showed that modulation of the N1 follows a gradient distribution. This distribution was fairly consistent across the visual field, extended more below the cued location than above, and was relatively unaffected by the range of cued locations. The N1 is also sensitive to structural information in the visual scene, specifically the presence of object boundaries. This is supported by a number of previous studies that demonstrated an enhanced spread of attention based N1 modulation within object boundaries (He et al., 2004, Martinez et al., 2006; Martinez et al., 2007). Experiment 3 suggests that this object based attention effect is mediated by a shifting of the center of the gradient of spatial attention towards the center of mass of the object. Neither of the feature-based selection experiments showed modulation of the P1 or N1 amplitude that was sensitive to item distance from the cued

feature value. Thus, the N1 seems to reflect a purely spatial orienting of the center of spatial attention, with a surrounding gradient whose location can be impacted by the presence of object boundaries.

After these early time windows indexing spatial attention, ERP effects in the later time windows are more complicated to interpret. In Experiments 2 and 3 there was evidence of modulation in the N2 time window that was sensitive to the size of the cued range. While essentially spatial in nature, this time window could also be interpreted as a indexing whether a stimulus fell within the range of the cued area, and thus had a feature in common with target stimuli. The most parsimonious interpretation of amplitude in the N2 time window is an index of a second round of processing that induces more precise selection for stimuli that are potential targets. Amplitude in this time window was invariant to the presence of object boundaries, as shown in Experiment 3. That modulation was found for the N2 time window suggests that adjusting spatial attention to fit the cue size requires recurrent connections from higher processing areas. Further research is needed to determine how much of a shared attentional network there is for the N1 and N2, and specifically whether both of these time windows index preferential processing in the same areas of extrastriate visual cortex.

Within a similar time frame after stimulus presentation as the N2, Experiments 4 and 5 demonstrated attention to features modulated amplitude in the SN time window. This selection occurred in a later time window than the earliest indexes of spatial attention, which is consistent with previous studies of feature based attention (Hillyard & Münte, 1984; Anllo-Vento, Luck, & Hillyard, 1998; Vierck & Miller, 2005; Vierck & Miller, 2008). The primacy of spatial selection over selection based on features such as

color and size is also seen in studies demonstrating that location is a more effective partial report cue for images held in iconic memory (Von Wright, 1970). In the current studies, feature based attention showed a spread of selection to similar feature values. This spread followed a gradient distribution when color was the critical feature, but a more diffuse spread when selecting based on size. Both size and color selection showed no sensitivity to the range of cued values in the SN time window. This is interesting because it runs somewhat counter to the behavioral findings of Experiments 4 and 5, as well as previous studies using techniques such as eye-tracking to measure feature guided search (Stroud et al, 2012). Modulation of the SN time window showed a gradient extending from the center of the cued area in feature space, while response rate was dependent upon both the center of the cued area as well as cued range. The disparity in cue range sensitivity between the response data and the SN data suggest that the SN time window indexes a stage of selection not strictly tied to target evaluation, and likely represents perceptual processing benefits for items similar to the central cued feature.

Taking into account all of the data discussed above, a hierarchical model of visual attention begins to emerge. Such hierarchical models are not new, but the current studies help to flesh out some of the details about the specifics of selection at each stage of processing. Spatial attention seems to have a special place in this hierarchy as it occurs earlier than selection based on features, and in some cases may be a pre-requisite for selection based on features (Hillyard, 1984). While the impact of orienting spatial attention seems to occur quite early in processing, scaling the size of the area selected does not happen until later, closer to the time range of the SN and feature based selection. One interesting avenue of future research will be to determine if the mechanisms

underlying scaling the attended region are shared with those responsible for attention to features. There are still a number of unanswered question regarding how and when in the hierarchy spatial attention interacts with attention based on features. Specifically, it is unclear whether feature selection at an attended location shares a common mechanism with feature selection across the visual field used to guide spatial attention. By mapping out the shared and differing parameters of these selection stages, their distribution across feature space, as well as how automatic or responsive to task demands they are, we can begin to develop a more complete model of attention that applies in a variety of environments.

TABLES

Table 1. Behavioral response data for Experiment 1.

	Correct response, percentage		False alarms, total[a]		Response times ms	
Position	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
1	78.5	1.9	6.4	2.1	547.5	13.9
2	78.0	2.5	6.0	2.0	541.8	11.9
3	80.3	2.6	2.6	1.0	543.3	16.2
4	74.5	3.7	3.6	1.6	557.1	15.9
5	75.5	3.4	4.9	2.0	562.2	14.7
6	68.3	3.4	5.1	1.8	549.4	16.2
7	75.9	4.4	5.7	2.0	551.4	11.6
8	76.2	3.9	5.2	1.6	553.7	15.4
9	78.5	2.8	3.1	1.1	555.1	15.7
10	81.9	2.6	3.7	1.4	546.9	15.3
11	74.8	3.5	7.2	2.6	554.2	11.7
12	74.5	4.4	7.1	2.7	552.3	12.5

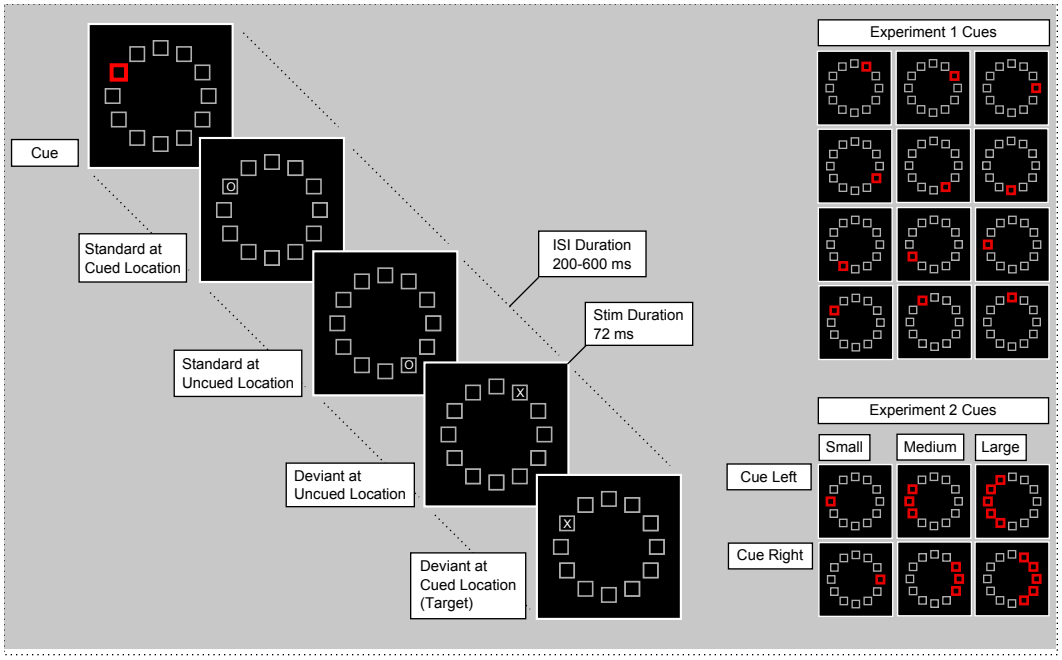
[a]Due to the rapid presentation rate of stimuli, false alarms were calculated for each cue location and not assigned to the appearance of deviants or standards.

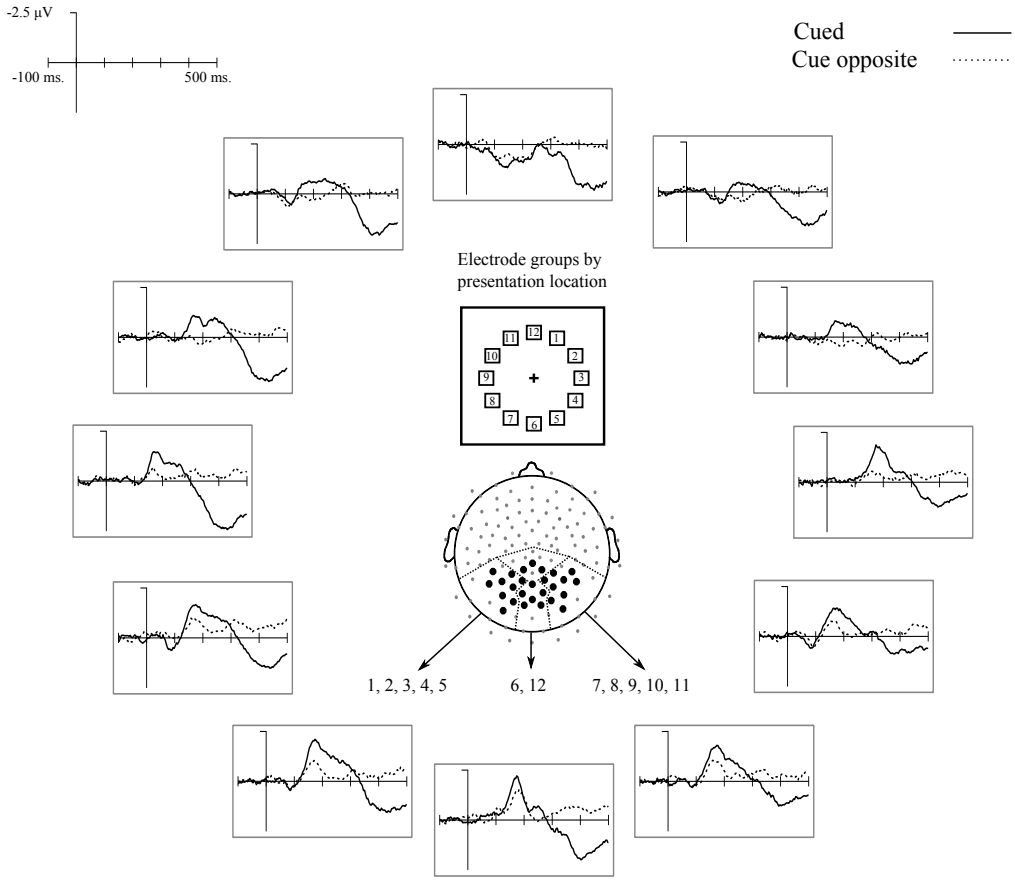
Table 2. Behavioral response data for Experiment 2.

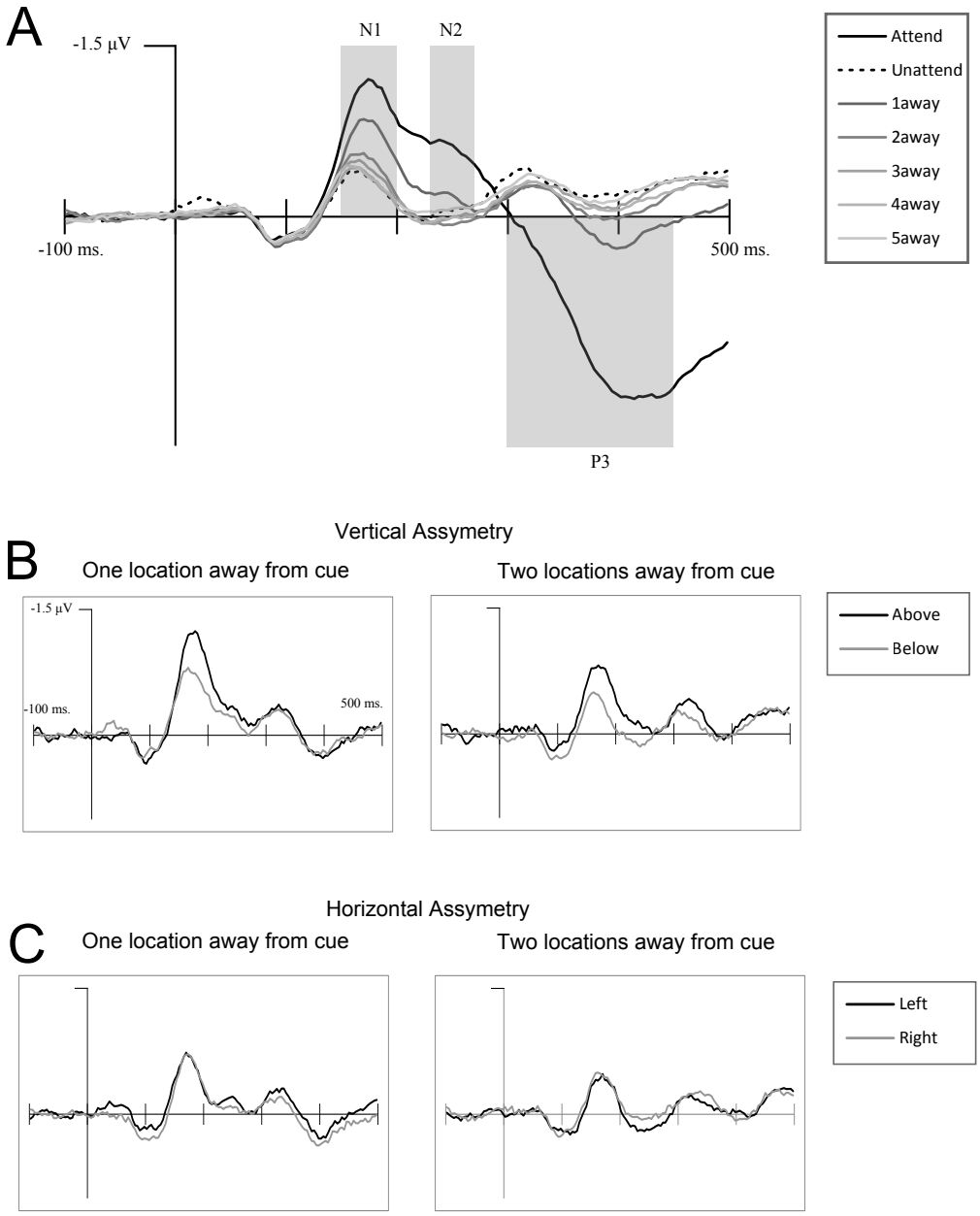
Cue	Target location	Hits, percentage of targets		False alarms, total [a]		Response times ms	
		Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
Small				16.4	3.8		
	Midline	80.3	1.5			501.3	9.5
Medium				33.1	8.2		
	Midline	80.7	1.4			489.7	9.1
	1 away	70	2.9			533.0	11.9
Large				56.1	14.2		
	Midline	79.7	1.8			487.3	11.1
	1 away	70.4	2.5			509.4	12.1
	2 away	52.9	5.2			566.0	11.8

[a] Due to the rapid presentation rate of stimuli, false alarms were calculated for each cue condition and not assigned to the appearance of deviants or standards at a specific location.

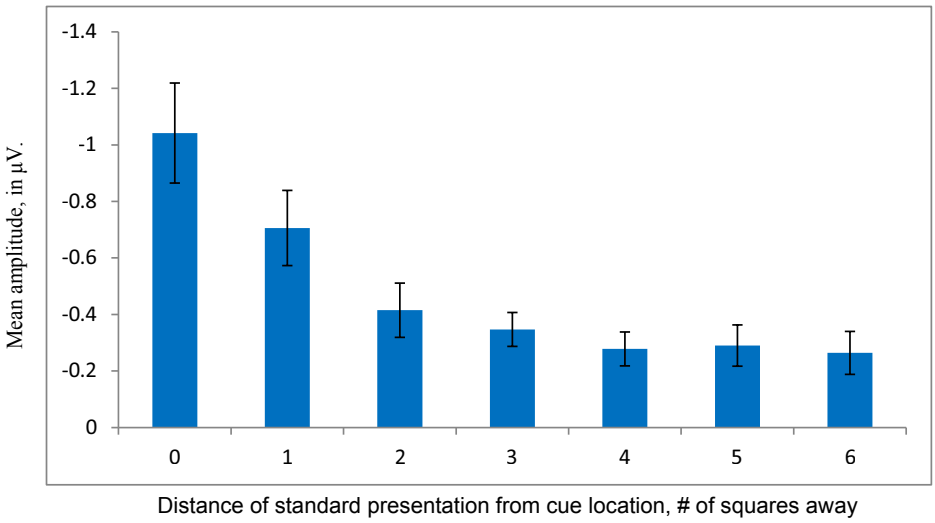
FIGURES


Cue
Standard at Cued Location
Standard at Uncued Location
Deviant at Uncued Location
Deviant at Cued Location (Target)
ISI Duration 200-600 ms
Stim Duration 72 ms
Experiment 1 Cues
Experiment 2 Cues
Small
Medium
Large
Cue Left
Cue Right

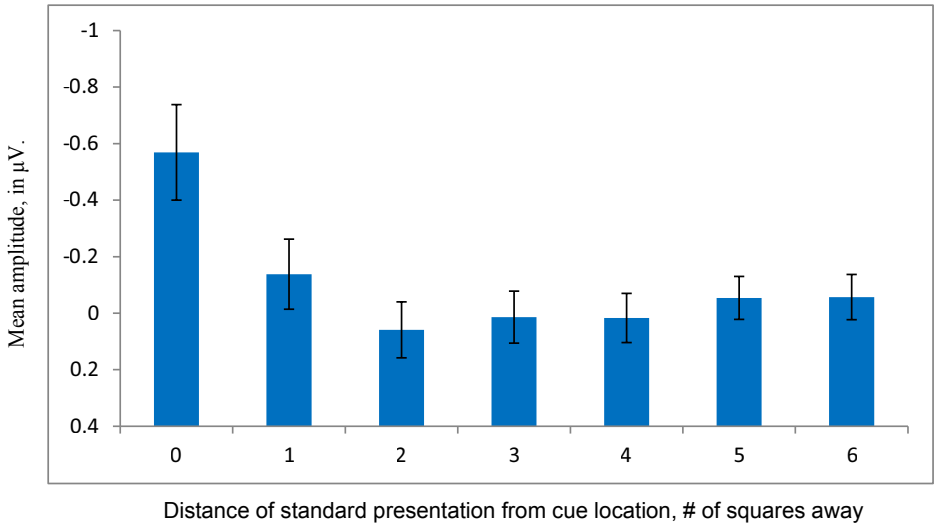

-2.5 µV
-100 ms.
500 ms.
Cued
Cue opposite
Electrode groups by
presentation location
12
1
2
3
4
5
6
7
8
9
10
11
1, 2, 3, 4, 5
6, 12
7, 8, 9, 10, 11


A
-1.5 µV
N1
N2
-100 ms.
500 ms.
P3
Attend
Unattend
1away
2away
3away
4away
5away
Vertical Assymetry
B
One location away from cue
Two locations away from cue
-1.5 µV
-100 ms.
500 ms.
Above
Below
Horizontal Assymetry
C
One location away from cue
Two locations away from cue
Left
Right

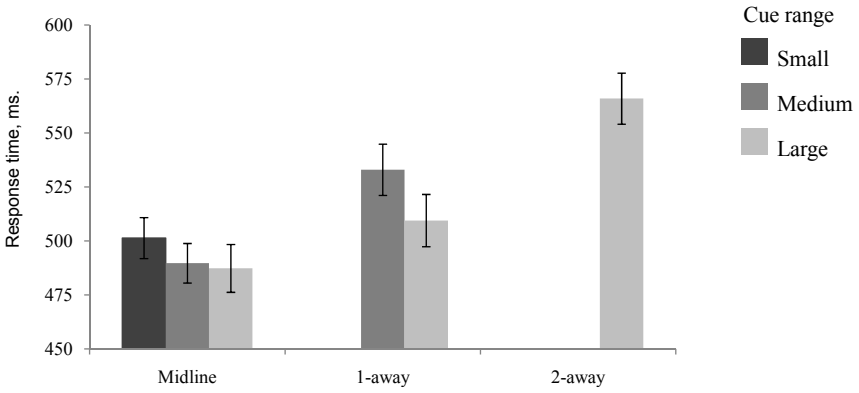
Effects of cue distance on N1 amplitude



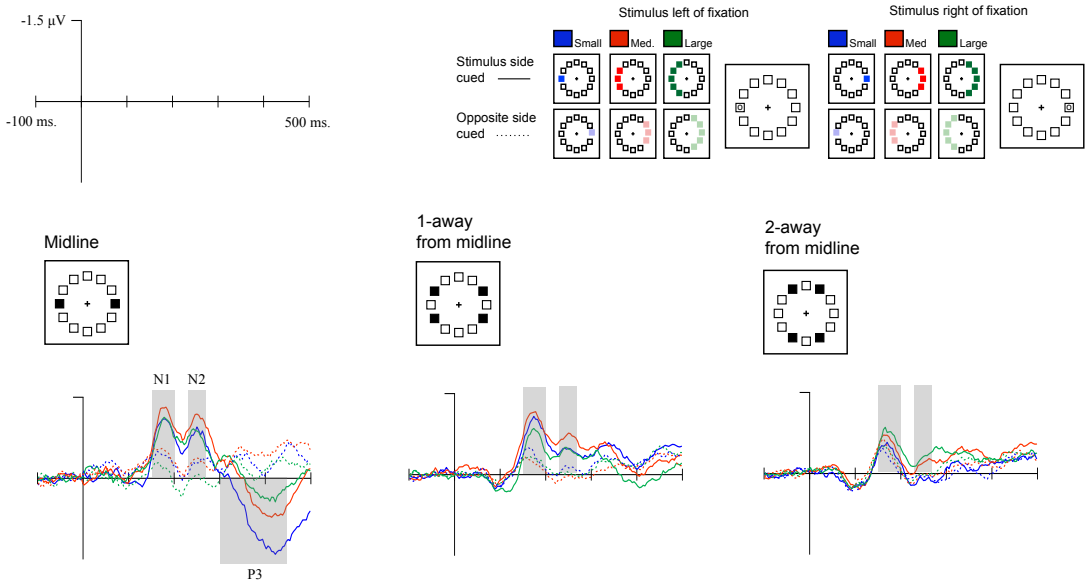
Effects of cue distance on N2 amplitude



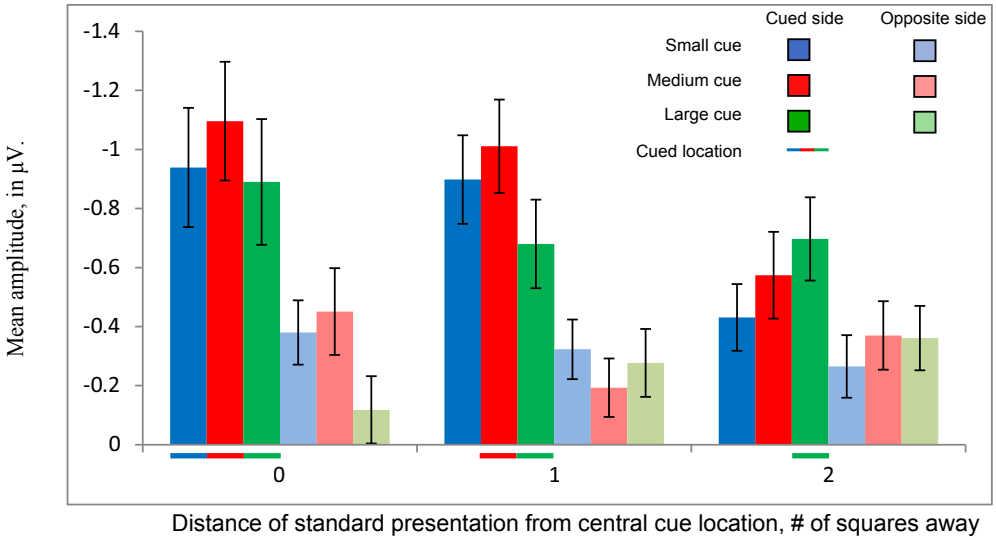
Effect of cue size on response times, exp. 2



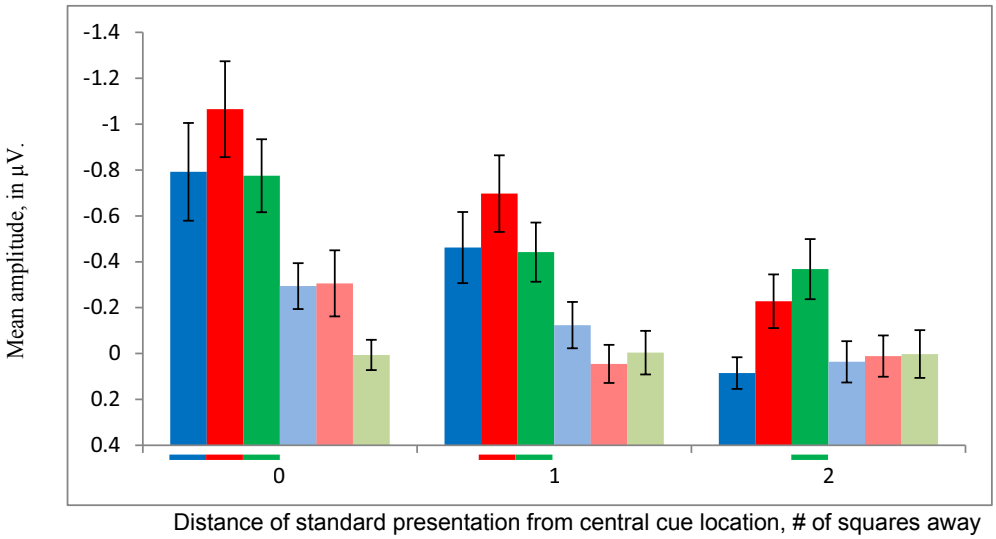
ERPs at contralateral electrodes evoked by standards in all cue conditions

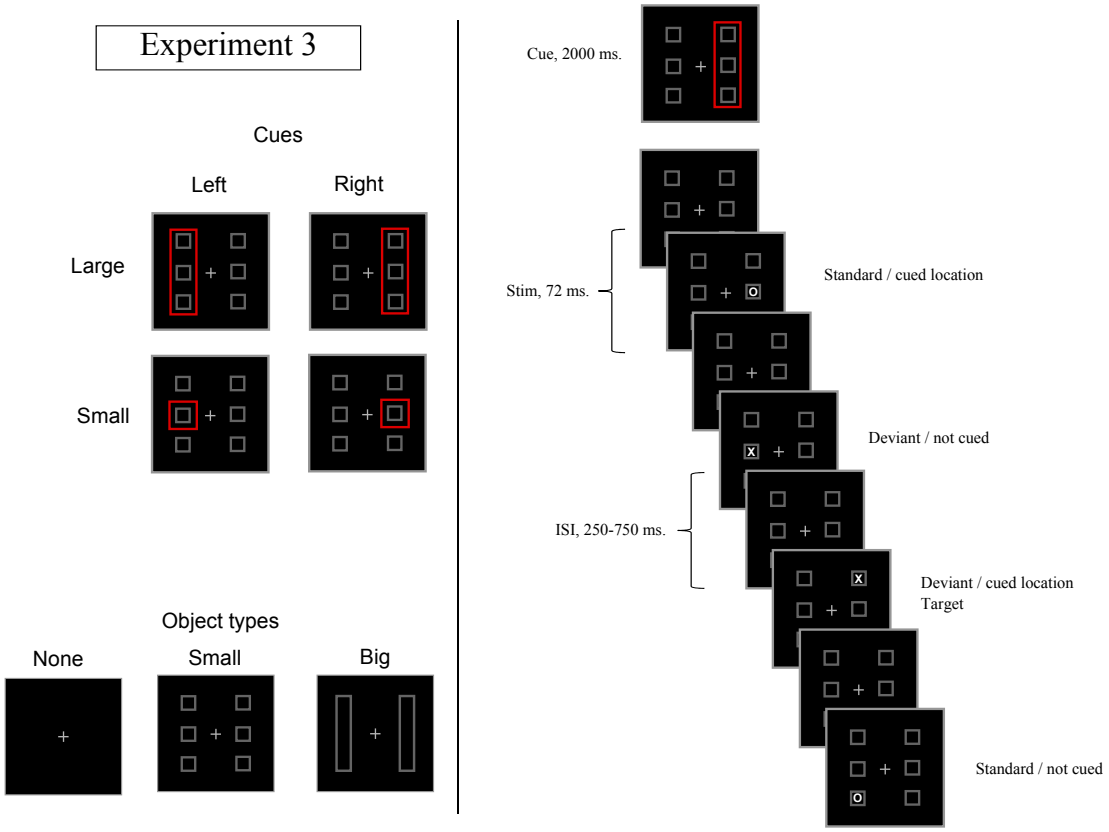


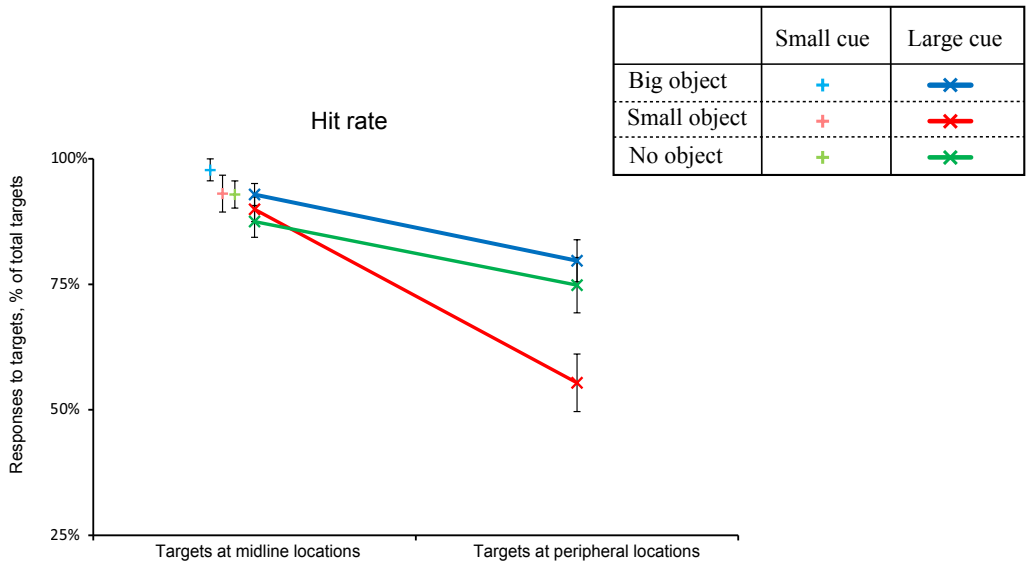
Effects of cue size and distance on N1 amplitude

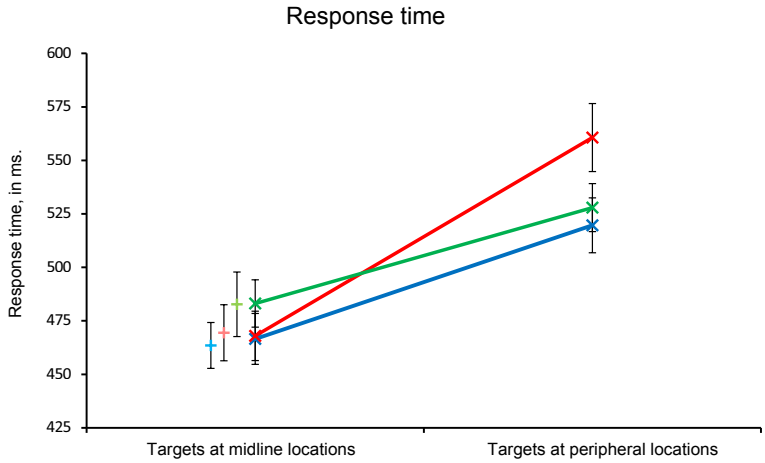


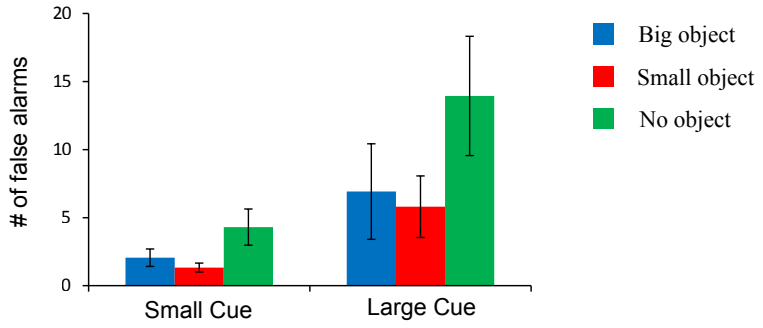
Effects of cue size and distance on N2 amplitude

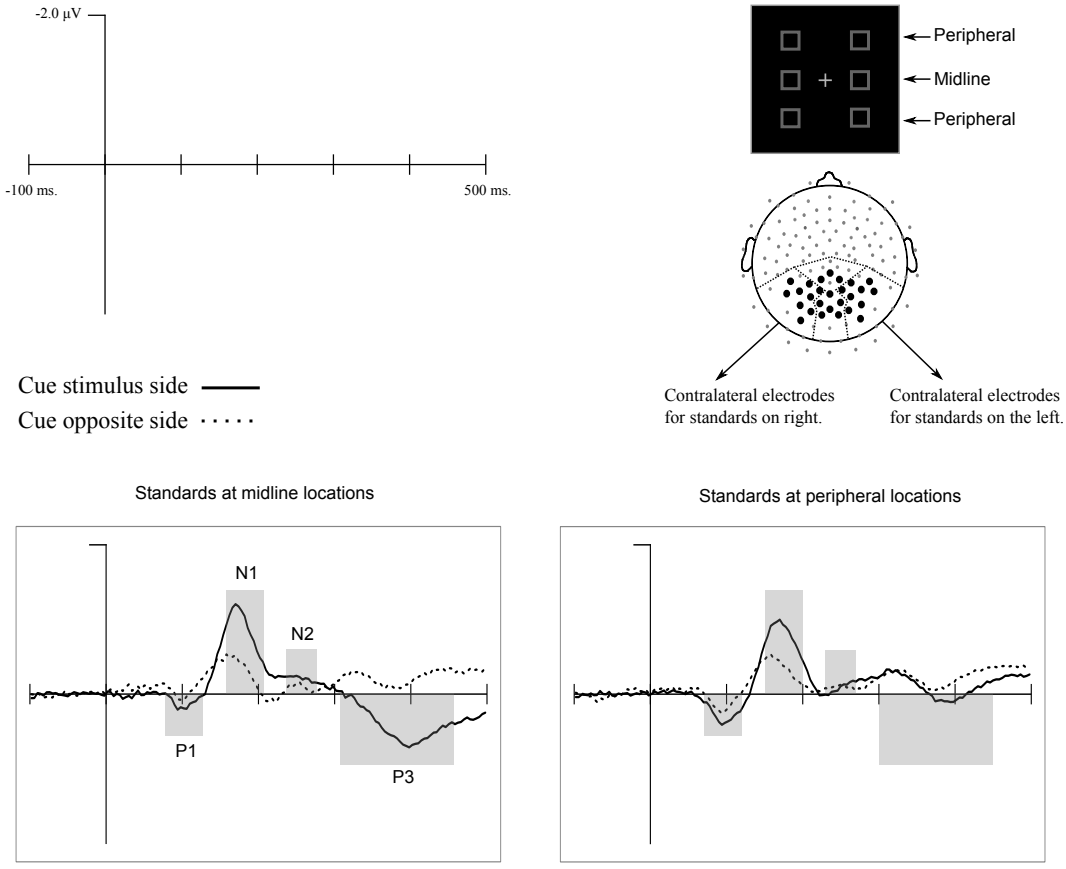


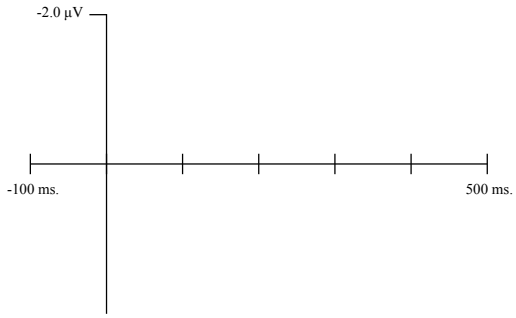

Experiment 3
Cues
Left
Right
Large
Small
Object types
None
Small
Big
Cue, 2000 ms.
Stim, 72 ms.
Standard / cued location
Deviant / not cued
ISI, 250-750 ms.
Deviant / cued location
Target
Standard / not cued


Small cue
Large cue
Big object
Small object
No object
Hit rate
100%
75%
50%
25%
Responses to targets, % of total targets
Targets at midline locations
Targets at peripheral locations


Response time
600
575
550
525
500
475
450
425
Response time, in ms.
Targets at midline locations
Targets at peripheral locations

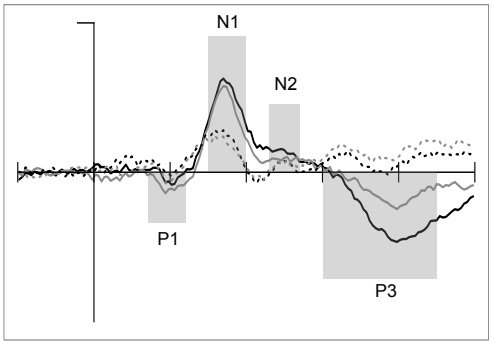

# of false alarms
20
15
10
5
0
Small Cue
Large Cue
Big object
Small object
No object


-2.0 µV
-100 ms.
500 ms.
Cue stimulus side
Cue opposite side
Peripheral
Midline
Peripheral
Contralateral electrodes for standards on right.
Contralateral electrodes for standards on the left.
Standards at midline locations
N1
N2
P1
P3
Standards at peripheral locations

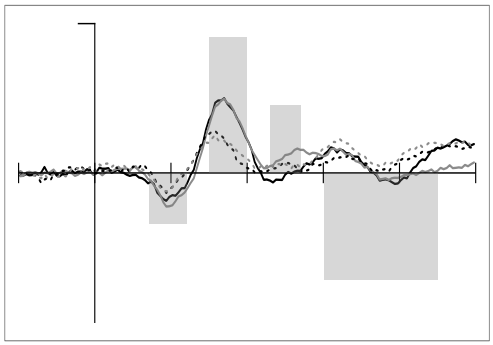


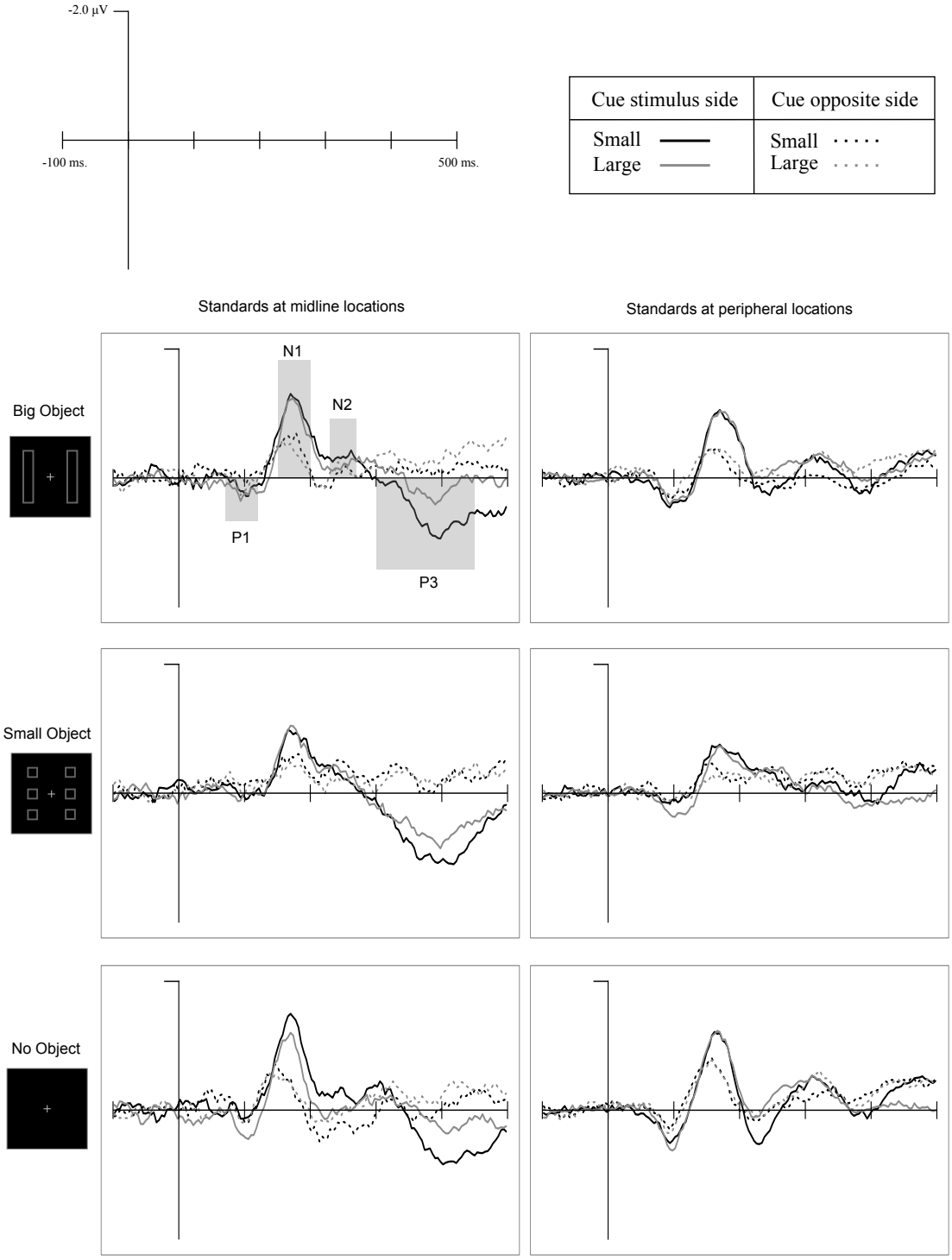
Cue stimulus side	Cue opposite side
Small ——— Large ———	Small ····· Large ·····

Standards at midline locations



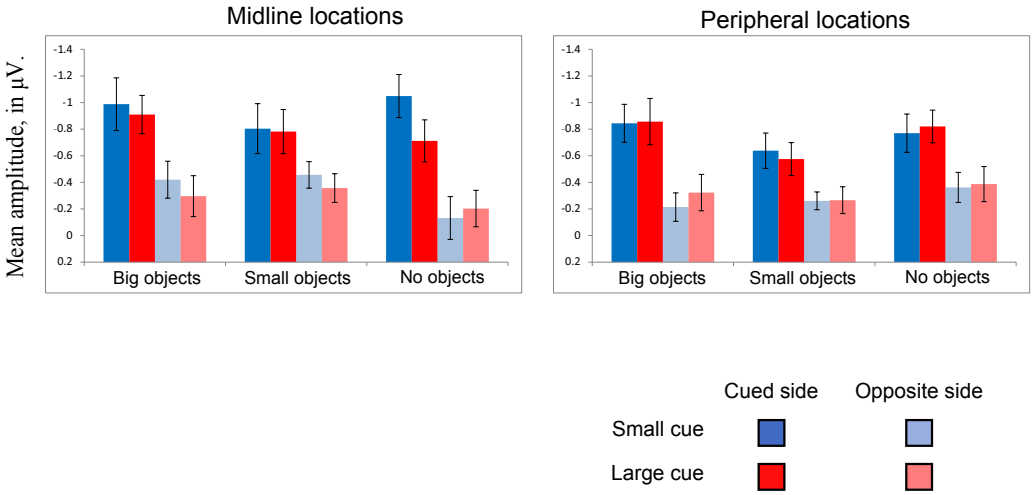
Standards at peripheral locations



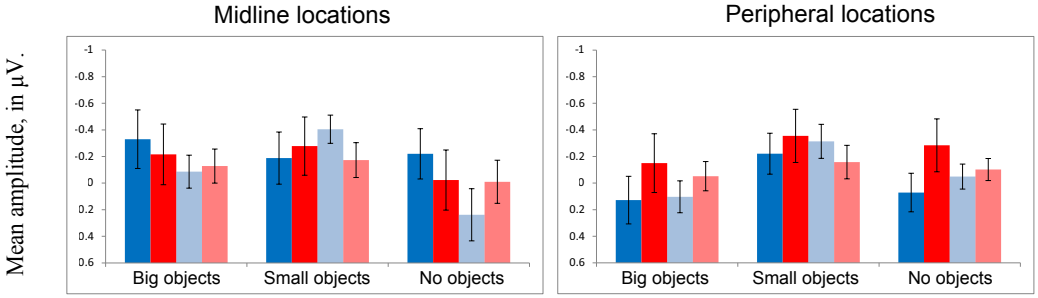

-2.0 µV
-100 ms.
500 ms.
Cue stimulus side
Cue opposite side
Small
Large
Small
Large
Standards at midline locations
Standards at peripheral locations
Big Object
N1
N2
P1
P3
Small Object
No Object

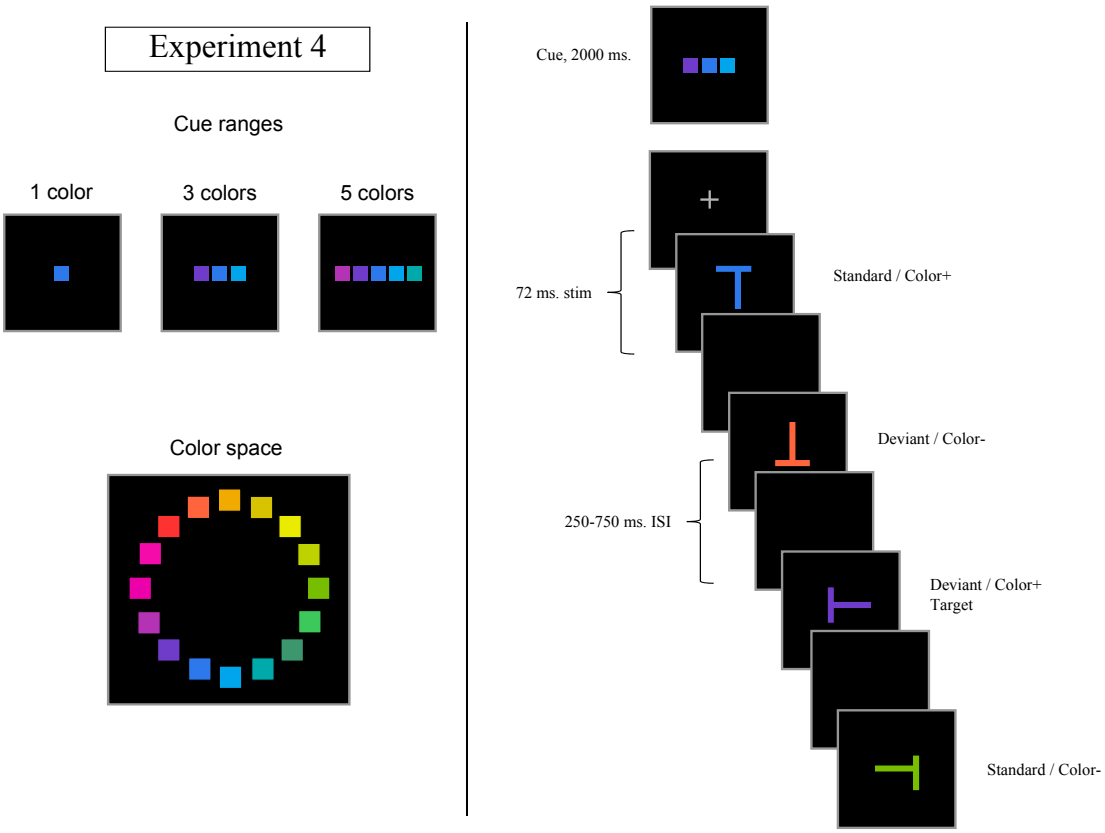
Effects of cue size and object condition

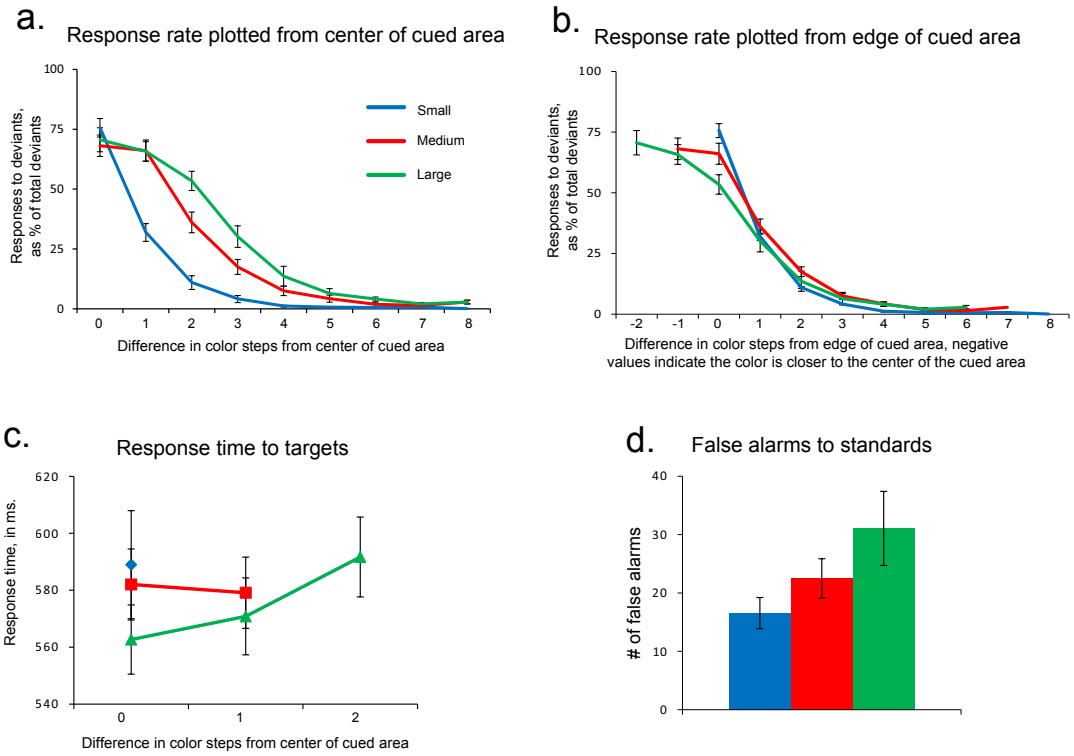
N1 amplitude

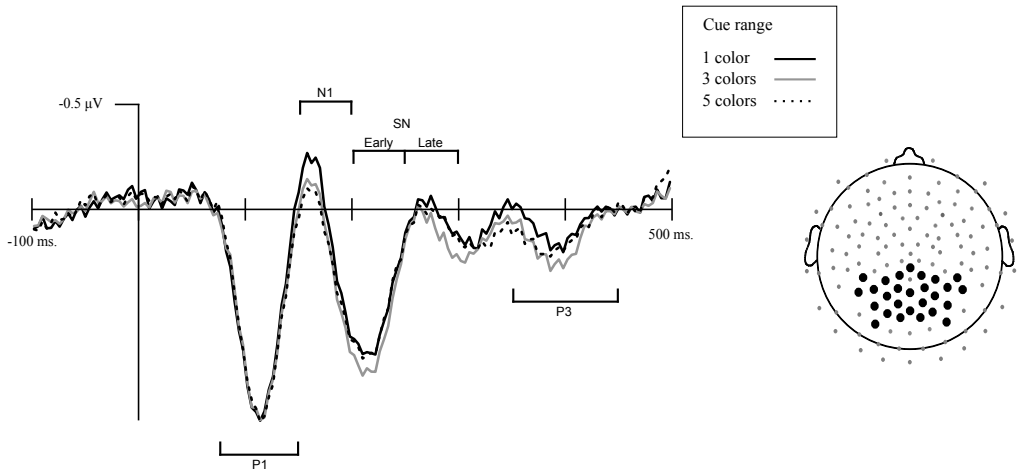


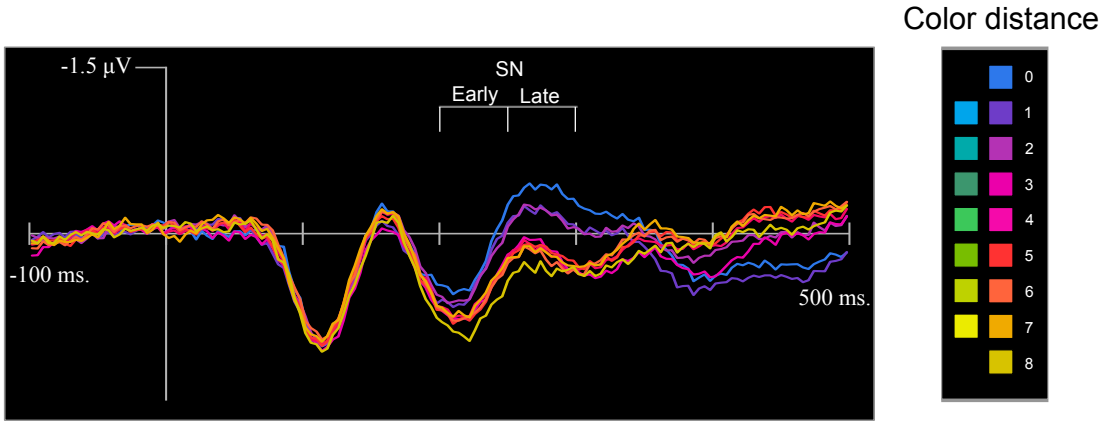
N2 amplitude



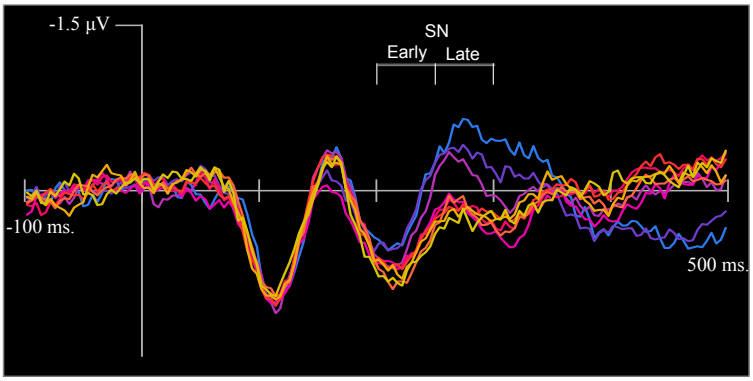

Experiment 4
Cue ranges
1 color
3 colors
5 colors
Color space
Cue, 2000 ms.
72 ms. stim
Standard / Color+
Deviant / Color-
250-750 ms. ISI
Deviant / Color+
Target
Standard / Color-


a.
Response rate plotted from center of cued area
Responses to deviants, as % of total deviants
Small
Medium
Large
Difference in color steps from center of cued area
b.
Response rate plotted from edge of cued area
Responses to deviants, as % of total deviants
Difference in color steps from edge of cued area, negative values indicate the color is closer to the center of the cued area
c.
Response time to targets
Response time, in ms.
Difference in color steps from center of cued area
d.
False alarms to standards
# of false alarms

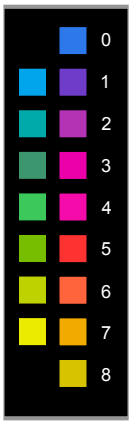

Cue range
1 color
3 colors
5 colors
-0.5 µV
N1
SN
Early
Late
-100 ms.
500 ms.
P3
P1


Color distance
-1.5 µV
SN
Early
Late
-100 ms.
500 ms.
0
1
2
3
4
5
6
7
8

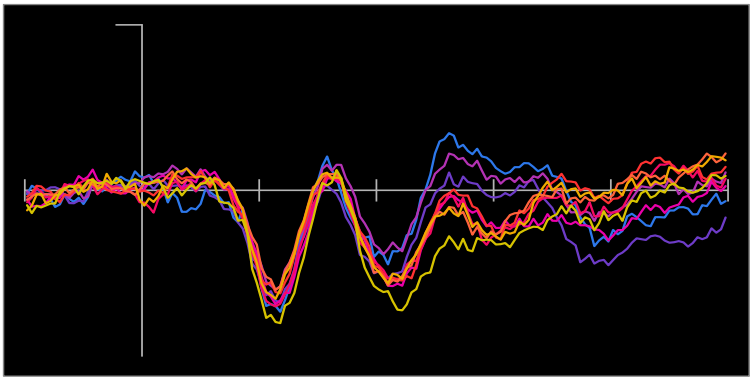
Cue range 1



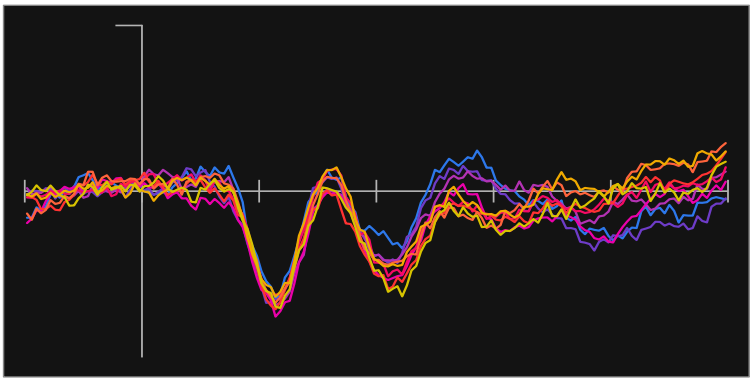
Color distance



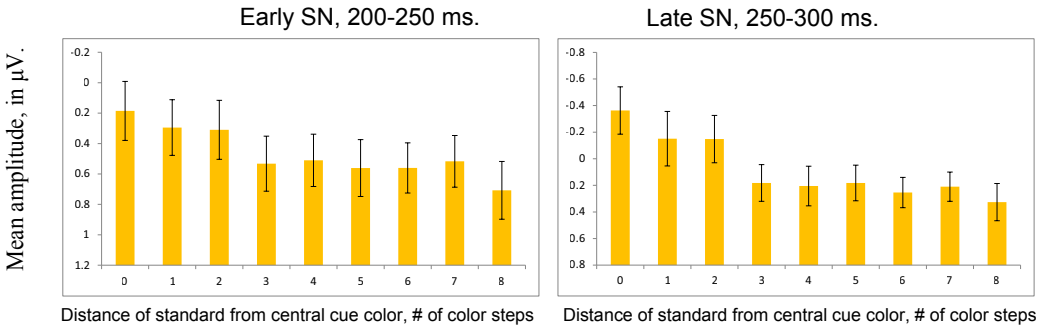
Cue range 3



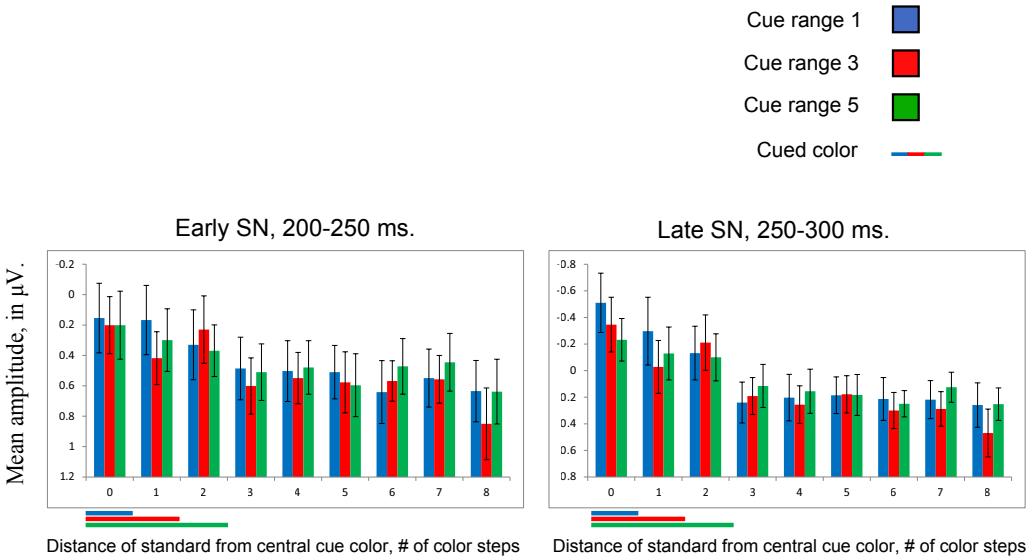
Cue range 5



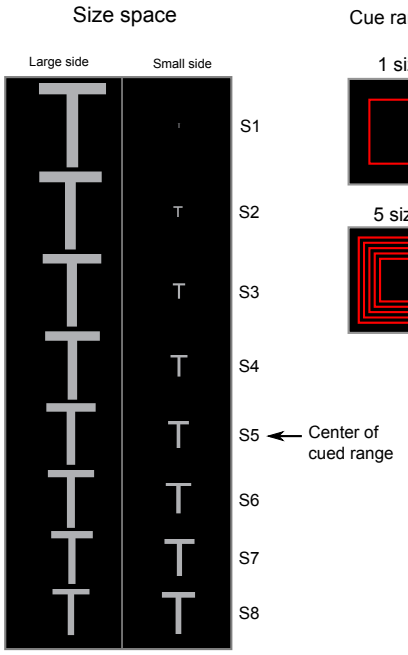
Effects of cue distance on SN amplitude

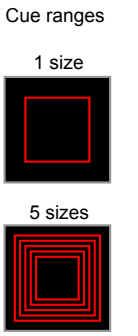


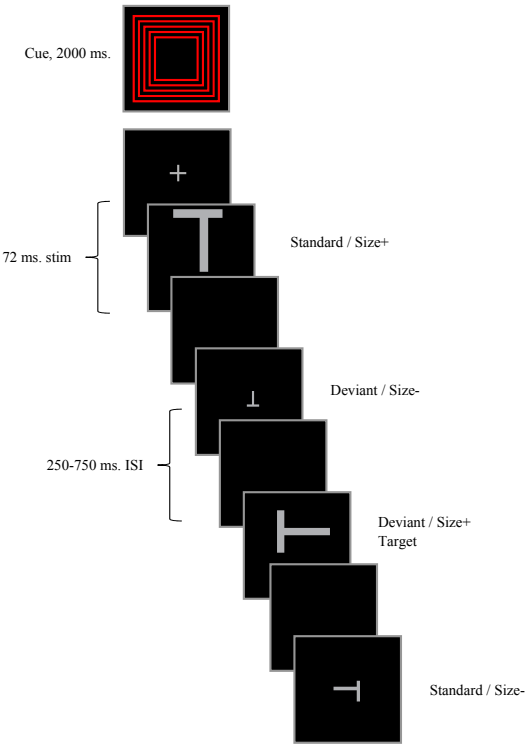
Effects of cue distance and range on SN amplitude



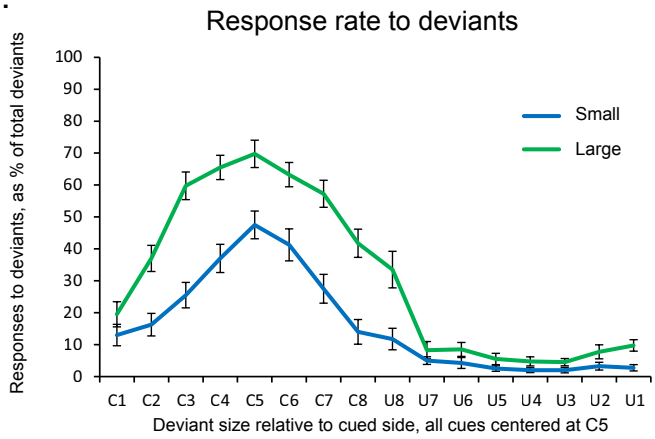
Experiment 5



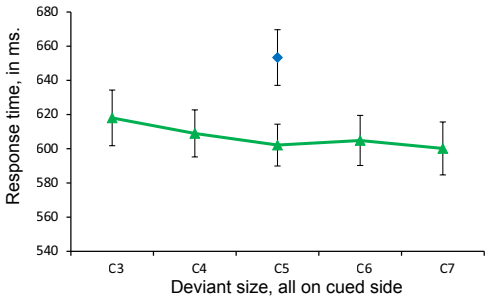




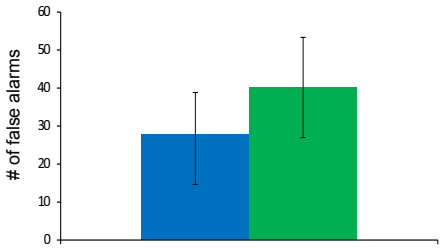
a.

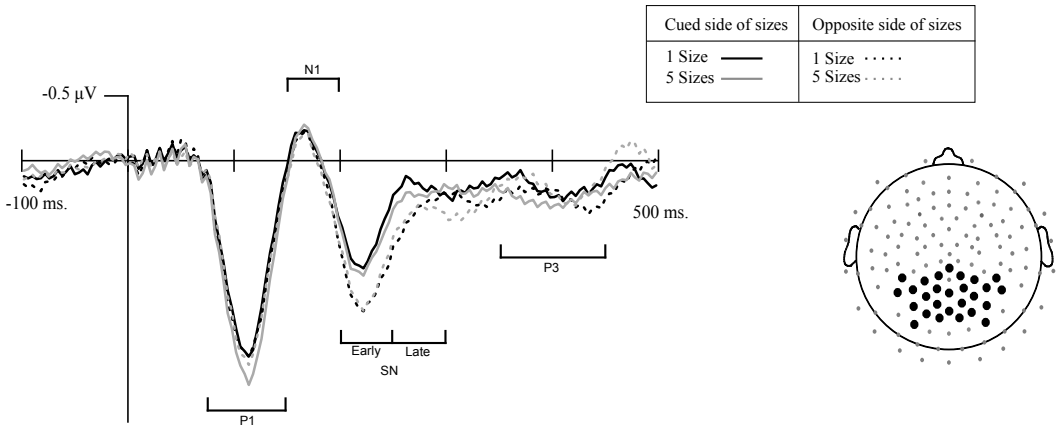

Response rate to deviants
Responses to deviants, as % of total deviants
100
90
80
70
60
50
40
30
20
10
0
Small
Large
C1 C2 C3 C4 C5 C6 C7 C8 U8 U7 U6 U5 U4 U3 U2 U1
Deviant size relative to cued side, all cues centered at C5

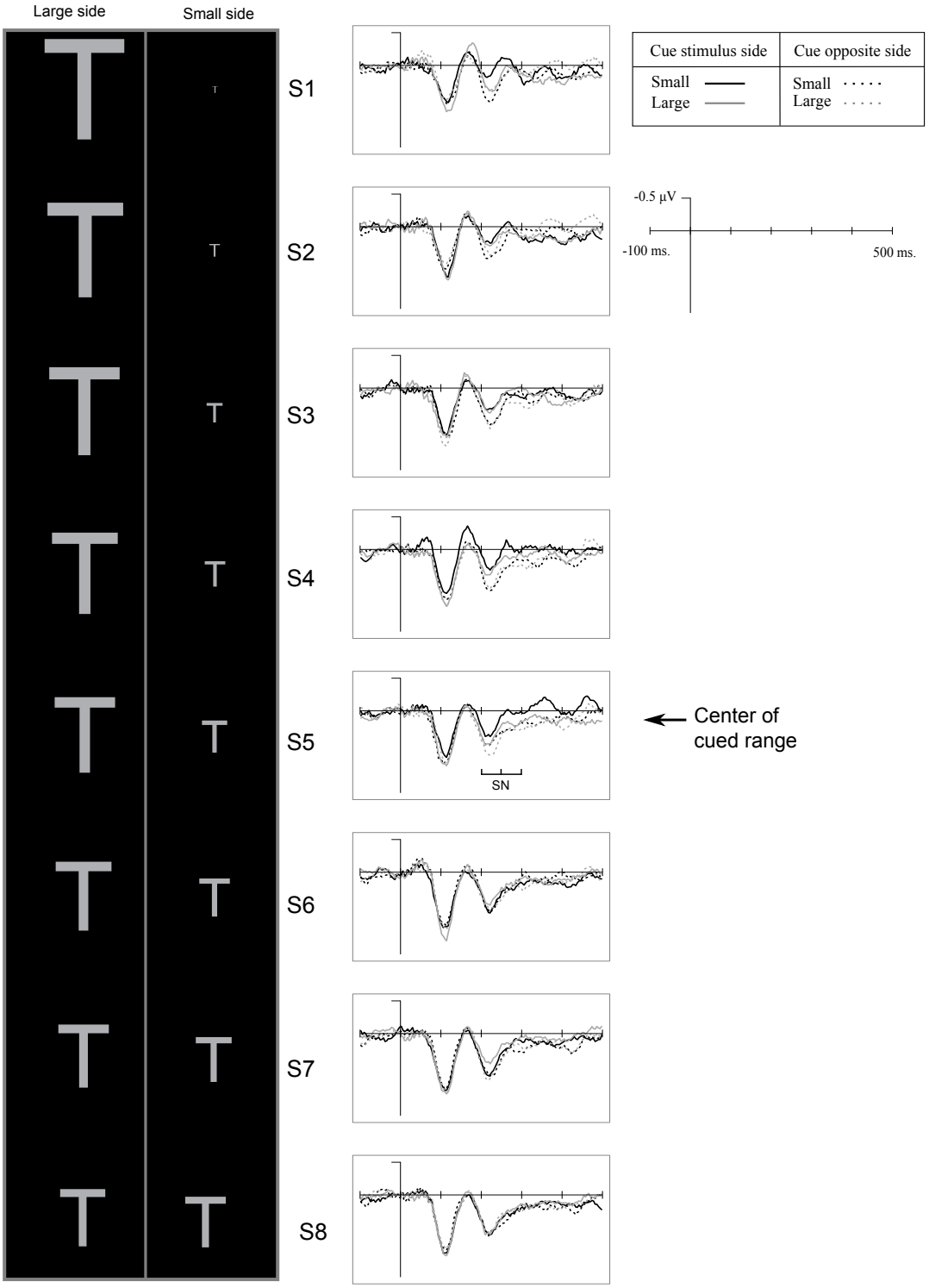
b.

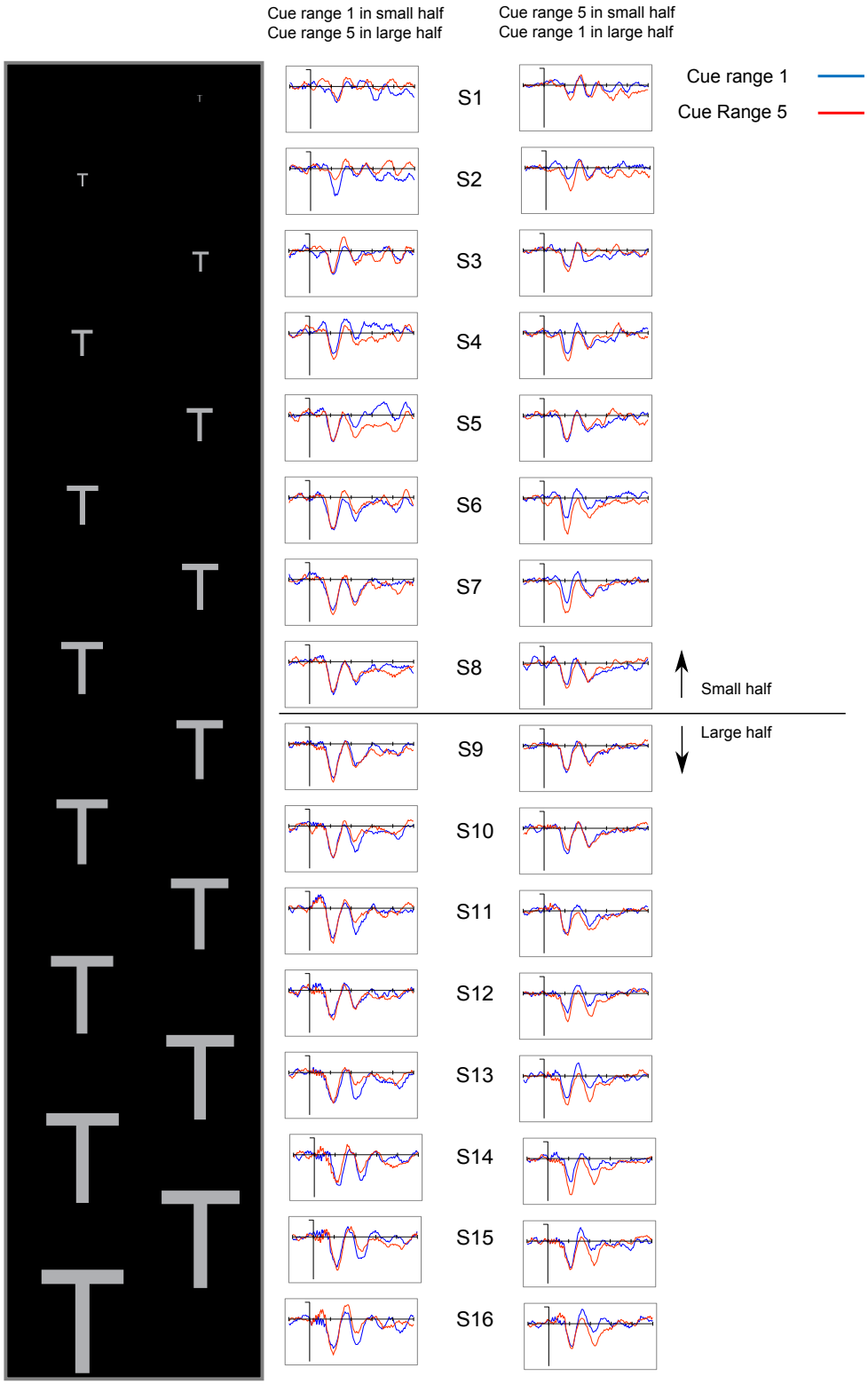

Response time to deviants
Response time, in ms.
680
660
640
620
600
580
560
540
C3 C4 C5 C6 C7
Deviant size, all on cued side

c.

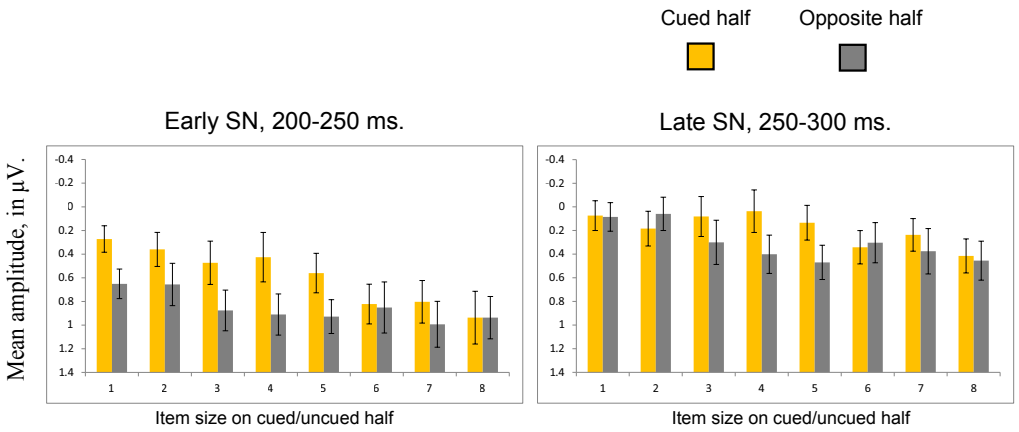

False alarms to standards
# of false alarms
60
50
40
30
20
10
0


Cued side of sizes
Opposite side of sizes
1 Size
5 Sizes
1 Size
5 Sizes
-0.5 µV
N1
-100 ms.
500 ms.
P3
Early
Late
SN
P1


Large side
Small side
S1
S2
S3
S4
S5
S6
S7
S8
Cue stimulus side
Cue opposite side
Small
Large
Small
Large
-0.5 µV
-100 ms.
500 ms.
SN
Center of cued range


Cue range 1 in small half
Cue range 5 in large half
Cue range 5 in small half
Cue range 1 in large half
Cue range 1
Cue Range 5
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
S13
S14
S15
S16
Small half
Large half

Effects of cued half of sizes on SN amplitude



Effects of cue range on SN amplitude

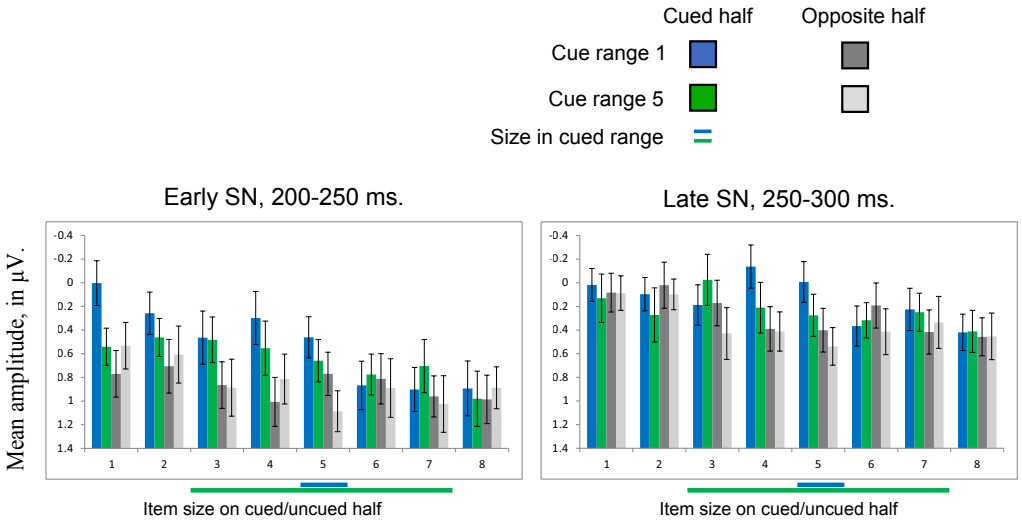


FIGURE CAPTIONS

Figure 1. Illustration of the experimental design. Squares indicating the 12 stimuli presentation locations stayed on the screen throughout the ~2 minute blocks. The cue consisted of changing the border color (from gray to red) and thickness of the squares to be monitored for 2 seconds at the beginning of each block. All cues are illustrated separately for Experiments 1 and 2. The stimuli were presented for 72 ms each with a variable ISI of 200-600 ms.

Figure 2. Grand-average ERPs time locked to the onset of standards plotted individually for all twelve locations surrounding fixation in Experiment 1. Waveforms shown are from the group of 9 posterior electrodes used in analyses. For standards at locations to the left or right of fixation, electrode groups contralateral to the standard were used. For the 6 and 12 o'clock positions, electrodes in the medial group were used. Modulation of amplitude in the N1 (150 to 200 ms), N2 (230 to 270 ms), and P3 (300 to 450 ms) time windows can be seen as a result of participants monitoring the side of standard presentation (black line) compared to the opposite side (dashed line).

Figure 3. Grand-average ERPs time locked to the onset of standards averaged across all twelve locations surrounding fixation in Experiment 1. Waveforms shown are from the group of 9 posterior electrodes used in analyses. Comparing waveforms for standards at varying distances from the cue (a), reveals a gradient of selection is seen in the N1 and P3 time windows. For the N2 time window, modulation is only significant when the standard location is cued. An asymmetry of selection is seen in the vertical dimension (b), such that monitoring one or two locations away above the standard (black line) results in greater evoked N1 amplitude compared to monitoring a similar distance below the standard (grey line). No asymmetry of selection is found in the horizontal dimension (c).

Figure 4. Mean amplitudes in the N1 and N2 time windows evoked by standards in Experiment 1.

Figure 5. Response times for targets in all cue conditions in Experiment 2.

Figure 6. Grand average ERPs time locked to the onset of standards in Experiment 2. Standards presented at: squares on the midline directly to the left and right of fixation, squares 1-away directly above or below the midline, and squares 2-away above and below the midline. Waveforms evoked by standards in the small (blue), medium (red), and large (green) cue conditions are shown when the cue was on the same (solid lines) and opposite (dashed lines) side of fixation relative to the standard. Averages are shown over clusters of 9 posterior electrodes contralateral to the hemifield that the standard was presented in. Comparisons were made during the P1, N1, N2, and P3 time windows.

Grey boxes indicate the time windows that were used to measure mean amplitude. For locations 2 squares away from the midline, Comparisons during the P3 time window were made across all 27 posterior electrodes

Figure 7. Mean amplitudes in the N1 and N2 time windows evoked by standards in Experiment 2.

Figure 8. Experimental design and example stimuli for Experiment 3.

Figure 9. Effect of cue size and object type on responses to targets in Experiment 3. Hit rate and response time are plotted separately as a function of target location. In the small cue condition, targets could only appear at the midline location.

Figure 10. Effect of cue size and object condition on false alarms in Experiment 3.

Figure 11. Grand-average ERPs as a function of cue side relative to the standard in Experiment 3. ERPs time locked to the onset of standards presented at: squares on the midline directly to the left and right of fixation and peripheral squares directly above or below the midline. Waveforms evoked by standards are shown when the cue was on the same (solid lines) and opposite (dashed lines) side of fixation relative to the standard. Averages are shown over clusters of 9 posterior electrodes contralateral to the hemifield that the standard was presented in. Comparisons were made during the P1, N1, N2, and P3 time windows.

Figure 12. Grand-average ERPs as a function of cue size and cue side relative to the standard in Experiment 3. ERPs time locked to the onset of standards presented at: squares on the midline directly to the left and right of fixation and peripheral squares directly above or below the midline. Waveforms evoked by standards in the small (black) and large (grey) cue conditions are shown when the cue was on the same (solid lines) and opposite (dashed lines) side of fixation relative to the standard.

Figure 13. Grand-average ERPs plotted separately for each object type condition in Experiment 3. ERPs time locked to the onset of standards presented at: squares on the midline directly to the left and right of fixation and peripheral squares directly above or below the midline. Waveforms evoked by standards in the small (black) and large (grey) cue conditions are shown when the cue was on the same (solid lines) and opposite (dashed lines) side of fixation relative to the standard.

Figure 14. Mean amplitudes in the N1 and N2 time windows evoked by standards in Experiment 3.

Figure 15. Experimental design and example stimuli for Experiment 4.

Figure 16. Behavioral data for Experiment 4. (a) Response rate to deviants as a function of cue range and distance from the central cued hue. (b) Response rate to deviants as a

function of cue range and distance from the edge of the cued range. (c) Response time to deviants as a function of cue range and distance from the central cued hue. (d) False alarm rate to standards plotted across cue range.

Figure 17. Grand average ERPs time locked to the onset of standards presented at varying distances from the central cued hue, averaged across cue ranges in Experiment 4. Waveforms evoked by standards at the same distance from the central cued hue are averaged. Averages are shown over 27 posterior electrodes. The primary effects of color distance were seen in the SN time window.

Figure 18. Grand average ERPs time locked to the onset of standards in each of the three cue ranges in Experiment 4. Waveforms are averaged across all color distances. Averages are shown over 27 posterior electrodes. Comparisons were made during the P1, N1in Exp, SN, and P3 time windows.

Figure 19. Grand average ERPs time locked to the onset of standards presented at varying distances from the central cued hue, plotted separately for each cue range in Experiment 4.

Figure 20. Mean amplitudes in the early and late SN time windows evoked by standards in Experiment 4.

Figure 21. Experimental design and example stimuli for Experiment 5.

Figure 22. Behavioral data for Experiment 5. (a) Response rate to deviants as a function of cue range and distance from the central cued hue. (b) Response time to deviants as a function of cue range and distance from the central cued hue. (c) False alarm rate to standards plotted across cue range.

Figure 23. Grand average ERPs time locked to the onset of standards in different cue ranges in Experiment 5. Waveforms evoked by standards in the small (black) and large (grey) cue conditions are shown when the cue was on the same (solid lines) and opposite (dashed lines) side of the set of possible sizes relative to the standard. Averages are shown over 27 posterior electrodes. Comparisons were made during the P1, N1, SN, and P3 time windows.

Figure 24. Grand average ERPs time locked to the onset of standards plotted separately by standard size in Experiment 5. Waveforms evoked by standards in the small (black) and large (grey) cue conditions are shown when the cue was on the same (solid lines) and opposite (dashed lines) side of the set of possible sizes relative to the standard. Cues were centered on item size five (S5).

Figure 25. Grand average ERPs time locked to the onset of standards in all 16 sizes in Experiment 5. Waveforms evoked by standards in the 1 size (blue) and 5 size (red) cue ranges are shown for all standard sizes. Grand averages are plotted separately for two subject groups based on whether they received the cue 1 range in the small half of sizes

and the cue 5 range in the large half of sizes, or vice versa. Averages are shown over 27 posterior electrodes.

Figure 26. Mean amplitudes in the early and late SN time windows evoked by standards in Experiment 5.

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