Hemifield asymmetries in the spatial distribution of selective attention

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ABSTRACT

Hemifield asymmetries in the spatial distribution of selective attention

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Visual attention is involved in many everyday tasks, such as finding one's shoes, driving, or looking for a face in a crowd. Often attention must be allocated or split onto more than one location. Yet how does the visual system accomplish this, and what cost does it have in terms of performance in visual tasks? This dissertation reports the results of an investigation of the claim that attention could be allocated to two or more non-contiguous locations simultaneously. This study uses a technique, which to the best of my knowledge, has not been used by other investigators studying the splitting of attention. The stimulus used in the current thesis consisted of four possible cue locations, with each potential location located in 45 degree increments (45, 135, 225, 315 degrees) at the same eccentricity. Experiment 1 replicated the results of previous attention studies, but using the new cueing paradigm. The results showed that the spotlight of attention could change location when multiple potential locations are present. The advantage of the new paradigm is the possibility of cueing different locations within and between visual hemifields. This was explored in Experiments 2 and 3, to examine the role of hemispheric asymmetries in the debate over multifocal attention. Specifically, two locations were cued in Experiment 2, and Experiment 3 examined the differences of splitting the attentional beam within and across hemifields. Finally, Experiment 4 investigated the effect of cueing all four locations at the same time. The results from the current thesis confirm that observers can allocate attention to two or more simultaneous locations, without observing any attentional enhancement coming from the in-between cued locations. However, these results stemmed from attending to two locations across hemifields. The present thesis provides more evidence in support of the ability to split attention, and describes the impact that multifocal attention plays in visual perception.

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DEDICATION

I dedicate this dissertation to the memory of my late supervisor Dr. Michael von Grünau. I will always remember him as an exceptional mentor and I am forever grateful for all that he has taught me during the years we worked together. You are dearly missed both as a supervisor and a good friend.

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INTRODUCTION

Visual search is involved in many everyday tasks, such as finding one's shoes, or looking for a face in a crowd. Since only a small portion of the visual information that reaches the retina can be used at any one time, a great deal of it must be ignored. This is where visual selective attention has an important function. Yet, after much research, we still have only a limited idea of how attention works. The problem with visual attention has been recognized since the beginning of the scientific study of psychology. The following quote from William James' 1890 textbook, *The Principles of Psychology,* illustrates the problem: "Millions of items…are present to my senses which never properly enter my experience. Why? Because they have no *interest* for me. *My experience is what I agree to attend to…* Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects of trains of thought…It implies withdrawal from some things in order to deal effectively with others" (italics in the original text) (p. 403).

Psychologists have described attention as orienting to sensory stimuli (e.g., Posner, 1995). Visual attention is also thought of as an enhancement of visual processing at the location or for the object to which attention is directed (i.e., the metaphor of the 'spotlight of attention'). Attention may also be thought of as a filter that limits the amount of information that the visual system ultimately processes (Broadbent, 1958). The spotlight of attention has been described in many theories of object detection and object perception (e.g., Treisman & Gelade, 1980; Julesz, 1984; Wolfe, 1994; Eriksen & Hoffman, 1972; Broadbent, 1958; Neisser, 1967). Yet many questions exist about the process by which attention is used to select items of interest in our visual environment. For example:Is it possible to split attention between two or more non-contiguous spatial locations? Does this depend on if the two (or more) spatial locations are within the same visual hemifield, or in different hemifields? And is there a cost in terms of performances such as, target discrimination when attention is split from one to multiple spatial locations? These are questions that the current thesis aims to address.

General Background

Early researchers (e.g., James, 1890; Neisser, 1967) stated that we need an attentional mechanism, which would allow humans to focus on some elements within our visual environments, while ignoring irrelevant elements. For instance, Neisser (1967) referred to the fact that as the number of objects in our visual environment increases, there is an exponentially increasing number of conjunctions between visual features. Consequently, there is a need for a mechanism of focal attention, which can select only those features and objects that are relevant for any particular task. The definition of "attention" is often vague. However, for the current thesis, attention will be defined as an internal cognitive process whereby one actively selects environmental information (i.e., sensation). In more general terms, attention can be defined as an ability to focus and maintain interest in a given task.

The way in which attention can be used to select specific objects or features within a scene has been studied intensely for the last 30 years (for a recent review, see Carrasco, 2011). Visual attention has been compared to a "spotlight" that can "illuminate" or "highlight" an object or objects of interest (Posner & Cohen, 1984). Posner, Snyder, and Davidson (1980) formulated this spotlight model theory of attention in this way: selective attention is like "a spotlight that enhances the efficiency of the detection of events within its beam" (p. 172).

This location-based attentional selection has been characterized in terms of a “gradient” or activity distribution that is spread across some internal representation of space (Downing, 1988; Laberge & Brown, 1989) or a “zoom lens” that can focus on a particular spatial location or be distributed over a wider area of space (Eriksen & St. James, 1986; Eriksen & Yeh, 1985). However, these terms are not mutually exclusive. The spotlight of attention can also be characterized as having ill-defined edges, rather than being sharply defined (Panagopoulos, von Grünau, & Galera, 2004). Theories of detection and visual attention have emphasized that the spotlight of attention can help to process the visual information that falls within its beam so that this information is processed faster and more accurately (Posner, 1980; Eriksen & Hoffman, 1972; Julesz, 1984; Yeshurun & Carasco, 1998). Conversely, the remainder of the visual field is partially filtered out and/or suppressed.

One of the major tools for investigating the visual system, and the role of attention in visual object recognition, has been the visual search task. In its most simple format, the idea behind the visual search paradigm is that an observer must search for a pre-specified target among a variable number of distractor elements in some random location, and the reaction time (RT; i.e., the time between the presentation of a stimulus, and the time of the subsequent response to the stimulus) to the detection of the presence or absence of the target will be measured, as well as accuracy (to monitor any potential trade-off that exists between reaction time and accuracy). Thus, the visual search paradigm is a discrimination task in which the participant must determine if the target stimulus is present among the distractor stimuli, or absent. In many instances, the task becomes more difficult as the number of stimuli presented increases, thus it is expected that RT to respond will increase (Treisman & Gelade, 1980). Reaction time can therefore be used as a measure of the difficulty in a discrimination task, as long as the error rate remains relatively constant. The increase of RT with increasing display size can be described by the slope of the RT-display size relationship (Treisman & Gelade, 1980). It is assumed that this slope should be twice as steep for the situation where the target is absent when the search is difficult, as compared to the situation where the target is present. This increase in slope in the target absent condition can be explained by the fact that, when the target is absent, the observer has to search until all the items in the visual display have been searched before the observer can conclude that the target is absent. Conversely, when the target is present, it will on average, be detected after half of the items have been examined, thus, cutting the search time down by half. While the RT shows how fast the detection of the target among the distractors occurs, on a given trial, the slope shows how much the average RT will increase per item.

One way to compare search tasks is to describe the efficiency with which one can search through a visual display. An efficient search is when one can direct attention to the target as soon as the display appears, regardless of the display size. An inefficient search occurs when one must examine each item until the target is found. Different types of search tasks differ in their efficiency. In a feature search, the target is defined by the presence of a single feature, such as a salient color or orientation. If the target is sufficiently salient, it does not matter how many distractors there are. The target is said to "pop out" of the display. We can process the color or orientation of all the items in the display at the same time (in parallel). When RT is measured it will not change with changes in display size. In a conjunction search, no single feature defines the target. Rather, the target is defined by the conjunction of two or more features (e.g., searching for a red vertical target among red horizontal and blue vertical distractors). In this type of search, RT will increase as the number of items in the display increases. Treisman and Gelade (1980) found that the function relating search times was flat (i.e., similar) for target present and absent when a single feature (e.g., colour, orientation) was sufficient to define the target with respect to the distractors. However, RT increased linearly when subjects had to detect targets defined by a conjunction of features, when the features of the target are shared with distractor items.

Theories of Visual Search

In 1980, Treisman and Gelade developed a theory of object perception, the Feature-Integration Theory (FIT), which has greatly influenced the research on visual search. This theory assumes that in the early stages of visual processing, the visual display is decomposed into a number of elementary features. For instance, colour, luminance, and orientation are regarded as simple features according to the FIT (Treisman & Sato, 1990). If the target item contains a unique feature, for example the colour red and the target is surrounded by green distractors, then the target will be detected quickly, and the RT will be independent of the number of distractors. This type of visual search stimuli, where the unique feature can be detected rapidly irrespective of the set size is known as a parallel search (or "pop-out" search). That is, the information is processed simultaneously across the feature maps, such as color maps, and orientation maps, without effort or the need for the involvement of the spotlight of attention, also known as focused attention (Treisman & Gelade, 1980).

However, the detection of a target amongst distractors becomes more complicated when the target is defined by the presence of a conjunction of two different features, and each half of the distractors shares one of the features with the target. For instance, when the target is red and vertical, and the distractors are either red and horizontal, or green and vertical. Search stimuli that contain a conjunction require a serial search, according to the FIT, but there are cases of fast conjunction searches (Wolfe, Cave, & Franzel, 1989). Feature integration theory assumes that in a conjunction search, each stimulus has to be attended to in sequence. Only when a location is encountered where there is activity in both feature maps (e.g., in the example above, when the target orientation is vertical and the target colour is red), can the participant signal that the target has been found.

The serial-parallel dichotomy proposed in the FIT has been incorporated into other search models. For instance, the Guided Search model (Wolfe, 1994) adopts a two-stage architecture. The first stage detects all simple features in parallel. During the first stage, the information activated by simple features is added and registered in a global map of activation in which each location represents the probability of containing a target. Then the processed information from the first stage is used to guide a second stage that is serial in nature, and that takes place within limited areas of the visual field. In the second stage, attention is directed to the location with the highest activation level.

According to McElree and Carrasco (1999), the RT logic that motivates models such as the FIT and the Guided Search Model (GSM) provides less than satisfactory grounds for drawing a sharp dichotomy between parallel and serial processing. As a consequence, another search model has been proposed to account for the differential impact of set size on mean RT (Duncan & Humphreys, 1989). Duncan and Humphreys (1989) argued against the FIT. They believed that the similarities of the target and distractors were more important, as opposed to the number of features that was stressed in the FIT. When the distractors are similar to the target, the RT is longer than when the distractors are dissimilar. This suggests that more attention, and a longer search will be required in order to identify a target among similar distractors. In the real world, it is very rare to have a true feature search for the only green item among homogeneous distractors.

In a real-world search, attending to the location or locations that are likely to contain the target, can significantly improve the efficiency of the search, thereby leading to shorter reaction times. One way of achieving this is by the use of a spatial cue that directs an observer's attention to one confined area on a visual display.

Spatial cueing

One method for improving reaction times in a visual search is to indicate the location of the target before presenting the search array. Traditionally this is done by highlighting the area where the target may appear, or by using a symbolic cue (e.g., an arrow). This spatial cueing (in this case, cueing of the location) can influence target detection in a significant way. The effect of the cue and the type of cue has received much focus in the past 30 years (for a recent review, see Carrasco, 2011). One of the first studies that looked at spatial cueing was by Posner (1980). Posner (1980) conducted an experiment, in which he provided observers with a cue as to whether a given event would occur to the right or to the left of fixation. Posner found that when the location of the target was cued, it facilitated target detection. Therefore, cueing the location of the target decreased RT. Posner's experiments have shown that both bottom-up (i.e., exogenous) cues driven by stimulus salience, and top-down (i.e., endogenous) cognitive cueing can be used in this context. With exogenous cueing, some stimulus is briefly presented at the cued location before the target appears in this location. With endogenous cueing, the cue is presented in the center of the display and symbolically indicates the cued location (e.g., arrow, "left"). In either case, the observer's knowledge about where in space a target stimulus will occur affects the efficiency of detection. In other words, with spatial cueing we end up with search times that are significantly shorter compared to a no cue condition. Posner studied two types of visual cues: a valid cue which correctly identifies the location where the target is to appear, and an invalid cue that directs the observer's attention to an incorrect location. The valid cue had an effect of decreasing RT. Conversely, the invalid cue had an effect of increasing RT, respect to a no cue control. Thus facilitation and suppression can be present in the same situation, and is thought to be caused by the unconscious cueing of the region (or spotlight) of attention. According to a meta-analysis conducted by Solomon (2004), there is no capacity limit for either of the classic precueing effects, specifically lower RTs and enhanced sensitivity. However, exactly how precues increase sensitivity remains to be determined.

Functions of the Spotlight of Attention

A general function of the spotlight of attention, which is noted in many theories of object perception and attention, is to process the information that falls within its region (Posner, 1980; Duncan & Humphreys, 1989; Eriksen & Hoffman, 1972; Treisman & Gelade, 1980; Wolfe, 1996). However, there are at least two other functions of the spotlight of attention, which are specifically related to the FIT (Treisman & Gelade, 1980). The first one relates to the location of features, the second function involves the binding of features. According to the FIT (Treisman & Gelade, 1980), without attention, one is likely to experience an illusory conjunction. This involves an erroneous combination of two features in a visual scene, for example, seeing a red O when the display contains red letters and Os but no red Os.

Theories of detection and visual attention have emphasized that the spotlight of attention helps to process the information that falls within its region faster and more accurately (Posner, 1980; Eriksen & Hoffman, 1972; Julesz, 1984). In other words, attention aids in the detection of a target among distractors in a visual display.

Nothdurft (1999) conducted a visual search experiment for features where the participants had to search for a horizontal line among lines of different orientations. The items were arranged in a circle around a central fixation point. A large line between the fixation point and the target or between the distractor at the opposite direction of the target (i.e., anti-target) was presented immediately after target detection. The participants were asked to state the direction of apparent motion in the large line and were instructed not to move their eyes from the fixation point. Nothdurft (1999) found that the participants reported seeing a motion from the target to the fixation point, indicating that attention was focused on the target location immediately after target detection. This result supports the idea that the spotlight of attention, similarly to a flashlight, needs to highlight or "light up" the target in order to detect and locate its presence (also see: von Grünau, Dubé, & Kwas, 1996).

Another hypothesized function of the spotlight of attention is to locate features within the visual field. In the FIT, it was proposed that the attentional processes involved in the detection and the localization of a target were different. Detection of features such as colour, luminance, and orientation, are known to occur pre-attentively (e.g., Land, 1983). However, according to FIT, the features need to be bound to a spatial location in order to be located, and this was done through the help of the spotlight of attention. A number of psychophysical studies concerning the detection and recognition of objects have proposed a two-stage theory. The first stage is the "preattentive" stage, where the entire visual display is processed rapidly and in parallel. In the second "attentive" stage, attention is directed to particular locations in the visual field, for specific analysis and recognition of objects (Bergen & Julesz, 1983; Julesz, 1984).

The hypothesis is that precise information about spatial location may not be available at the feature level, which registers the whole display in parallel. Tasks where subjects must locate, as well as detect or identify an item require focal attention. However, for a location and discrimination task, a feature search will be inefficient. Without attention, it is suggested that individual feature locations are not directly accessible (Treisman & Gelade, 1980). Thus, locating a conjunction is a necessary condition for its detection and further analysis. Treisman and Gelade (1980) found support for this hypothesis with the results of a visual search experiment. They examined the dependency between reports of identity and reports of location on each trial. For a conjunction search, they predicted that the dependency will be high, that if the observer correctly identifies a conjunction he must have located it, in order to focus attention on it and integrate its features. On the other hand, it is possible to detect or identify a feature without necessarily knowing where it is. The search experiment consisted of a stimulus display constructed from two rows of six coloured letters, with the whole array taking a rectangular area. Each display contained one target item in any of eight inner positions (i.e., excluding the two positions at each end of each row). There were two possible conditions, either a feature condition, or a conjunction condition. The distractors were a pink letter “O” and a blue letter “X” in approximately equal numbers. In the feature condition, the possible targets were a letter “H” that was blue or pink in colour, and an orange letter “O” or “X”. In the conjunction condition, the possible targets were a pink letter “X” and a blue letter “O”. Each of the targets appeared equally often. The dependent variable in this experiment was accuracy, rather than response time. They found that the target identification was above chance, even when the participants made major location errors. Furthermore, Treisman and Gelade found that the RT to detect the feature was short, and did not vary as a function of the set size. However, the RT to locate the feature in space was long, and increased as the distractor set size increased. This is consistent with the hypothesis of serial search for conjunctions and parallel search for features (Treisman & Gelade, 1980).

In the real world, objects are usually made up of many features. Another function of the spotlight of attention is to integrate the features of an object. According to Treisman and Gelade (1980), "Focal attention provides the 'glue' which integrates the initially separate features into a unitary object" (p. 98). To illustrate the integrating function of the spotlight of attention, Treisman and Gelade conducted a conjunction search in which the display consisted of two rows of six coloured letters. The possible targets were a pink letter "X" or a blue letter "O", amongst pink "O's" and blue "X's" distractors. They found that when the participants failed to locate the target, the probability of identifying the presence of the target was at chance level (i.e., 50% accuracy). This result supports the hypothesis that the detection of the presence of an object made up of a conjunction of features requires the use of the spotlight of attention.

Attention can change the appearance of perceptual items

In recent years, several researchers have suggested that attention can intensify the sensory impression of a stimulus (eg.: Yeshurun & Carrasco, 1998; Pestilli & Carrasco, 2005; Carrasco, Ling & Read, 2004; Treue, 2004), leading to increased accuracy and/or decreases in reaction time in response to a stimulus. Attention has been shown to change the perceived appearance of a stimulus by increasing either its contrast, spatial frequency, or salience (intensity).

In the study by Carrasco, Ling, and Read (2004), they measured the effects of transient attention on perceived contrast. Their observers performed an orientation discrimination task contingent on the stimulus that appeared higher in contrast. This experimental design emphasized to observers the orientation judgment, when in fact the authors were interested in their contrast judgments. They were shown a pair of stimuli and asked to report the orientation of the stimulus that appeared higher in contrast: "Is the stimulus that looks higher in contrast tilted to the right or left?" The two stimuli were Gabor patches of 2 or 4 cycles per degree, with each Gabor being tilted 45 degrees to either the left or right. The two stimuli appeared on either side of a fixation point. The contrast of one Gabor was kept fixed at near-threshold level of 6% (Michelson Contrast). The authors named this patch the standard patch. The second test patch was varied in contrast from trial to trial, using a range of stimulus contrasts from 2.5 to 16% The results of this study demonstrated that when observers' transient attention was drawn to a stimulus location, observers reported that stimulus as having a higher perceived contrast than the physical contrast of the test Gabor. For example, the perceived contrast was 16% when the stimulus was attended, but in reality the test Gabor contrast was 8%. This finding was indicative of the fact that attention does change stimulus appearance. The data from the Carrasco and colleagues study (2004) provided evidence that attention changes the strength of a stimulus by enhancing its contrast or salience. In other words, attention appears to act by boosting the actual stimulus contrast, thereby improving observers' performance and/or reaction time in a discrimination task.

Neurophysiological mechanisms of Attention

The question of how attention acts to increase perceptual saliency has been a longstanding one in vision science. In the past twenty years, this question has been studied intensely, with numerous electrophysiological studies on primates showing that attention can affect visual processing at the single neuronal level (Busse, Katzner, & Treue, 2008; Moran & Desimone; 1985; Treue & Maunsell, 1996; Treue & Maunsell, 1999; Reynolds, Pasternak, &

Desimone, 2000; Williford & Maunsell, 2006; Luck, Chelazzi, Hillyard, & Desimone, 1997; Motter, 1993; McAdams & Maunsell, 1999; Reynolds, Chelazzi, & Desimone, 1999; Lee & Maunsell, 2010).

The first researchers to propose that attention acts at the neuronal level were Moran and Desimone (1985). In their experiment, they recorded from neurons in V1, V4 and the inferior temporal cortex (IT) in a macaque monkey. They recorded from neurons while presenting two stimuli within each neuron's receptive field. One of the two stimuli produced a stronger response when presented within the receptive field than the other. Therefore, each neuron had a preferred stimulus and a non-preferred stimulus. When both the preferred and non-preferred stimuli were presented without attention being focused on either stimulus, then the neuron's response was roughly the mean response of either stimulus when presented in isolation. However, the macaque monkeys were also trained to direct their attention to either the preferred or non-preferred stimulus. When attention was directed to the preferred stimulus, then the firing rate increased within neurons in V4 and IT, but not for V1. However, when attention was shifted to the non-preferred stimulus, then the firing rate decreased, again within neurons in V4 and IT, but not for V1. Based on this result, Moran and Desimone (1985) suggested that when attention is focused on one stimulus, then the neuron's receptive field shrinks around that attended stimulus, or becomes more sharply defined, thereby removing the non-attended stimulus. Moreover, when attention was directed to the preferred stimulus, the firing rate was high. When attention was directed to the non-preferred stimulus, the firing rate fell, as though the preferred stimulus was no longer within the RF.

This change in receptive field properties in V4 and IT when attending to a stimulus has been replicated in other studies (Connor, Gallant, Preddie, & Van Essen, 1996; 1997; Ghose & Maunsell, 2008; Luck et al., 1997; Lee & Maunsell, 2010; Reynolds et al., 1999). Changes in the receptive field properties have also been seen in other areas, including medial temporal area (Anton-Erxleben, Stephan, & Treue, 2009; Womelsdorf, Anton-Erxleben, Pieper, & Treue, 2006), and the lateral intra-parietal area (Hamed, Duhamel, Bremmer, & Graf, 2002). These changes in receptive field size vary from study-to-study, and range from a 5% change to a 25% change in size between attention and non-attended conditions (Anton-Erxleben, Stephan, & Treue, 2009; Womelsdorf, Anton-Erxleben, Pieper, & Treue, 2006).

In addition to attention modulating changes in the receptive field size, other studies have shown that the position of the receptive field can correspond to a shifting of the spatial positioning of the receptive field (Niebergall, Khayat, Treue, & Martinez-Trujillo, 2011; Womelsdorf et al., 2006). This shift in the receptive field occurs towards the attended stimulus, but declines as the distance between the attended stimulus and the receptive field increases (Womelsdorf et al., 2006).

Other neurophysiological studies, such as fMRI studies have shown that attention can change neuronal activity within the early visual areas, specifically, areas V1–V4 (Datta & DeYoe, 2009; Brefczynski, Datta, Lewis, & DeYoe, 2009; Fischer & Whitney, 1999). A study by Fischer and Whitney (1999), measured the spatial spread of fMRI BOLD responses to stimuli at adjacent spatial locations. The direction of attention to a nearby location led to a decrease in the spatial overlap of the responses to each stimulus location. From this result, the authors suggested that attention was a narrowing of spatial frequency tuning characteristics within the neurons, which corresponds to findings from single unit electrophysiology (Martinez-Trujillo & Treue, 2004). Taken together with the single-unit electrophysiology, the fMRI studies described above describe some of the properties of the physiological mechanisms that underlie attention. They show that modulating attention can increase and decrease the activity of the visual pathway, which may explain the increase in sensitivity by the visual system when attention is modulated.

Does attention select specific objects and/or locations?

The neurophysiological and imaging studies described in the previous section would suggest that modulation of attention of specific objects in the visual field can modulate neuronal activity. Yet, a long-standing debate in the study of attention has been whether attention is object-based or location-based? It has been difficult to disentangle the contribution of location-based and object-based components of visual attention. Location-based attention involves the selection of stimuli from spatial representations. A common metaphor for location-based attention is the “spotlight” metaphor, in which attention moves through the visual field and selects stimuli on the basis of spatial location (Eriksen & Eriksen, 1974; Eriksen & Hoffman, 1973; Hoffman & Nelson, 1981; Posner, 1980; Posner et al., 1980). Posner and colleagues (Posner & Cohen, 1984; Posner et al., 1980) provided a well-known experimental demonstration of location-based attention using a cueing paradigm. In this paradigm, observers see three side-by-side boxes, and are instructed to fixate on the central box. Cues appear as a brightening of one of the peripheral boxes. Following a cue, a target appears in one of the peripheral boxes, and observers make a simple response to the target. Observers RT is faster to targets when the cue is on the same side of fixation (i.e., a valid cue) compared with the other side of fixation (i.e., an invalid cue).

In a discrimination task with an endogenous predictive cue, Theeuwes (1989), found the classic location cueing effect, but no effect of the shape of the cue. Two experiments were conducted which tested the effect of two different types of cues on the allocation of attention in the visual field. Participants responded to a target appearing 6.5 degrees to the right or to the left of fixation in a field filled with small randomly positioned line segments. The target form was either a circle or diamond in which a horizontal or vertical line segment was positioned. Participants made a speeded discrimination response on the basis of the orientation of this line segment. In the first experiment, there was always one target on each trial. In the second experiment, both circle and diamond were presented left or right of fixation simultaneously and the line segment only appeared in one of the forms. In different conditions, the most likely target location (i.e., left or right) and form (i.e., circle or diamond) were cued. Reaction time measures showed that the validity of the location cue resulted in both costs and benefits, whereas the validity of the form cue had no such effects. The results cannot be reconciled with the claim of zoom lens theories that spatial attention can switch between different modes of operations. Instead, the results are consistent with a spotlight theory in which spatial attention involves selecting a particular restricted area of the visual field for which the perceptual efficiency is enhanced. In a detection task in which the effect of a random location and shape cueing could be examined separately, Schendel, Robertson, and Treisman (2001) found typical location cueing effects. The shape cueing effect was significant only at long SOAs, provided the location cue was valid.

Object-based attention selects from internal object representations that represent stimuli irrespective of their spatial location. The clearest demonstration of object-based attention was provided by Duncan (1984). Duncan presented subjects with targets consisting of two overlapping objects, a box and a line. Each of these objects varied on two dimensions: The box could be either short or tall and have a gap either on the left or right, and the line could be either dotted or dashed and could be tilted either clockwise or counter-clockwise. Observers were given brief presentations of these targets and asked to report either one or two dimensions. When two dimensions were reported, they could either be dimensions of one object, such as reporting the line's texture and tilt, or they could be dimensions of the two different objects, such as reporting the line's texture and the box's height. Duncan (1984) found that subjects were no worse at reporting two dimensions than one from a single object, but they were more accurate at reporting two dimensions when they were dimensions of the same object compared with when the dimensions were on different objects. Duncan argued that these results could not be accounted for by a spatial theory (i.e., spotlight) of attention because each object was equidistant from fixation.

Although these results were presented as evidence of object-based attention, attempts have been made to explain them in terms of location-based selection. For instance, Vecera and Farah (1994) considered a similar location-based explanation for Duncan's (1984) results. They raised the possibility that spatial attention may conform to an object's shape by selecting precisely the spatial locations occupied by the objects. They described this alternative mode as selection from a "grouped-array" representation. Thus, the poorer performance in Duncan's experiment when subjects made judgements about both objects may be attributable to a cost in activating a different group of locations rather than selecting a different object representation. Vecera and Farah set out to test this hypothesis by replicating Duncan's results and comparing them to a condition in which the two objects were on opposite sides of fixation. They hypothesized that if selection in Duncan's experiment was indeed location-based, there should be an increase in the effect size when the objects are placed apart from each other; due to the larger distance attention has to travel in this condition. However, they found no interaction between the two conditions, and concluded that Duncan's results were indeed due to visual selection of spatially invariant object representations, as postulated by Duncan.

Finally, Vecera and Farah (1994) demonstrated that when Duncan's objects were used in a cued detection task, the results were consistent with location-based selection. They concluded from their results that there may not be a single mechanism of attention that is consistent with Duncan's claim that object-based and location-based attention is not mutually exclusive. Instead, Vecera and Farah (1994) argued that the limitation of attention depends on the stimulus used in the experimental task.

In summary, the results of a large number of attentional studies, including spatial cueing studies (Posner et al., 1980; Posner & Cohen, 1984; Posner, 1980) neurophysiological studies (Luck, Chelazzi, Hillyard & Desimone, 1997; Reynolds, Pasternak, & Desimone, 2000; Busse, Katzner, & Treue, 2008 Lee & Maunsell, 2010) and studies that did not emphasize or encourage selection by location (Duncan, 1984; Baylis & Driver, 1993; Hübner & Backer, 1999) show that location plays a crucial role in visual attention. However, the data obtained to date do not rule out the possibility that both location-based and object-based mechanisms co-exist.

The Cue – Size Effect

The cue-size effect may be a likely, and possible explanation for some apparent failures in past studies to show attentional splitting, as will be discussed later in the thesis. When there are two windows of attention, attention needs to be spread over a larger area; two regions instead of one. Therefore, a reduction of attentional effect is to be expected.

It is a known phenomenon that objects near the attended location will receive privileged processing, in relation to objects appearing at unattended locations. Several studies have shown that the efficiency of processing inside the attended area is inversely related to the size of the area, an effect known as the cue-size effect (Eriksen & Yeh, 1985; Eriksen & St. James, 1986; Laberge, 1983; Castiello & Umiltà, 1990). There is also evidence that the capture of attention by a spatial cue depends on the object where the target is presented, showing slower target identification when the target is presented on an uncued object. (Egly, Driver & Rafal, 1994; Iani, Nicoletti, Rubichi & Umiltá, 2001; Macquistan, 1997).

Eriksen and Hoffman (1972) showed that attending to a reduced area of a stimulus display can cause an increase in the speed of response. They estimated the size of the spotlight of attention subtended approximately one degree of visual angle in diameter. However, they also proposed that the spotlight of attention can be constricted or enlarged, depending on the area of the display, as other studies demonstrated as well (Treisman, 1998; Treisman & Gelade, 1980; Eriksen & Hoffman, 1972; and Julesz, 1984). A restricted focus of attention was hypothesized to yield high resolution, while a large spotlight of attention was hypothesized to yield low resolution (Eriksen & Hoffman, 1972). Also, Eriksen and Hoffman postulated that unlike visual acuity, the mechanism(s) involved in focal attention are not dependent on retinal sensitivity. That is, visual acuity and focal attention are independent mechanisms. Eriksen and Hoffman conducted an experiment in which the participants had to identify a particular letter (e.g., C) in a circular display indicated by a cued line. When the distractors were similar to the target (e.g., O), target detection was slower than when the distractors were dissimilar to the target (e.g., X). This increase in reaction time suggests that increased attention was required in order to identify the target when the distractors were similar (Eriksen & Hoffman, 1972).

Multiple Object Tracking

Of core importance to the present thesis is to investigate if, and under what conditions the attentional beam can be split, and what cost does this splitting have on task performance? Most studies of attention have examined spatial cueing with two potential target locations (Posner et al., 1980; Posner & Cohen, 1984; Posner, 1980) or with searching for a target amongst multiple locations (Hollingworth, Maxcey-Richard, & Vecera, 2012) in the visual search paradigm. However, another way to explore whether there are multiple attentional spotlights is to ask subjects to track the movements of multiple objects (reviewed in Cavanagh & Alvarez, 2005). These experiments appear to show that subjects can allocate attention to four or five objects moving independently amongst other independently moving distractors (Pylyshyn & Storm, 1988; Yantis, 1992; Verstraten, Cavanagh, Labianca, 2000), although this number is dependent upon the speed of the moving dots, with increasing speed resulting in fewer objects being accurately tracked (Verstraten et al., 2000). This could mean that subjects can divide the spotlight of attention into 4-5 independent regions (Pylyshyn, 1989).

Pylyshyn and Storm (1988) had participants visually track, or visually follow and keep in memory a pre-specified subset of a larger number of identical, randomly moving objects in a display. The targets to be tracked were identified by briefly flashing them several times, prior to the onset of the movement. According to the model proposed by Pylyshyn and Storm, targets designated this way are automatically indexed. Participants tracked the target objects for 5 to 10 seconds, after which either a target or a distractor was probed by superimposing a bright square over it. The participants' task was to determine whether the probed object was a target or a distractor. According to Pylyshyn and Storm (1988), the indexing of the target objects would allow each of them to be simultaneously tracked and identified throughout the motion phase of the experiment, despite the fact that the targets were perceptually indistinguishable from the distractors.

Pylyshyn and Storm (1988) found that performance in this multiple object tracking was high. Participants were able to track up to five target objects at an accuracy close to 90%. Others have also reported similar findings (McKeever & Pylyshyn 1993; Yantis, 1992; Scholl & Pylyshyn, 1999; Cavanagh, 1999; Culham, Brandt, Cavanagh, Kanwisher, Dale, & Tootell, 1998). Moreover, using a simulation of the task, analyses by Pylyshyn and Storm (1988) and Mckeever and Pylyshyn (1993) indicate that a single spotlight of focused attention moving rapidly among the target objects and updating a record of their locations could not produce this level of tracking performance in the setup used in their studies.

Yantis (1992) proposed an additional mechanism, namely perceptual grouping to explain how multiple target objects are tracked in this task. Yantis (1992) argued that participants spontaneously group the targets together to form a virtual polygon, whose vertices correspond to the continually changing positions of the targets, and that it is this single "object" that is tracked throughout the trial. While it may be that observers conceptually group elements into a polygon, it is still the case that the individual targets themselves must be tracked in order to keep track of the location of the vertices of the virtual polygon.

One may wonder why we need to explore the splitting of the attentional beam with the spatial cueing technique that is used in the current thesis, when the work on multiple-object tracking (MOT) has already revealed that participants are able to attend to up to 5 independently moving objects. Thus, concluding that participants are able to divide the spotlight of attention into 5 independent and separate regions. In other words, what advantage does the task used in the current thesis have over the MOT task?

One issue with the MOT task is that in most studies, except in the original Pylyshyn and Storm (1988) study, researchers do not track eye movements. Since presentations are long and mostly inexperienced observers partake in the experiments, it is therefore doubtful that participants maintain fixation and refrain from any eye movements. Thus, participants may have used different strategies in different conditions, thereby making difficult to explain the "why" of the results from such studies. With spatial cueing on the other hand, short SOAs are used and this avoids eye movements from aiding performance.

Another issue with MOT is that participants may be using momentary similarities (or dissimilarities) of motion paths in mirror symmetric locations along the vertical meridian. It has been shown that the analysis of stimuli in mirror symmetrical locations to the left and right of the vertical meridian is faster and more efficient when compared to unilateral conditions (e.g., Wilson & Wilkinson, 2002).

The final issue with the MOT paradigm is that the mechanisms involved with working memory may limit the number and speed of the different targets to be tracked. There is no such issue with spatial cueing of multiple regions, because only one target is to be searched or discriminated at any one given trial. Therefore, working memory would not be a contributing factor when examining the results of spatial cueing experiments with multiple cued regions, and measuring any attentional enhancement at cued regions, compared to decreased performance at uncued regions.

Background for the present study

Another long standing debate surrounding the study of attention revolves around the question of whether the attentional beam can be split - or not - to cover non-contiguous regions of space. There are two groups of researchers that support or deny this theory: those who argue that attention cannot cover more than one spatial area at the same time split (Posner, Snyder, & Davidson, 1980; Eriksen and St. James, 1986; Eriksen & Yeh, 1985; Treisman, Kahneman and Burkell, 1983); and those whose studies conclude that attention can indeed be split to cover non-contiguous regions of space (Castiello and Umiltà, 1990; Heinze, Luck, Münte, Gös, Mangun, & Hillyard, 1994; Kramer and Hahn, 1995).

Focused attention is not divisible.

Previous researchers have suggested that, whether controlled endogenously or exogenously, there can only be one focus of attention at any one time. Posner, Snyder, and Davidson (1980) provided evidence that visual attention is allocated to single contiguous regions of the visual field, enhancing the processing of stimuli falling within the single contiguous spotlight. In their experiment, the participants had to react to the onset of a light emitting diode, which was positioned at different areas in the visual field. On each trial, the participants were given information about both the most frequent position and the second most frequent position. Posner and collaborators measured the RT of the participants' response to the presentation of the light. They found that the RT for detecting the light at the second most likely position increased as the second most likely position got farther away from the most likely position. Furthermore, Posner and collaborators found that the time needed to detect the target at the second most likely position was similar to the time for detecting the target at the least likely position. Posner et al. interpreted this result to mean that participants directed attention to the area of the display where the target was the most likely to appear. When the second most likely position fell outside the beam of focused attention, the time to detect the target at the second most likely position increased because this single 'beam' of attention had to be shifted. This finding supports the hypothesis that the attentional beam cannot be divided. How could this finding be explained with attention splitting? One possible explanation is that the likelihood of the position is taken into account, such that more attentional resources are given to the most likely position and progressively less for positions further away. In this way, attention can still be split into several beams, but each with different resources, which would explain the differential RTs.

Eriksen and St. James (1986) subsequently showed that this enhanced processing within the attentional spotlight falls off monotonically as one moves out from the locus of visual attention, and that the resolution of the spotlight varies inversely with the size of the region encompassed; known as the “zoom-lens” model. Many investigators have concluded that the spotlight is the primary processing bottleneck of the attentional system, as only stimuli falling within this region undergo extensive perceptual analysis (e.g., Eriksen & Hoffman, 1974; Yantis & Johnston, 1990), and only one such region can be attended to at any one time (Eriksen & Yeh, 1985).

Adding to the evidence for a unitary focus of attention, Treisman, Kahneman and Burkell (1983) found that when attention was divided between two spatial areas, performance was reduced. In this divided attention study where visual search was involved, the participants had to read a word while locating a gap within a rectangle simultaneously and as fast as possible. The participants performed better when the gap and the word were in the same spatial location, and worse when they appeared in different spatial locations. This experiment suggests that either: 1) dividing the spotlight of attention between two spatial areas reduces the speed of processing because the available resources are also divided or, 2) that the spotlight of attention cannot be divided and the two tasks are processed serially.

However, it can be argued that if the purpose of spatial selection is to prevent distractors from interfering with the processing of a target, it is not surprising that this sort of split of attention was not seen in cueing studies with no distractors present (Posner et al., 1980). Since there were no distractors in those displays, there would be little reason or incentive, for observers to maintain attention at two separate locations without selecting the region in between. Moreover, the visual search paradigm alone may be insufficient to answer the question on the divisibility of the spotlight of attention. It is unclear whether the spotlight of attention is indivisible (Eriksen & Hoffman, 1972), or is divisible with a cost in performance (Treisman et al., 1983) based on the results of visual search paradigms.

Focused attention can be split to cover non-contiguous locations

There is mounting evidence suggesting that attention can be divided across non-contiguous regions of space, but only under the right circumstances. For example, Castiello and Umiltà (1990) used an innovative approach to demonstrate attention to non-contiguous locations in a cueing paradigm, based on the assumption that the benefits of attention will be diminished over a larger area (Castiello and Umiltà, 1990). They presented subjects with two box cues of different size, one on each side of fixation, marking the two potential locations of an upcoming stimulus. Reaction time at detecting the stimulus increased with increasing box size, which was interpreted as being evidence that subjects could simultaneously deploy two independent attentional foci in opposite visual hemifields. However, their experiments, like other cueing studies exploring this issue, leave open the possibility that subjects may attend to one location on some trials and to another location on other trials, producing mean response times that resemble a shift of attention. Castiello and Umiltà argued against this strategy by presenting the response time distributions and comparing variances between different conditions. Their evidence, therefore, does not completely exclude the possibility of attention to different locations.

A different approach comes from Heinze, Luck, Münte, Gös, Mangun, & Hillyard, 1994. Their subjects compared two shapes that were either at two contiguous locations or separated by another shape. Spatial attention was measured, using the first positive (termed 'P1') potential component of event-related brain potentials to probe stimuli that appeared after the stimuli that were to be compared. They found attentional enhancement of the P1 component for probes appearing at locations occupied by either of the targets to be compared and also for probes at the location in between the two targets. They concluded that the intervening region was selected along with the two targets. However, as they point out, the P1 component is an indirect measure and may not reflect all aspects of spatial attention.

Kramer and Hahn (1995) suggested that one important characteristic of the studies that failed to find evidence for split attention is that the targets and distractors have been presented as sudden onsets, which can automatically capture attention (Theeuwes, 1995). This may make it difficult or impossible for subjects to maintain their attentional focus on previously cued locations. When these sudden onsets appear, they capture participants' attention and this may wipe out the memory of previously cued locations. To test their hypothesis, Kramer and Hahn (1995) used an experimental paradigm modeled after that of Pan and Eriksen (1993), who used response competition to show that subjects were unable to selectively ignore stimuli that were located between two cued locations. Kramer and Hahn used boxes to cue two target locations separated by two distractor locations. The subjects determined whether the letters presented inside the two cue boxes were the same, while ignoring intervening distractor letters. In one condition, the letters were presented as sudden onsets, and in the other, they were revealed by the removal of segments of a figure-eight pre-mask (non-onset condition). As was predicted, distractor letters interfered with performance in the sudden-onset condition (as in Pan & Eriksen, 1993) but not in the non-onset condition.

A study by Bichot, Cave, and Pashler (1999) investigated subjects' ability to simultaneously attend to multiple non-contiguous locations in visual search by using two different methods. In one set of experiments, subjects attended to red digits presented in multiple frames with green digits, similar to the paradigm used in Cave and Pashler (1995). Accuracy was no better when red digits appeared successively than when red digits appeared simultaneously, implying split attention to the two locations simultaneously. Another experiment demonstrated split attention with an array of spatial probes, similar to one of the techniques used in the studies by Kim and Cave (1995) and Tsal and Lavie (1993). When the probe at one of two target locations was correctly reported, the probe at the other target location was more often reported correctly than any of the probes at distractor locations, including those between the targets. Together, these experiments provide strong converging evidence that when two targets are easily discriminated from distractors by a basic property, spatial attention can be split across both locations.

In a more recent study, McMains and Somers (2004) used fMRI to test whether attending to two separate locations leads to separate regions of neural enhancement in early retinotopic visual areas. Rapid serial sequences of letters and digits were presented independently in a four quadrant layout, with sequences being presented at the corners of the screen (i.e., top left , top right, bottom left, bottom right). In addition, a task-irrelevant sequence of digits was presented at fixation. The participants were instructed to maintain fixation on the central rapid seriel visual presentation (RSVP) stream, while covertly monitoring two of the RSVPs being presented in opposite sides of the screen (e.g., upper left and right). Participants were instructed to indicate when they perceived a digit in either stream. The control condition task was identical, except that participants only had to covertly attend to one RSVP location (e.g., upper left). McMains and Somers found that attending to the separated left and right stimuli led to greater fMRI activity in corresponding retinotopic regions, than when stimuli were ignored or when one location was attended. Also, no attentional enhancement was found for the central foveal stimulus. A rival hypothesis was that perhaps subjects were rapidly shifting a single spotlight from one location to the other. To test this, they asked participants to view similar displays of letter/digit sequences and to identify digits in either a single location or two locations. The items in the sequence were presented at varying rates of 40 to 250 ms/item. McMains and Somers hypothesized that if subjects were shifting attention from one location to the other, they should require at least twice the amount of time to identify a pair of letters in two locations than to identify a single letter in a single location. They found that subjects were almost equally good at monitoring two locations than they were at monitoring a single location at all presentation rates. Their results implied that participants were able to attend to the two locations simultaneously with minimal cost.

Additional evidence supporting the claim that attention can be split across non-contiguous locations comes from the electrophysiological study of Müller, Malinowski, Gruber, & Hillyard (2003). In their study they used an electrophysiological measure of attentional allocation (steady-state visual evoked potential; SSVEP) to show that the spotlight may be divided between spatially separated locations over more extended time periods. SSVEP is the electrophysiological response of the visual cortex to a flickering stimulus. SSVEP amplitude is increased when attention is focused upon the location of the flickering stimulus. Participants were asked to maintain fixation on a central white cross. The stimuli consisted of repetitively flashed white rectangles with superimposed red symbols that were presented at four positions along the horizontal meridian. The participants' task was to pay attention to the symbol sequences at two of the four positions, and to push a button upon detecting the simultaneous occurrence of a particular target symbol at those two positions. Müller et al. found that for all stimuli the SSVEP amplitudes were enlarged when attention was directed to their position. More importantly, they found that the SSVEP amplitudes to an intermediate ignored position, was reduced in relation to when that same position was attended. Müller et al. concluded that the SSVEP recordings provide evidence that the spotlight can be divided to facilitate processing of stimuli in non-contiguous locations over several seconds.

From the results of the Müller et al study (2003), it can be concluded with electrophysiological evidence that participants are able to attend to non-contiguous locations for several seconds, while ignoring in-between regions. For the current thesis, it would be interesting to find similar results with behavioral evidence such as target discrimination. When a target to be discriminated appears in between two cued locations, what happens to performance? Do RTs increase when the target appears in between two cued regions?

Attention by grouping

An important question for the current thesis is: When multiple attention cues are presented, how are they treated by the visual system? For example; if four cued locations are presented simultaneously, then the visual system can perceive these are either four individual objects, or by Gestalt heuristic of onset, group them together as a single object. A proposed mechanism of attentional selection is the grouped array theory originally developed by Vecera and Farah (1994). According to this theory, attending to an object involves attending to a set of locations that have been grouped together. Spatial attention is the selection mechanism in the grouped array account, and selection occurs by enhancing the perceptual processing of the locations within the attended object. In other words, targets appearing on the attended object will be more perceptible than targets appearing at other unattended objects. When attention is directed to a particular location, targets at that location are identified more efficiently. The grouped array hypothesis provides an explanation for some object-based attentional effects (Egly, Driver, & Rafal, 1994).

Whether or not attention is location-based or object-based depends on the task. Indeed, Vecera and Farah (1994) proposed that attention is object-based only when the task involves shape judgments that use object-centered representations (in the sense of Marr, 1982). In contrast, they predicted that attention would be location-based when the task involves judgment of visual features such as color or brightness. Egly, Driver, and Rafal (1994) performed an investigation that included both location-based and object-based components to visual attention. In their first experiment, they examined both location-based and object-based components of covert visual orienting within a single task, which was a modified spatial cueing paradigm. They cued participants to one location within an object and examined performance differences for the cued part of that object versus an un-cued part of the same object. This led to a measure of the spatial component of visual attention, because detecting a target at the un-cued part of the cued object required an attentional shift in location but did not require attention to be shifted to another object. The authors also compared performance on the un-cued part of the cued object with processing for parts from a simultaneously presented un-cued object. The probed parts of the un-cued object were the same distance from the cue as the un-cued part of the cued object and had the same retinal eccentricity. Comparing performance for these conditions allowed the researchers to compare within- and between-objects shifts of attention.

In their first experiment, Egly, Driver, and Rafal (1994) wanted to examine how cueing one part of an object affects the processing of other parts of that object and equidistant parts from another object. They presented two outline rectangles either above and below fixation or to the left and right of fixation. The task was to detect the "filling in" of one of the four ends of the two rectangles to yield a solid square at that end. Before the appearance of this square, one of the ends of a rectangle was brightened. On valid-cue trials, the square then appeared at the cued end of the cued rectangle. On the invalid-cue trials, the square appeared either at the un-cued end of the cued rectangle (this was the within-object shift) or at an equidistant end of the un-cued rectangle (this was the between-objects shift). The results revealed both location-based and object-based components of visual attention within the same task. They found RT to detect brightening at one location within an object was delayed if attention had been directed by the cue to a different location within the same object. This led to a cost when attention needs to be shifted to a new location in an attended object and thus revealed a purely spatial component of attentional selection.

However, detection was significantly delayed if attention had to be shifted to a different object. Since the distance and direction of between-objects shifts were identical across trials to within-object shifts, the authors concluded that the additional cost of between-objects shifts must reflect a time cost for shifting attention between objects, thus demonstrating an object-based component of attention. Thus, within the same detection task, there can be both object-based and location-based components of covert visual attention (Egly et al., 1994).

According to the grouped array hypothesis, spatial attention forms a sensitivity gradient around the attended object. In one such study (Hollingworth, Maxcey-Richard, & Vecera, 2012), on each trial the target could appear at one of four possible locations relative to the cue: at the cued location (valid condition), at a near location within the cued object, at a far location within the cued object, and at a far location within the un-cued object. The three locations within the cued object allowed for an examination of spatial gradient effects within an attended object. Of importance, the far locations in the cued and un-cued objects were equally distant from the cue, providing an examination of object-based effects independently of distance. Consistent with the grouped array claim that attention forms a spatial gradient around the attended object, there was an effect of distance within the cued object, with discrimination accuracy decreasing with increasing cue-target distance. The researchers found discrimination accuracy was 17% higher when the target appeared at the near location compared to when it appeared at the far location within the cued object. They also found a reliable effect of same-different object. The results showed that discrimination accuracy in the same object far condition was significantly higher than accuracy in the different object far condition (this result replicated the basic finding of Egly et al., 1994).

Based on the results from the Hollingworth et al study (2012), it can be concluded that attention by way of spatial cueing improves performance on a discrimination task. Moreover, this performance was directly related to the distance between the cue and the target. As the distance between the cue and the target increased, performance dropped. When the target appeared near the cue, participants' discrimination performance was at its best. This suggests that there is a limit to the size of the attentional spotlight. For optimal performance, cue and target should be near one another. For the current thesis, it would be interesting to find a similar effect of the distance between the cue and the target. Since multiple regions of attention are being studied in the current thesis, what will be the effect if the target is placed in between two cues? Will this hamper participants' discrimination performance due to the distance between the cues and the target? This leads to a further question: How constricted are these attentional beams and can they overlap?

The present study

The purpose of the present study is to investigate the claim that attention could be allocated to two or more non-contiguous locations simultaneously. This study uses a technique, which to the best of my knowledge, has not been used by other investigators studying the splitting of attention.

An important condition that must be met in order for attentional splitting to occur, is that there must be two or more separate areas of activation, or perceptual facilitation in terms of target discrimination, with no activation in between those areas. In addition, it would be interesting to find that there is no cost in performance (in terms of RT) with one focus of attention or two foci of attention (or more). This would suggest that there is no cost in RT with more than one focus of attention. This would imply that two or more target locations could be selected and processed at once.

All of the experiments in this study involve exogenous cueing. The cue is always stimulus-driven (peripherally positioned) and elicits bottom-up processing. In the present study, it is expected that RT to target discrimination will be shorter in the valid cue condition as compared to the invalid or no cue condition. This hypothesis is tested in Experiment 1 of the present thesis. Moreover, if attention can be split into two spotlights that are focused on two spatially distant regions, then RT should be longer when the target appears in between two cued regions. This would imply that there is little or no activation in between the two cued regions. This hypothesis is tested in Experiment 2. Experiment 3 compares RT for target discrimination when only one area is selected for processing versus two cued areas. It is expected that RT will be the same when attending to one or two non-contiguous regions. This would imply that the attentional beam can be separated to cover more than one area at the same time.

Another hypothesis is that there will be no difference in RT for target discrimination when participants are attending to one, two, or more separate regions. This will imply that there is no cost in RT when attending to two or more areas and that, more than one location can be selected at once. Experiment 4, involves cueing one of the four place holders that make up the visual stimulus, and cueing all four place holders and measuring differences in RT for target discrimination. It is expected that there will be no difference in RT when attention is placed in one region or four regions. This would lend support to the premise that more than one non-contiguous area can be selected for processing at the same time.

EXPERIMENT 1

Cueing one spot – A single focus of attention

Purpose

Posner, Snyder and Davidson's (1980) studies have shown that a subject's knowledge of where in space a stimulus will occur affects the efficiency of detection. More specifically, cueing the spatial location where the target will appear can reduce the time required to detect the target. Their findings led to the idea of attention as an internal eye or spotlight, with cueing affecting the position of the spotlight. Theories of detection and visual attention have emphasized that the spotlight of attention helps to process the information that falls within its beam faster and more accurately (Posner, 1980; Eriksen & Hoffman, 1972; Julesz, 1984; Yeshurun & Carrasco, 1998), and the remainder of the visual field is partially filtered out and/or suppressed. The position of the spotlight in space is flexible and can be changed with the proper cue.

Why does a cued location, that causes a shift in attention, cause a decrease in reaction times? Researchers have provided evidence that attention can increase the perceptual awareness of targets such as increases in acuity, contrast sensitivity (e.g., Yeshurun & Carrasco, 1998; Pestilli & Carrasco, 2005; Carrasco, Ling & Read, 2004; Treue, 2004). The cued stimulus becomes easier to detect, and therefore easier to discriminate. In other words, this causes a perceptual increase when attention is directed to a stimulus location. Attention causes the stimulus to be more visible, and this causes the stimulus to be easier to discriminate. Recently, researchers have been suggesting that attention can intensify the sensory impression of a stimulus (e.g., Yeshurun & Carrasco, 1998; Pestilli & Carrasco, 2005; Carrasco, Ling & Read, 2004; Treue, 2004). In such studies, attention has been found to change the strength of a stimulus by increasing its perceived contrast or salience. In addition, attention provides a sensorial boost to a perceptual stimulus. As an example, Carrasco found a doubling effect of contrast sensitivity when attention was deployed to the target region (Carrasco, Ling & Read, 2004).

Carrasco and colleagues have shown that attending to a region in the field of view, either through endogenous or exogenous shifts of attention, can cause an increase in both visual resolution and contrast sensitivity (Carrasco, Ling, & Read, 2004; Yeshurun & Carrasco, 1998; Carrasco et al., 2002). Attention has also been shown to enhance neuronal (McAdams & Maunsell, 1999; Treue & Martinez-Trujillo, 1999), and behavioural sensitivity (Lu & Dosher, 1998; Baldassi & Burr, 2000), which may be the mechanism behind the perceived increase in resolution and contrast seen in psychophysical studies.

However, what are the spatial limits of attention? More specifically, when moving beyond two potential stimuli locations, is there a limit of how many locations we can attend to? In addition, how does visual attention behave at multiple locations? The problem with addressing these questions with the paradigm used by Posner and colleagues (1980), is that the stimulus locations are limited to only two spatial locations (i.e., left and right), of which only one can be cued at any time. Because the main aim of this thesis is to investigate cueing at multiple locations (i.e., greater than two), and cueing more than one location at a time, I wanted to assess if the new stimulus paradigm used throughout this thesis can be used to obtain the same cueing effect results as previously reported by Posner and colleagues (1980). Briefly (as the stimulus is described in detail in the method section), the new stimulus consists of four possible cue locations, with each potential location located in 45 degree increments (45, 135, 225, 315 degrees) at the same eccentricity. In any one trial, one of the circle stimuli can be cued by changing the circle from black to white. After this, a discrimination target, the letter T, was presented in a location that was either congruent or non-congruent with the cued location. Cues could be valid, invalid, or non-informative. If this new stimulus operates the same way as Posner's stimulus, it is expected that for the valid cue condition response times will be the shortest as opposed to the invalid cue, where response times will be the longest in comparison to the non-informative cue condition.

Method

Participants

A total of twelve undergraduate observers with self-reported normal (i.e., 20/20) or corrected-to-normal vision participated in the experiment. All participants in this and subsequent experiments were treated according to the Canadian Institutes of Health Research, Natural Sciences and Engineering Research Council of Canada, and the Social Sciences and Humanities Research Council of Canada, Tri-Council Policy Statement: Ethical Conduct for research involving Humans (2010), and was approved by the Concordia University Human Research Ethics committee. Participants received compensation for their time via a course credit system within the Department of Psychology at Concordia University, or were members of the Visual Perception Lab at Concordia University.

Apparatus and Stimuli

The stimuli were presented on a 19-inch Apple color monitor, at a resolution of 1024 x 768 pixels, with a screen refresh rate of 99 Hz, and controlled by a Power Macintosh G4. The experiment was programmed using the Vpixx software (Version 2.03,Vpixx technologies, Saint-Bruno, QC). The distance from the screen to the participant's eye was set at 57 cm. A chin-forehead stabilizer was used in order to prevent the participant's head from moving. The testing took place in a dark and quiet room.

All of the test stimuli consisted of four black circles and a black letter "T" (luminance of 18.4 cd/m^2), presented on a grey background (luminance of 22.4 cd/m^2). The circles were positioned at a distance of 6.5° of visual angle from the fixation point, and formed an imaginary square around the fixation point. The target was present on all trials, and was positioned randomly at a distance of 1° of visual angle from one of the four circles. The target could either appear at the top right, bottom right, top left or bottom left quadrant of the screen. On half the trials, the target was positioned to the left, and on the other half to the right. The cue consisted of one of the black circles flashing white. The cue was valid when the target appeared near the circle that flashed white and invalid when it appeared near a black circle (see Figure 1.1 & Figure 1.2).When none of the black circles flashed white, it was considered a non-informative (i.e., neutral cue) trial.

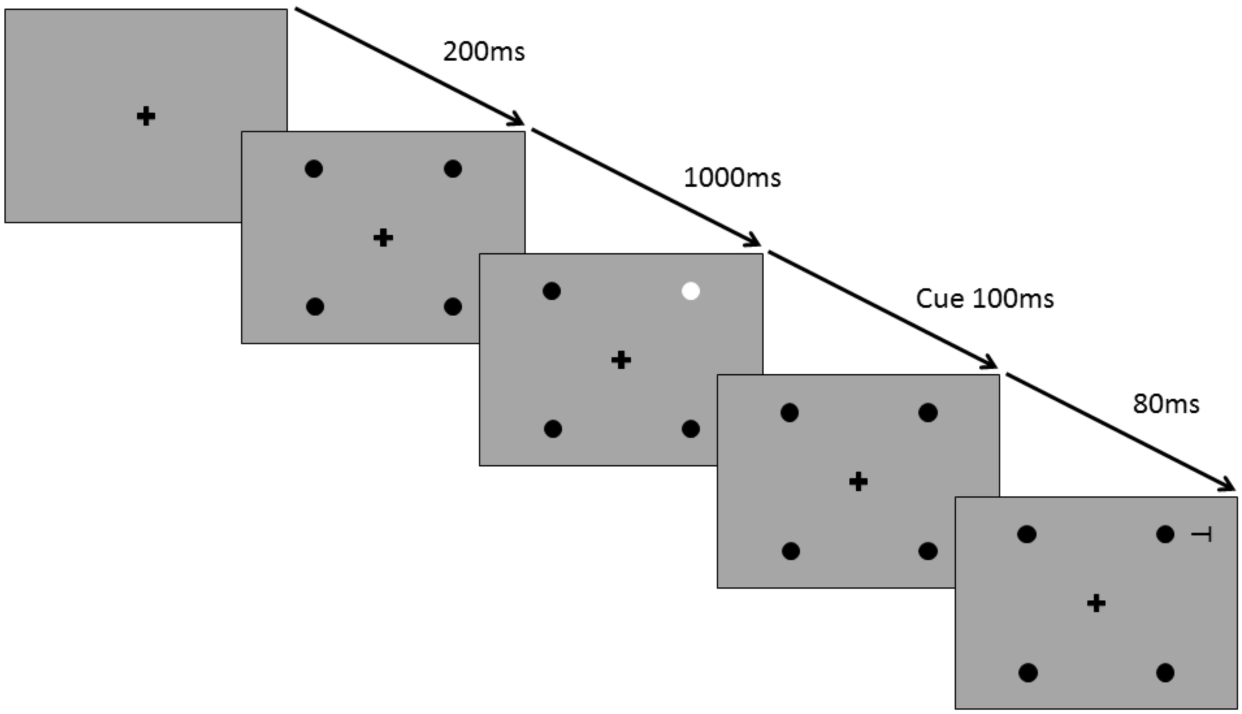

Figure 1.1. Example of a valid (i.e., congruent) cueing trial. In a valid trial, the discrimination target (i.e., T) would only appear next to the cued location. The participant's task was to discriminate the direction of the T (either to the left or right).

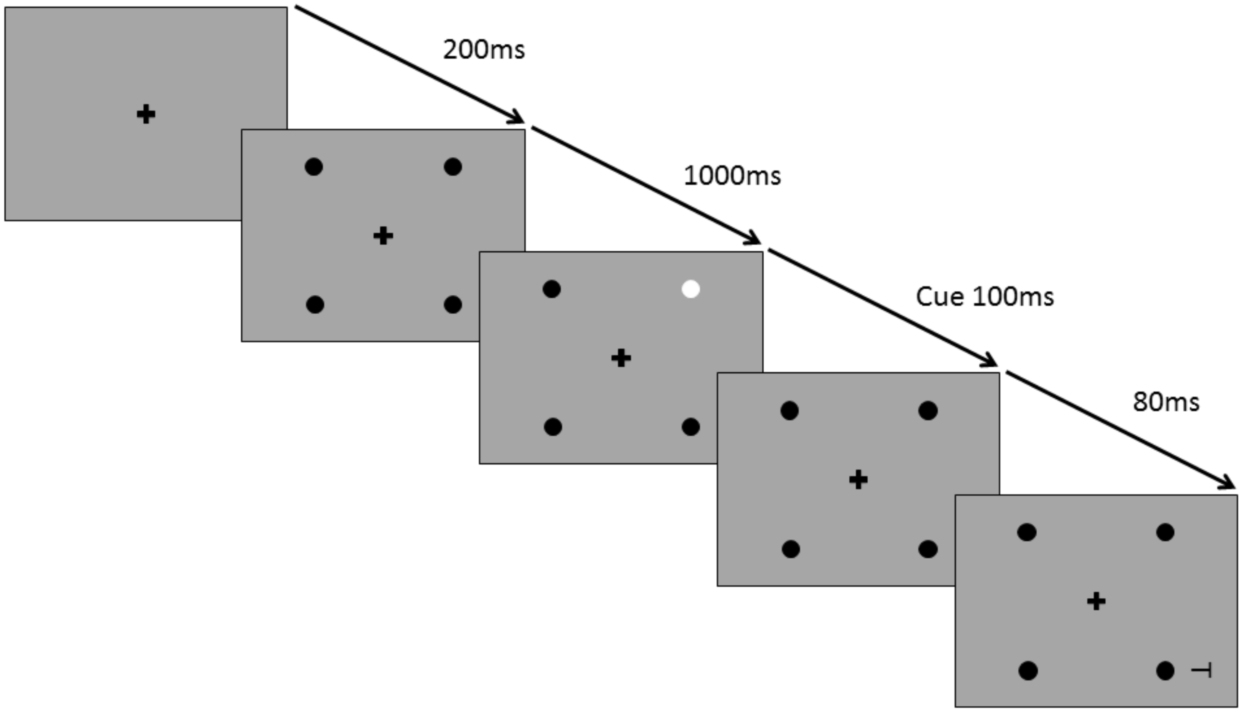

Figure 1.2. Example of an invalid (i.e., incongruent) cueing trial. Note that on an invalid trial, the discrimination target (i.e., T) could appear at any one of the three non-cued locations.

For the target discrimination stimulus, a letter T was used that had a size of 1º x 1º, with a line thickness of .08° of visual angle. The length of the top (i.e., horizontal) bar was .8° of visual angle, and the length of the vertical bar was 1° of visual angle. The letter T was rotated 90° to the left or to the right. The fixation was a black cross positioned in the middle of the screen and occupied .5˚ of visual angle.

Design and Procedure

This experiment had a one factor within-subject design. The independent variable is the type of cue with three levels: valid (level 1), invalid (level 2), and non-informative (level 3). The dependent variable (response time, or RT) was the time required to discriminate the target orientation (left or right). The response time was measured in milliseconds, and only correct trials were used. The observer was asked to respond as quickly and as accurately as possible**.** Reaction times and error rates were recorded by the computer.

A trial consisted of the fixation cross, which was presented for 200 ms, followed by the four black circles for 1 second. Then the cue was presented for 100 ms. Next, a gray screen was presented for 80 ms, after which the discrimination target was presented and remained on the screen until the participant made a response via a keyboard press. If the participant thought that the discrimination target pointed left, they responded using the left arrow key. Conversely, if the participant thought that the discrimination target pointed right, then they responded using the right arrow key. Participants were instructed to be as accurate, yet fast as possible in making their response. In addition, participants were instructed to maintain fixation on the fixation cross at all times during the experiment.

Experiment 1 consisted of 480 trials, and lasted approximately 20 minutes. The composition of the 480 trials was as follows: the target could be in 1 of 4 positions (quadrants of the screen), (4), the target could be pointing to the left or right (2), the cue could be valid (33%), invalid (50%), or non-informative (17%). Each of these 48 conditions was repeated 10 times. Errors were infrequent (~5%) and were examined for speed-accuracy trade off, but none was found.

Statistical Analyses

Many researchers are starting to believe that relying on and reporting *p*-values alone is a bad thing for science. Instead, reporting descriptive statistics has become the trend in many scientific journals, and indeed is now a requirement in many American Psychological Association journals. Specifically, researchers are starting to use measures of effect size more frequently (e.g., Cohen, 1994; Kline, 2004). Therefore, in this thesis, I do not solely rely on *p*-values. Instead, I also report the appropriate effect size measures, partial eta squared ($\eta_p^2 = SS_{effect}/SS_{effect}+SS_{error}$) for ANOVAs, and Cohen's d for difference scores ($d=M_1-M_2/SD_{pooled}$). The advantage of a measure of effect size is that it is not influenced by sample size. However, for a fixed η_p^2 in the population, the corresponding *F* ratio ($F = SS_{effect}/SS_{error} * df_{error}/df_{effect}$) increases with the number of degrees of freedom in the error term. Consequently, a small effect size (η_p^2) becomes statistically significant with a large enough sample. Conversely, relatively large values of η_p^2 may not be statistically significant if we are using a small sample size. Consequently, the effect size stays closer to the data, and is a measure of a magnitude of any difference in the data.

As noted by Cohen (1988), whether a particular effect size magnitude is considered large or small depends on the relevant literature. It would be worthwhile to survey the literature in vision science journals to determine the range of effect sizes typically found. In the writing of this thesis, I attempted to measure the effect sizes of the relevant literature on exogenous attention. However, many of the articles failed to report the necessary statistics (e.g., t values, f ratios, sum of squares, degrees of freedom) that are required for the calculation of an effect size. In addition, in the most relevant literature that relates to this thesis, the probability values (*p*) are reported in great and less than format (e.g., $p > .05$, $p < .001$). Thus, it was not possible to use the literature to relate the magnitude of the effect sizes reported in the current thesis to descriptive categorizations (e.g., large, small). Consequently, throughout the rest of the thesis, I categorize the effect size as small ($\eta_p^2 < 0.3$), medium ($0.3 < \eta_p^2 < 0.5$), large ($0.5 < \eta_p^2 < 0.6$), and very large ($\eta_p^2 > 0.6$). The same categorization will be used for the Cohen's *d* effect size measure. It should be acknowledged that the choice of these values is somewhat arbitrary. However, because the actual effect sizes are reported, and not just the categorization, readers are free to judge whether they agree with the characterizations in this thesis. Further, future researchers will be able to compare their results to the reported effect size.

The results are analyzed using ANOVA conducted with SPSS (version 15). For each participant, each data point represents the average mean RTs for each condition. The average mean RTs for each participant were subjected to a repeated-measures ANOVA using SPSS. All response times less than 100 ms or greater than 1000 ms were removed as outliers prior to the statistical analysis. In this and all subsequent analyses, I will report partial eta-square (η_p^2) as an effect size measure, and the reported *p*-values correspond to those obtained following the Greenhouse-Geisser correction for violations of sphericity (Greenhouse & Geisser, 1959). Note that although the Greenhouse-Geisser correction is applied, the degrees of freedom for the effect and error are the original degrees of freedom. In addition, difference scores and Cohen's d will be calculated and reported in a descriptive table for all group comparisons, for all experiments.

Results

The first experiment concerned whether spatial cueing would reduce the time required to detect the target. To investigate the role that spatial cueing has on the spotlight of attention, three types of cues were used. Namely, valid, invalid and non-informative cues were used to guide subjects' attention. Figure 1.3 depicts the results of the cue effect, with the response time (in milliseconds) plotted on the y-axis, and the three types of cues (valid, invalid, and non-informative) are plotted on the x-axis. As can be observed in Figure 1.3, the valid cue led to the shortest RTs (M = 490.87, SD = 19, 95% CI [478.8, 503.0]), with longer RTs for both the invalid (M = 536.08, SD = 22.5, 95% CI [521.8, 550.4]) and neutral cues (M = 542.06, SD = 17.3, 95% CI [531.1, 553.1]). A repeated-measures ANOVA on RTs for cue type was performed, and showed a significant main effect of cue type: $F(2,22) = 16.1$, $p = .001$, $\eta_p^2 = .59$. Thus, the type of cue does have an effect on reaction times.

To investigate this finding further, difference scores between the three cue type conditions were calculated (see Table 1). The difference between the valid cue and the invalid cue (d = 1.19), was greater than the small difference between the invalid cue and the non-informative neutral cue (d = .17). Moreover, the difference between the valid cue and the neutral (d = 1.79) was very large in comparison to the difference between the invalid and neutral cues, and between the difference between the valid and invalid cues. This result would suggest that spatial cueing can affect the position of the spotlight, and most importantly for the current thesis, can change the location of the attentional spotlight.

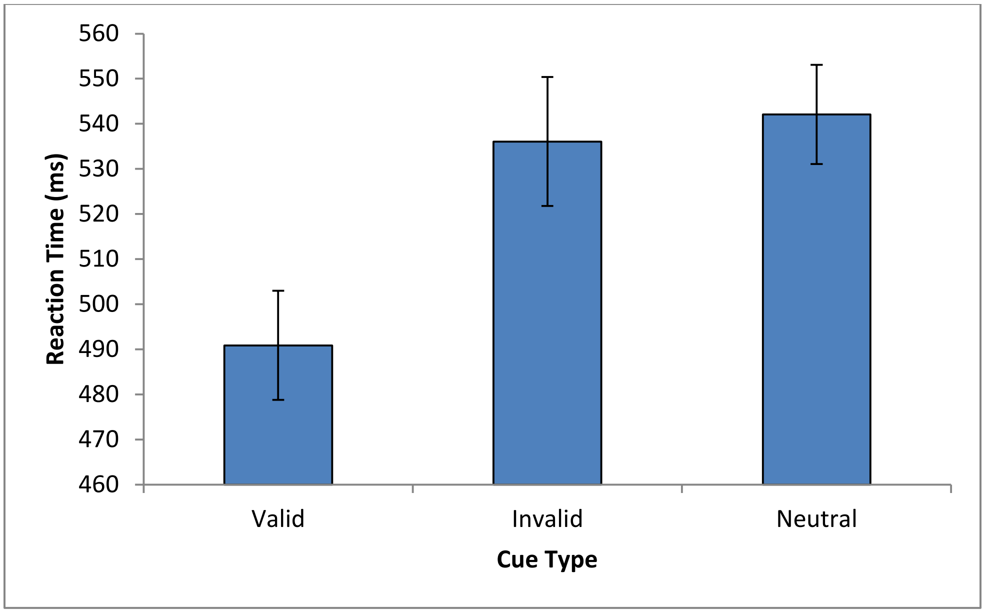

Figure 1.3. Effect of cue type (valid, invalid, neutral) on reaction times. Error bars represent 95% confidence intervals around the mean after normalization to remove between-subject variability (Loftus & Masson, 1994).

	Mean D.	SD	Lower	Upper	D
Valid-Invalid	-45.2049	37.93411	-69.307	-21.1027	-1.19167
Valid-Non-Informative	-51.1885	28.57359	-69.3433	-33.0337	-1.79146
Invalid-Non-Informative	-5.98368	35.39292	-28.4713	16.50391	-0.16906

Table 1. Difference scores for all condition comparisons for Experiment 1.

Discussion

This experiment concerned the location of the spotlight of attention. Previous research by Posner and colleagues (1980) has shown that knowing where the target will appear speeds up detection times. In addition, they showed that spatial cueing by highlighting one of two locations could change the location of the attentional spotlight. Stimuli that lie within the spotlight are processed with greater efficiency compared to stimuli that lie outside of the spotlight of attention. But the question remained: would the same cue location effect remain if more than two possible cue locations existed? The aim of the current experiment was therefore to replicate the effect observed by Posner and colleagues (1980), but using a four potential location stimulus instead of the two cue locations used by Posner. From the results observed in Experiment 1, the answer is yes: attention can be successfully cued to one of four locations. The results of this experiment support the hypothesis that the spotlight of attention can change location when multiple potential locations are present.

As can be seen in Figure 1 of Posner and colleagues study (1980), with two potential cue locations, there is an increase in response times when the cue was presented in an invalid configuration, in comparison to the decrease in reaction times observed when the cue was valid. The results of the current experiment show the same trend, with reaction times decreasing when the target appears next to the cued location. However, the magnitude of the valid/invalid change in response time cannot be compared directly, as Posner does not report the necessary statistical values required to calculate an effect size.

An explanation as to why cueing a location leads to decreased RTs is that the stimulus is more salient, and thus the visual system encodes and responds to it faster. Carrasco and colleagues (2004) showed that attention could alter appearance, such as boosting the apparent stimulus contrast. In their study, they assessed the effects of transient attention on perceived contrast. They found that when observers' attention was drawn to a stimulus location, observers reported that stimulus as being higher in contrast than it really was. This indicated that attention changes appearance.

The findings of experiment 1 are in agreement with the previous studies of exogenous cued attention. However, the stimulus configuration (i.e., 4 potential cue locations) used in the current experiment is novel. The reason why it is important to have more than the two locations is that this new stimulus allows the possibility of cueing more than two spatial locations. This is an essential feature of the stimulus that is important to the current thesis, as it allows the investigation of different characteristics of attention. This new stimulus paradigm can be used to answer questions that the standard two-cued location paradigm cannot answer. For example, and of importance to this thesis, is how attention is selecting the different potential cue locations. More specifically, is attention being split between the different locations as would be proposed by the attentional spotlight model (Posner, 1980). This is the idea that our attention moves around our field of vision so that stimuli falling within its beam are processed preferentially. In other words, can two separate areas be selected for processing at the same time? Using terminology from the spotlight of attention, can there be more than one attentional beam? Or is attention operating across the entire stimulus, as has been proposed in the zoom lens model (Eriksen & St. James, 1986; LaBerge, 1983). In the zoom lens metaphor, we zoom in and out depending on the task. The zoom lens model of visual attention proposes that the attended region can be adjusted in size and predicts a tradeoff between its size and processing efficiency because of limited processing capacities. This question will be addressed in Experiment 2.

EXPERIMENT 2

Cueing two spots – Two foci of attention

Purpose

In experiment 2, the aim is to expand on experiment 1, by cueing more than one location at a time. Specifically, what happens when two locations are cued simultaneously?

Previous researchers have shown that attention to multiple locations can be thought to operate in two different modes. The first mode is commonly referred to as the spotlight model of attention (Posner, Nissen, & Ogden, 1978; Muller, Malinowski, Gruber, & Hillyard, 2003; Posner, 1980; Eriksen & Hoffman, 1972; Julesz, 1984; Yeshurun & Carrasco, 1998). This is the concept that our attention moves around our field of vision so that the things falling within its beam are processed preferentially. Moreover, stimuli that lie outside of the attentional beam are partially filtered out or suppressed.

The second mode of attention is commonly referred to as the zoom-lens model of attention. According to this model, the size of the focus depends on the size of the stimulus and is adjusted accordingly. The zoom-lens of attention can be described in terms of an inverse relationship between the size of focus and the efficiency of processing. Since attentional resources are assumed to be fixed, then it follows that the larger the focus is, the slower processing will be of that region of the visual scene since this fixed resource will be distributed over a larger area. It is thought that the focus of attention can subtend a minimum of 1° of visual angle (Eriksen & Hoffman, 1972, 1973). However the maximum size has not yet been determined.

The question then becomes – how would either of these models respond to the stimulus described in Experiment 1? If attention behaves like a spotlight, then there should be no reaction time benefit (i.e., decreased reaction times) by presenting a discrimination target in-between the two cued locations. However, if attention is working like the zoom-lens model, then we should see the same or a similar reaction time benefit when the discrimination target is located in-between the two cued locations, as we do when the discrimination target is located near one of the cued locations.

The purpose of this experiment was to measure the effects of valid and invalid cueing on RT for target discrimination, when two non-contiguous regions are attended. This experiment used an additional type of invalid cue, namely the in-between two cued spots. Specifically, the in-between condition occurred when two spots were cued and the target appeared in between these two cued regions. The goal of this experiment was to investigate whether cueing can result in two separate attentional areas, without any attentional enhancement occurring at un-cued regions or in between two cued regions.

As was the case in Experiment 1, it was expected that the valid cue would reduce RT, while the invalid, as well as the in-between cues should increase RT.

Method

Participants

The participants were thirteen subjects from Concordia University, all with self-reported normal (20/20) or corrected-to-normal vision.

Apparatus and Stimuli

The apparatus and stimuli were similar to Experiment 1, except that in this experiment there were two cues, which consisted of two of the black circles flashing white. Either the two top spots were cued, the two bottom spots, the two spots on the left of fixation, or the two spots on the right of fixation.

In the valid cue condition, the target appeared near one of the circles that flashed white, and invalid when it appeared near a black circle. In the in-between condition, two spots were cued and then the target appeared in-between these two cued region (see Figure 2.1, Figure 2.2 and Figure 2.3).

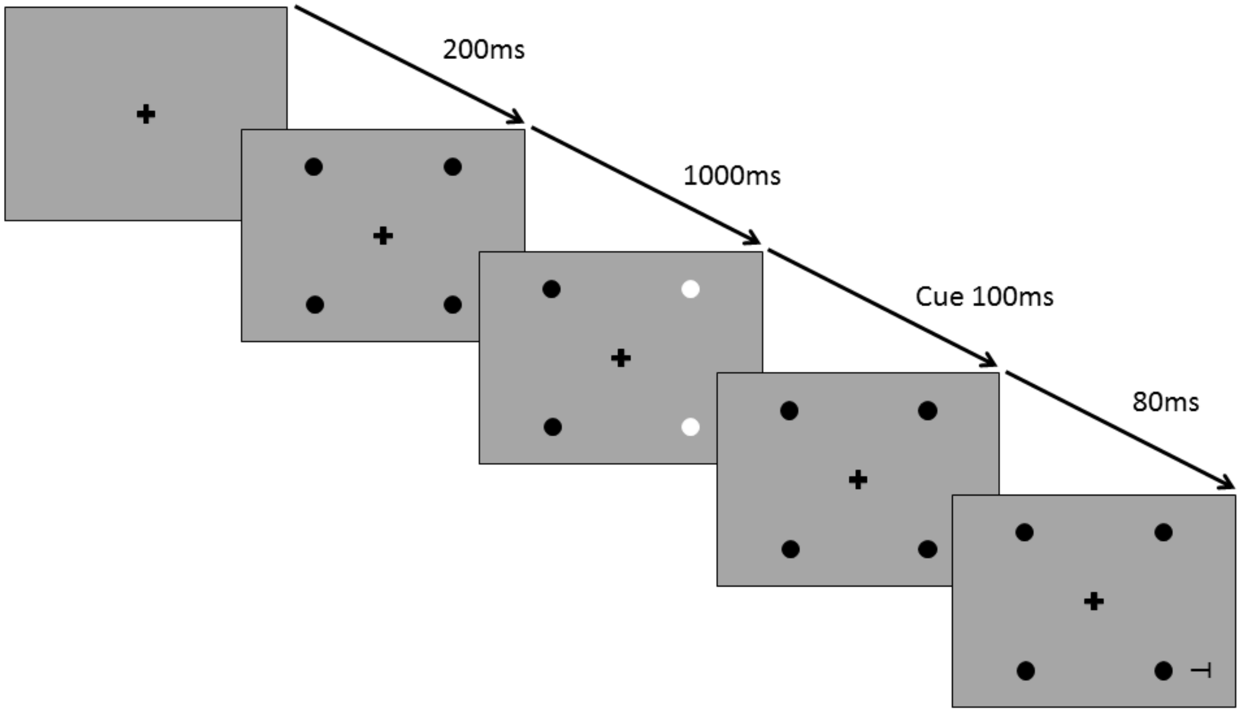

Figure 2.1. Example of a two spots valid cue trial. Here the discrimimation target appears next to the bottom right cued location.

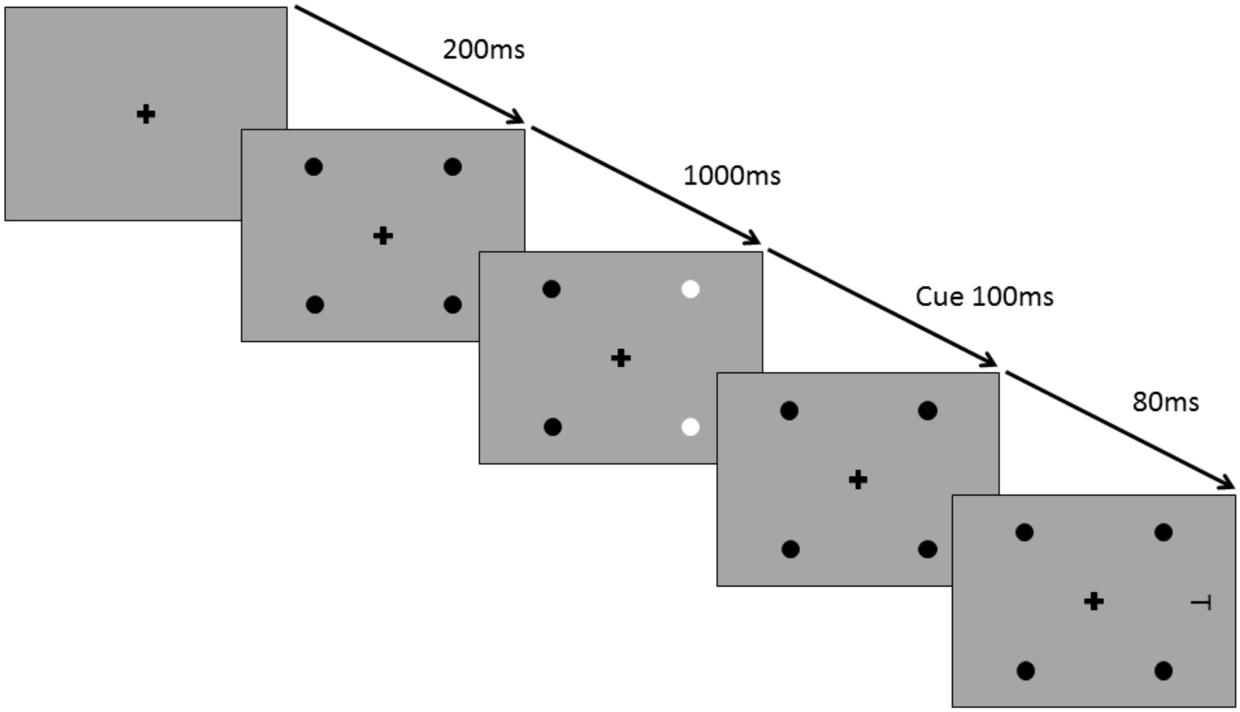

Figure 2.2. Example of two cued locations. Here the discrimimation target appears inbetween the two cued locations.

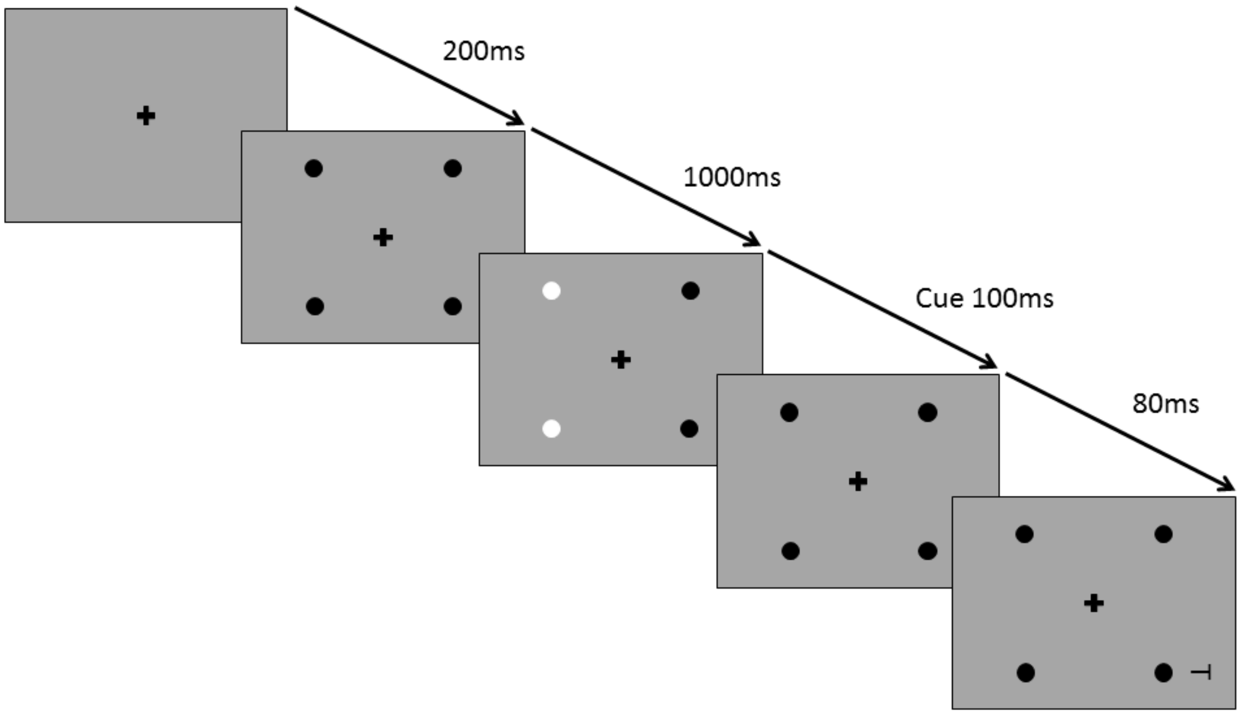

Figure 2.3. Example of an two-cued invalid trial. Here the discrimination target appears near a non-cued spot.

Design and Procedure

This experiment had a one factor within-subject design. The independent variable is the type of cue with three levels: valid (level 1), invalid (level 2), and in-between (level 3). The dependent variable (response time, RT) was the time required to detect the target orientation (left or right). Reaction times and error rates were recorded in the same way as experiment 1. The presentation timings were also the same as experiment 1.

Experiment 2 consisted of 720 trials, and lasted approximately 45 minutes. The composition of the 720 trials was as follows: the target could be in 1 of 4 positions (quadrants of the screen), (4), the target could be pointing to the left or right (2), the cue could be valid (67%), invalid (22%), or in-between (11%). Each of these 72 conditions was repeated 10 times. Errors were infrequent (~5%) and were examined for speed-accuracy trade off, but none was found.

Results

This experiment concerned the attentional selection of two separate areas. To investigate whether cueing can result in two separate attentional areas, without any attentional enhancement occurring at un-cued regions or in between two cued regions, two clearly defined and separate areas were cued. The results of the effect of cue type on reaction time are shown in Figure 2.4. Similar to experiment 1, the results show that the shortest RTs occur when a valid cue is presented (*M* = 504.1, *SD* = 14.2, 95% CI [495.5, 512.7]), and longest when the cue is invalid (*M = 521.49, SD = 10.4,* 95% CI [515.2, 527.8]). Interestingly, the in-between cue appears to give RTs that lie between these valid and invalid conditions (*M* = 518.5, *SD* = 17.3, 95% *CI* [508.0, 529.0]). A repeated-measures ANOVA on RTs for Cue Type (valid, invalid, and in-between) found a significant main effect of the cue type: F(2,24) = 3.697, $p = .04$, $\eta_p^2 = .24$.

To explore the magnitude of the increase in RTs from the valid to invalid/in-between conditions, the difference scores between each cueing condition and the effect size of the difference were calculated (Table 2.1). A very large difference was observed between the valid cue and the invalid cue ($d = .97$), which was greater than the difference found between the valid cue and the in-between cue ($d = .48$), which in turn, was greater than the difference between the invalid cue and the in-between cue, which had a small effect size, ($d = .12$). Taken together, these data would suggest that spatial cueing can affect the position of the spotlight. Further, the in-between cue condition would suggest that attention is split between the two cue locations, with no overlap or spilling of attention between the two locations.

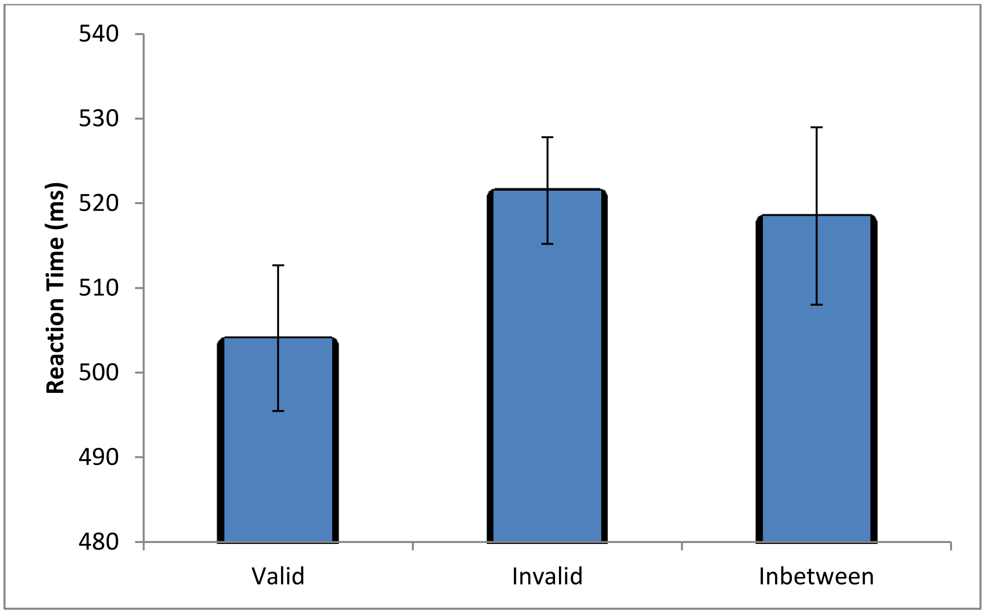

Figure 2.4. Effect of cue type (valid, invalid, and in-between) on reaction times (in milliseconds). Error bars represent 95% confidence intervals around the mean after normalization to remove between-subject variability (Loftus & Masson, 1994).

	Mean D.	SD	Lower	Upper	D
Valid-Invalid	-17.44	17.99	-28.31	-6.57	-0.97
Valid-Between	-14.44	29.93	-32.52	3.65	-0.48
Invalid-Between	3.00	24.79	-11.98	17.98	0.12

Table 2.1 Difference scores for all condition comparisons for Experiment 2.

Previous studies of attention have shown a hemispheric effect on attention (Harter, Aine, & Schroeder, 1982; Kraft, Muller, Hagendorf, Schira, Dick, et al., 2005; Ibos, Duhamel, & Hamed, 2009; McMains & Somers, 2004; Muller, Malinowski, Gruber, & Hilyard, 2003; Awh & Pashler, 2000). Therefore, a further analysis was performed to investigate if the configuration of the cues had an effect on the splitting of attention. Of particular interest was to examine if there was a difference between the horizontal (two top cues and two bottom cues), and the vertical (two cues left of fixation and two cue right of fixation) cue configurations. Figure 2.5 depicts the results of the interaction effect between the cue type and the configuration type. A repeated-measures ANOVA on RTs for configuration was performed. A significant interaction between cue type and configuration type (horizontal vs. vertical) was found, $F(2,24) = 8.975$, $p = .003$, $\eta_p^2 = .43$. In the vertical configuration, the difference between the valid cue ($M = 502.76$, $SD = 13$, 95% CI [494.9, 510.6] and invalid cue ($M = 523.16$, $SD = 17.2$, 95% CI [512.7, 533.6],$d = 1.21$), was greater than the difference between the valid cue and the in-between cue ($M = 496.3$, $SD = 19.2$, 95% CI [484.7, 507.9], $d = .36$), and was also greater than the difference between the invalid and the in-between ($d = 1.10$). In the horizontal configuration, the difference between the valid cue ($M = 505.36$, $SD = 22.5$, 95% CI [491.7, 519.0] and in-between cue ($M = 540.70$, $SD = 39.9$, 95% CI [516.6, 564.8], $d = .65$) was greater than the difference between the invalid ($M = 519.8$, $SD = 11.4$, 95% CI [512.9, 526.7] and in-between cue conditions ($d = .53$), and was also greater than the difference between the valid and invalid cue conditions ($d = .47$).

When investigating the configuration conditions using difference scores between the cue conditions, the difference between the horizontal and the vertical configurations for the in-between cue condition ($d = .85$) was greater than the difference between the horizontal and vertical configurations for the invalid cue ($d = .16$), and was also greater than the difference between the two configuration types for the valid cue (*d* = .11). See table 2.2 for the difference scores for all comparisons for the interaction between configuration and cue type for this experiment. Thus, although there is only a small difference in the RTs between the valid and invalid cue conditions due to the cue configuration, there is a large difference in the in-between conditions, with RTs being longer in the horizontal cue configuration.

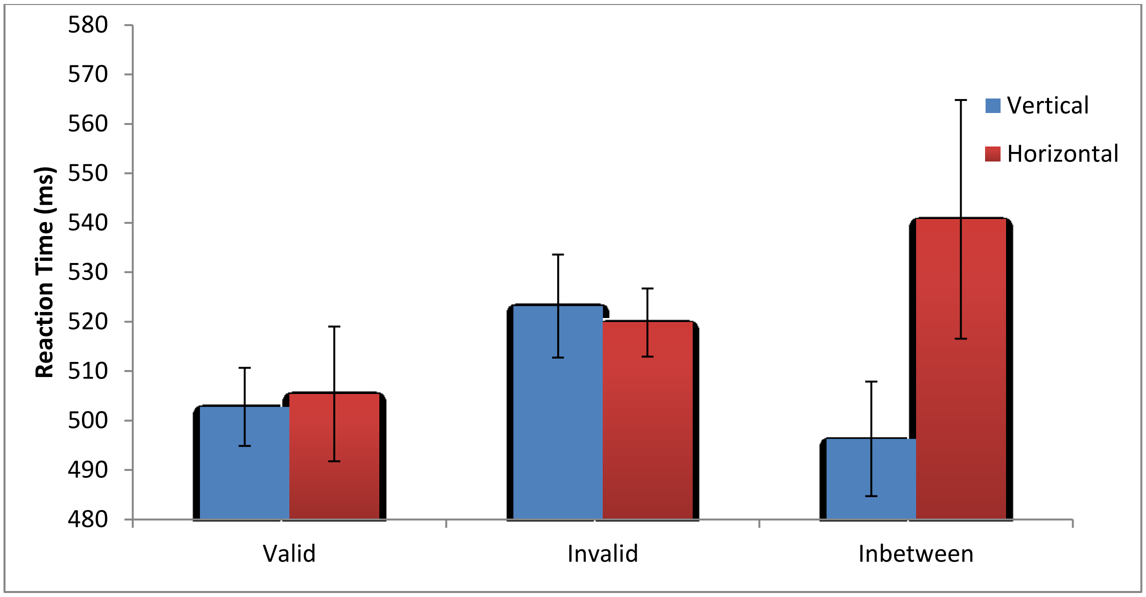

Figure 2.5. Interaction Effect of cue type (valid, invalid, and in-between) and configuration type (vertical and horizontal) on reaction times. Error bars represent 95% confidence intervals around the mean after normalization to remove between-subject variability (Loftus & Masson, 1994).

		Mean D.	SD	Lower	Upper	D
Vertical	Valid-Invalid	-20.4	16.91	-30.62	-10.19	-1.21
	Valid-Between	6.46	17.98	-4.4	17.33	0.36
	Invalid-Between	26.87	24.41	12.12	41.62	1.1
Horizontal	Valid-Invalid	-14.47	30.98	-33.2	4.25	-0.47
	Valid-Between	-35.34	53.99	-67.97	-2.71	-0.66
	Invalid-Between	-20.87	39.1	-44.5	2.76	-0.53
Vertical - Horizontal	Valid	-2.6	23.34	-16.71	11.5	-0.11
	Invalid	3.33	20.47	-9.04	15.69	0.16
	Between	-44.41	52.2	-75.95	-12.86	-0.85

Table 2.2. Difference scores for all comparisons for the configuration by cue type interaction for Experiment 2.

Discussion

This experiment concerned the attentional selection of two separate areas, where two separate and non-contiguous regions were cued. The questions addressed in Experiment 2 were the following: Can attention be split between two regions with no activation in-between the two cued regions? Or does attention work like the zoom lens model – focusing out to cover both cued regions and the region between them? The results from the experiment show that when the results are collapsed over configuration, RTs are shortest in the valid condition, and are longer in both the invalid and in-between conditions. In addition, there is only a small difference between the RTs of the invalid and in-between conditions. However, when the results are separated into the horizontal and vertical cue configuration, there is a significant cue configuration difference. Specifically, in the horizontal configuration, RTs were significantly longer for the in-between cue condition than for the valid or invalid cue conditions. However, this increase in RTs is not seen for the in-between condition in the vertical configuration.

The finding that RTs increase in the in-between horizontal condition and not the vertical cue configuration would suggest that attention can be split across hemifields (i.e., in the horizontal condition), but cannot be split within the same hemifield (i.e., vertical configuration). This conclusion is made because the in-between cue behaves more like a valid cue in the vertical cue configuration, and more like an invalid cue in the horizontal cue configuration. Thus, it can be concluded that the in-between cue in the vertical configuration is more in line with the zoom-lens model. In this case, attention focuses out to cover both cues regions, as well as the region between them. Whereas, the effect of the in-between cue in the horizontal configuration fits more with the spotlight model of attention. Based on this, attention can be split between the two cued regions, without spilling out into the region in-between them.

This ability to split attention between hemifields, but not within hemifields, is in agreement with previous studies in the literature as surveyed in the general introduction using other attention paradigms (Kraft et al. 2005; Ibos, Duhamel, & Hamed, 2009; McMains & Somers, 2004; Muller, Malinowski, Gruber, & Hilyard, 2003). One factor that has been proposed to account for this differential ability to split attention between hemifields and within the same hemifield is that visual acuity is higher along the horizontal than the vertical meridian (Beirne, Zlatkova, & Anderson, 2005; Rovamo, Virsu, Laurinen, & Hyvarinen, 1982; Millidot & Lamont, 1974). Another factor that may account for this hemispheric effect is task difficulty.

A study by Kraft and colleagues (2005) showed that in a discrimination task, performance is always better when the stimuli are presented between hemifields than within the same hemifield. In other words, there is a benefit in discrimination performance when having to attend to simultaneous stimuli presented in different hemifields. In very general terms, the visual system finds it easier to organize two foci of attention in separate hemispheres than in the same hemisphere. This is largely due to the bilateral field advantage. The Bilateral Field Advantage (BFA) in visual information processing refers to the fact that visual tasks are processed more quickly and/or more accurately when the visual inputs are distributed across the vertical meridian, compared to when the inputs are all presented within the same hemifield. Early evidence of BFA was provided more than 40 years ago by Dimond and Beaumont (1971). In that study, participants had to report pairs of digits that were briefly presented for 250 ms either within the same hemifield or across the two hemifields. The authors observed a higher number of pairs of digits were correctly reported when the stimuli were presented to both hemifields as compared to only one hemifield (Dimond & Beaumont, 1971). The fact that the results of the current experiment failed to show splitting of the attentional spotlight in the vertical configuration suggests that it is more difficult to split attention within than across hemifields.

The findings of the current thesis imply that attentional selectivity may operate under different constraints depending on the location of the attended region, for example, between and within hemifields. It can be speculated that electrophysiological studies or imaging studies can potentially address this question, by looking at how attentional neurons encoding each spotlight as a function of the between or within hemifield configuration (in the present thesis, the horizontal and vertical configuration).

EXPERIMENT 3A

Mixed one and two cued spots in a vertical configuration

Purpose

The aim of Experiment 3A was to expand on the findings within experiment 2. Specifically, this experiment was concerned with addressing the question: Is there a cost in response time when moving from attending to one cued location to two cued locations? This experiment measured the effects of valid and invalid cueing on RT for target discrimination, when one and two non-contiguous regions are attended. This experiment also used the in-between cue condition, as in Experiment 2. Specifically, the in-between condition occurred when two spots were cued and the target appeared in between these two cued regions. The goal of this experiment was to investigate whether cueing can result in two separate attentional areas, without any attentional enhancement occurring at un-cued regions or in between two cued regions, as well as to investigate if there is a cost in RT when attending to two separate locations, compared to a single location.

As was the case in Experiment 2, it was expected that the valid cue would reduce RT, while the invalid, as well as the in-between cues should increase RT. Moreover, it was expected that there will be no difference in RT for one and two cued spots. This would imply that there is no cost in performance when attending to two cued locations, rather than one location.

Method

Participants

The participants were ten subjects from Concordia University, all with self-reported normal (20/20) or corrected-to-normal vision.

Apparatus and Stimuli

The apparatus and stimuli were similar to the two previous experiments. On half the trials only one spot was cued by flashing white. When two spots were cued, either the two spots on the left of fixation, or the two spots on the right of fixation flashed white.

It was a valid cue condition, when the target appeared near one of the circles that flashed white and invalid when it appeared near a black circle. The in-between condition occurred when two spots were cued and the target appeared in between these two cued region (see Figure 3a.1, Figure 3a.2 and Figure 3a.3). By definition, the in-between cue condition refers to presenting the target in between two cued regions, and thus was only present in the two spots cue condition.

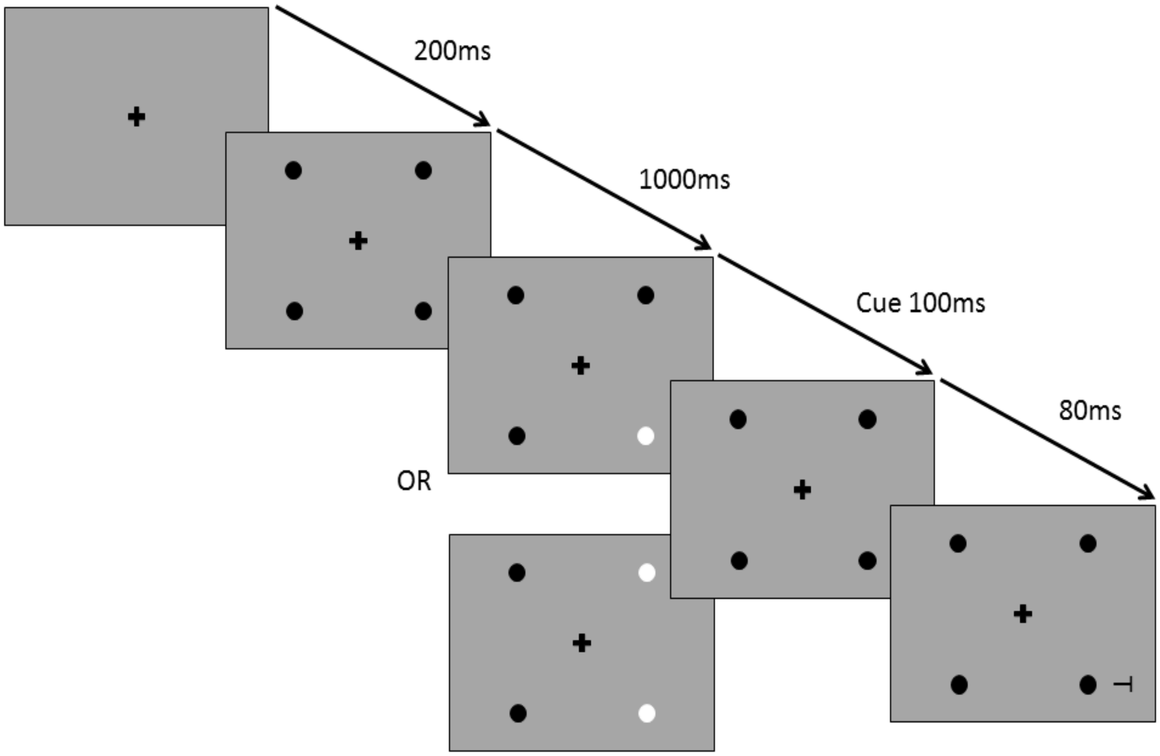

Figure 3a.1. Example of a one cued spot and a two-cued spots trial. Here the discrimination target appears near a cued location, making this a valid cue trial.

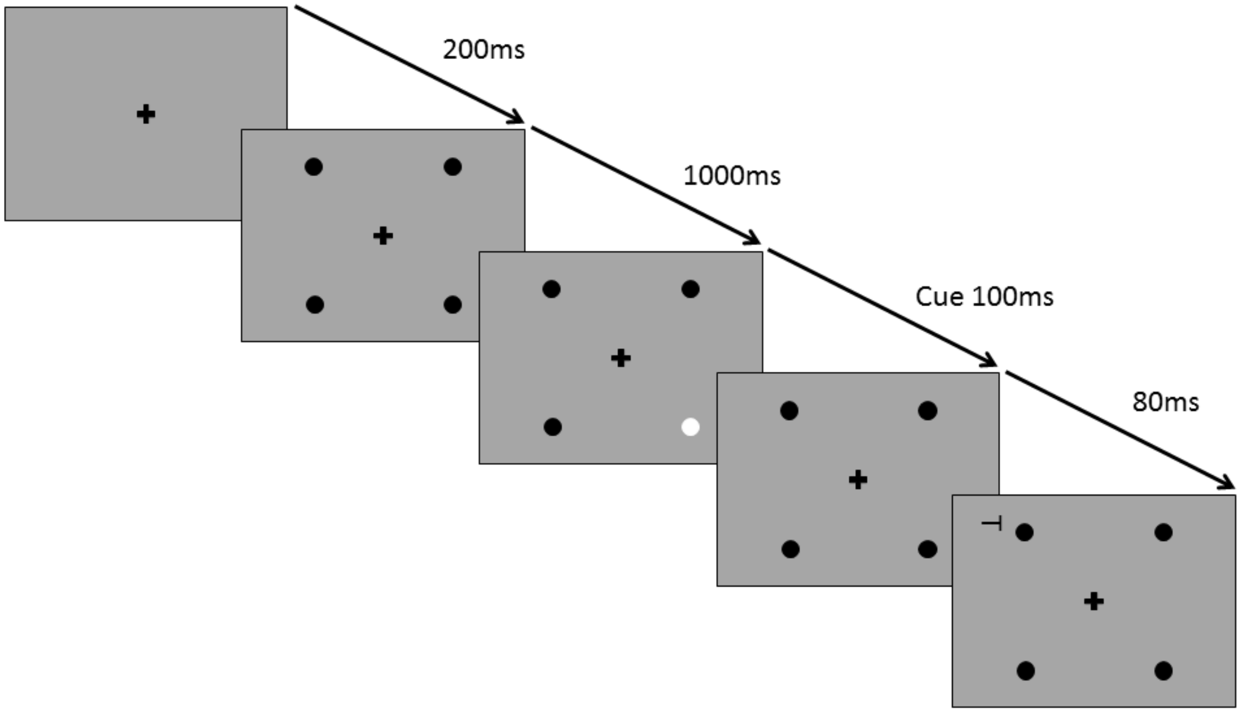

Figure 3a.2. Example of a one cued spot trial. Here the discrimination target appears near an uncued spot, making this an invalid trial.

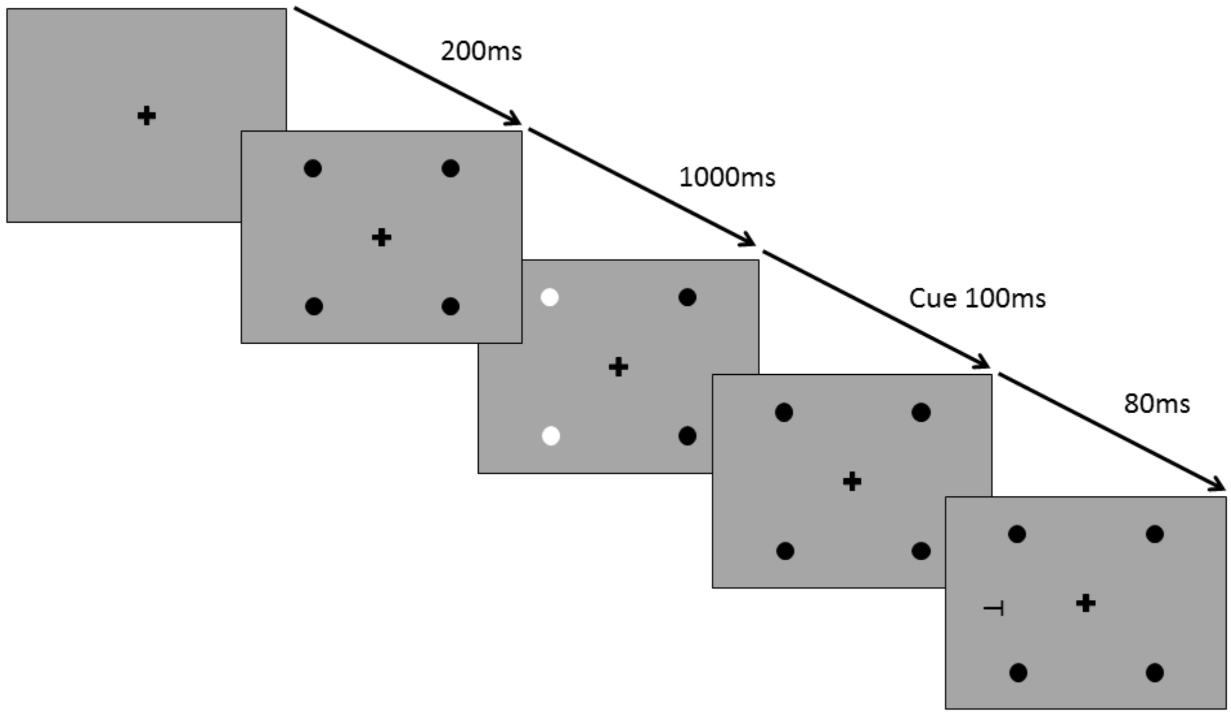

Figure 3a.3. Example of a two cued spots trial. Here the discrimination target appears in between the two cued regions.

Design and Procedure

This experiment had a two-factor within-subjects design .The first independent variable is the number of cued spots, with two levels: one spot (level 1) and two spots (level 2). The second independent variable is the cue type with two levels: valid (level 1) and invalid (level 2). The dependent variable (response time, RT) was the time required to discriminate the target orientation (left or right) in milliseconds. Only correct trials (~95% of all trials) were used in the analysis. The observer was asked to respond as quickly and as accurately as possible**.** Presentation timings, reaction times and error rates were recorded in the same way as the in the previous experiments.

Experiment 3A consisted of 672 trials and lasted approximately 35 minutes. The composition of the 672 trials was as follows: For the one spot condition, the target could be in 1 of 4 positions (quadrants of the screen), the target could be pointing to the left or right, the cue could be valid or invalid. There were 24 trials per location, for a total of 192 valid trials, of which half of the trials had the target pointing to the left and in the other half, the target was pointing to the right. On an invalid trial, the discrimination target could appear at any one of the three non-cued locations. There were 24 trials per location, for a total of 144 invalid trials, of which half of the trials had the target pointing to the left and in the other half, the target was pointing to the right.

For the two spots condition, the target could be in 1 of 4 positions (quadrants of the screen), the target could be pointing to the left or right, the cue could be valid, invalid, or in-between. There was a total 192 valid cue trials, of which half of the trials contained the target on the left of fixation and the other half on the right of fixation. Half the trials on the left of fixation had the target letter pointing to the left and in the other half, the target was pointing to the right.

In addition, half the trials on the right of fixation had the target letter pointing to the left and in the other half, the target was pointing to the right. There was a total 96 invalid cue trials of which half of the trials contained the target on the left of fixation and the other half on the right of fixation. Half the trials on the left of fixation had the target letter pointing to the left and in the other half, the target was pointing to the right. In addition, half the trials on the right of fixation had the target letter pointing to the left and in the other half, the target was pointing to the right. There were a total of 48 trials for the in-between cue condition of which half of the trials contained the target on the left of fixation and the other half on the right of fixation. Half the trials on the left of fixation had the target letter pointing to the left and in the other half, the target was pointing to the right. In addition, half the trials on the right of fixation had the target letter pointing to the left and in the other half, the target was pointing to the right. Errors were infrequent (~5%) and were examined for speed-accuracy trade off, but none was found.

Results

This experiment concerned the attentional selection of one versus two separate areas. To investigate whether cueing can result in two separate attentional areas, without any attentional enhancement occurring at uncued regions or in between two cued regions, two clearly defined and separate areas were cued. Figure 3a.4 depicts the results of the main analysis. The response time is plotted on the y-axis and the number of cued spots, one spot and two spots are plotted on the x-axis for both valid and invalid cues. Figure 3a.4 shows that the valid cue led to shorter RTs compared to the invalid cue, for both one spot and two spots. However, the difference between the valid cue (*M* = 460.06, *SD* = 13.7, 95% CI [450.3, 469.9] and the invalid cue (*M* = 492.09, SD = 11.8, 95% CI [483.7, 500.5] for two spots is slightly smaller (*d* = 1.32), when compared to the difference found for the one spot condition, with an effect size of 1.42 (Valid cue*:* *M* = 447.65, *SD* = 17.7, and 95% CI [435.0, 460.3]; Invalid cue: *M* = 501.58, *SD* =21.0, and 95% CI [486.6, 516.6]).

A two-way within-subjects ANOVA (spots x cue) on RTs for target discrimination was performed. A significant interaction between number of cued spots and cue type was found: $F(1,9) = 9.276$, $p = .014$, $\eta_p^2 = .51$. This result suggests that cueing can affect the position of the spotlight, and most importantly, can change the location of the attentional spotlight. However, there was no significant difference for one and two cued spots, F((1,9) = .351, $p = .568$, $\eta_p^2 = .04$. This result would suggest that there was no cost in RT performance when having to pay attention to one single spot and two spots simultaneously.

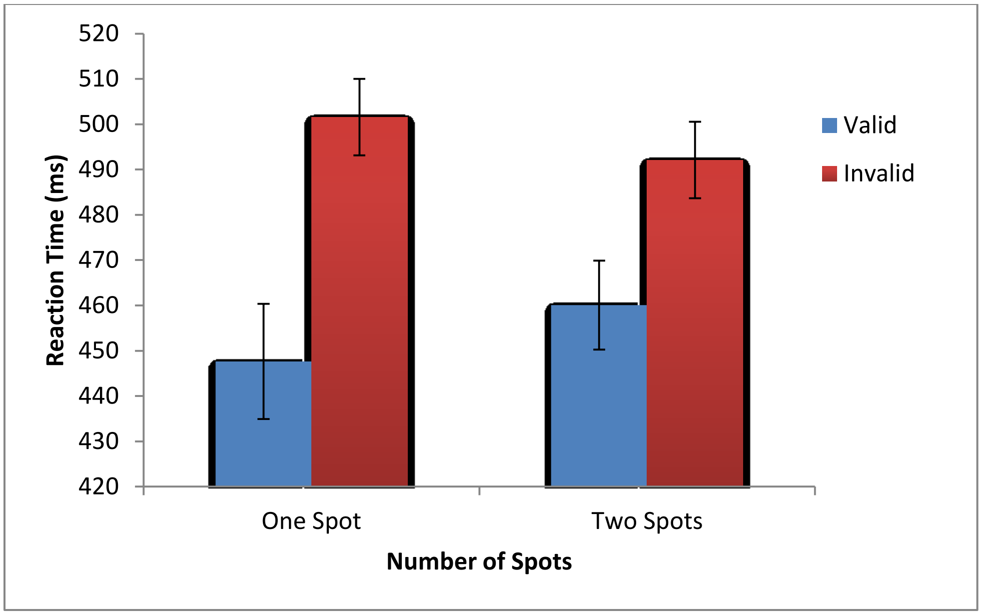

Figure 3a.4. Interaction effect of spots by cue type on reaction times. Error bars represent 95% confidence intervals around the mean after normalization to remove between-subject variability (Loftus & Masson, 1994).

The results of the ANOVA imply that participants can easily attend to either one or two separate areas without their attentional stores being taxed. However, if you look at Figure 3a.4, there appears to be an interaction effect within the results. When you look at the effect number of spots for valid trials, then the RTs increase as you increase the number of spots from one to two. Conversely, for invalid trials, RTs seem to decrease from one to two spots. To investigate this further, the difference scores were analyzed between the different cue conditions, thereby separating out one and two spot conditions into valid and invalid cues. When this analysis was conducted, there is an effect of the number of cued spots. See Table 3a.1 for all the difference scores. The difference between one spot (M = 501.58, SD = 21.0), 95% CI [486.6, 516.6] and two spots (M = 492.09, SD =11.8), 95% CI [483.7, 500.5] for the invalid cue is medium (d = .58). However, the difference of the number of cued spots for the valid cue condition (One spot: M = 447.65, SD = 17.7, and 95% CI [435.0, 460.3]; Two spots: M = 460.06, SD = 13.7, and 95% CI [450.3, 469.9]) was very large, with an effect size of 1.17. Thus the findings from the difference scores would suggest that there is a cost of increasing the number of cued spots on RTs, but only for those trials that contain the valid cue condition.

		Mean D.	SD	Lower	Upper	d
One	V-Invalid	-53.93	38.10	-81.18	-26.68	-1.42
Two	V-Invalid	-32.03	24.34	-49.44	-14.62	-1.32
Valid	one-two	-12.41	10.65	-20.03	-4.79	-1.17
Invalid	one-two	9.49	16.33	-2.19	21.17	0.58

Table 3a.1 Difference scores for all comparisons for the number of spots by cue type interaction for Experiment 3A.

To investigate whether cueing can result in two separate attentional areas, without any attentional enhancement occurring at un-cued regions or in between two cued regions, two clearly defined and separate areas were cued. In order to examine the in-between condition which is not present in the one spot condition, an analysis of the two spots condition was done separately. Figure 3a.5 depicts the results of the cue effect. Figure 3a.5 shows that the valid cue led to the shortest RTs. A repeated-measures ANOVA on RTs for Cue Type (valid, invalid, and in-between) was performed. The cue type main effect was significant: $F(2,18) = 14.14$, $p = .000$, $\eta_p^2 = .61$. The difference between the invalid cue (*M* = 492.09, *SD* = 9.9 and 95% CI [485.0, 499.2] and in-between cue (*M* = 458.6, *SD* = 11.9 and 95% CI [450.1, 467.1]), was greater (*d* = 2.32) than the difference between the valid cue (*M* = 460.1, *SD* = 16.4 and 95% CI [448.3, 471.8] and the invalid cue (*d* = 1.32). In addition, there was no difference between the valid cue and the in-between cue (*d* = .06). See Table 3a.2 for the difference scores for all comparisons for the effect of cue for this experiment.

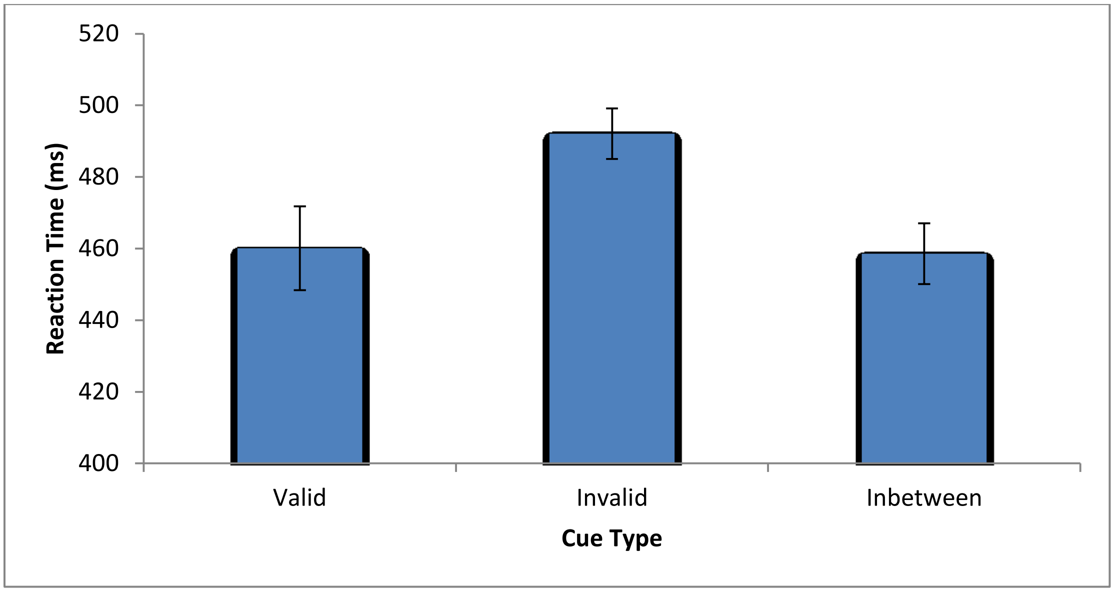

Figure 3a.5. Effect of cue type (valid, invalid, and in-between) on reaction times. Error bars represent 95% confidence intervals around the mean after normalization to remove between-subject variability (Loftus & Masson, 1994).

	Mean D.	SD	Lower	Upper	D
Valid-Invalid	-32.03	24.34	-49.44	-14.62	-1.32
Valid-Between	1.48	26.83	-17.71	20.67	0.06
Invalid-Between	33.51	14.45	23.18	43.84	2.32

Table 3a.2 Difference scores for all comparisons for the cue condition for two cued spots for Experiment 3A.

Discussion

The goal of Experiment 3A was to expand on experiment 2 by addressing the following question: Is there a cost in response time performance when moving from attending to one cued location to two cued locations? In Experiment 3A, a direct comparison of attention cost/benefit for a single focus of attention and two separate foci was possible.

The results from this experiment show an interaction between number of cued spots and cue type. Specifically, the difference between valid and invalid for two spots was smaller than for the one spot condition.

There was also a significant effect of cue type. Specifically, the valid cue condition led to shorter RTs compared to the invalid cue type. This result suggests that cueing can affect the position of the spotlight, and most importantly, can change the location of the attentional spotlight.

Based on the difference scores, it can be concluded that that there is a cost of increasing the number of cued spots on RTs, but only for valid trials. One reason why RTs increase for valid trial when attending to two spots may be because there are simply many more valid trials, thus making this a more statistically likely outcome. This would mean that participants would expect the target to appear near the cued region as compared to the situation with the invalid cue, which appears less often or even the in-between cue, which appears even more rarely. Thus, participants are most of the time paying attention to the cued region, and when they have to pay attention to two cued regions, they require more time to do the task. Thus, we observe longer RTs for valid trials when attending to two spots. On the other hand, with the invalid trials there is less of an effect on RTs when attending to two spots. This is perhaps because participants have learned that the target is not likely to appear near a location that has not been cued. Thus, participants' attention is not placed at the uncued region(s). Therefore, whether there is one or two spots to attend to, makes no difference in RTs for the invalid trials.

To investigate whether cueing can result in two separate attentional areas, without any attentional enhancement occurring at un-cued regions or in between two cued regions, two clearly defined and separate areas were cued. In essence, this was a replication of Experiment 2. The results from the current experiment agree with the results from Experiment 2. Specifically, the difference score effect sizes from the current experiment are similar to those in Experiment 2. For instance, in the current experiment the difference between valid and invalid had an effect size of 1.3. Moreover, the difference between valid and in-between had an effect size of .1. In Experiment 2, the difference between valid and invalid had an effect size of 1.2, and the difference between valid and in-between had an effect size of 0.3. In order to examine the in-between condition that is not present in the one spot condition, an analysis of the two spots condition was done separately. The cue type main effect was significant. From this result, it can be concluded that the cue was effective in changing the location of the spotlight. Moreover, the cue was effective in decreasing the RT to discriminate the target. There was a large difference between the valid and invalid cues. There was also a large difference between the invalid and the in-between cues. However, a small difference between the valid and in-between cue conditions was found. The in-between cue condition failed to show a significant cost in performance (e.g., did not lead to the longest RTs). This lack of cost in RT for the in-between cue condition could be due to perceptual grouping (Egly, Driver, & Rafal, 1994; Mastropasqua & Turatto, 2013; Hollingworth, Maxcey – Richard, &Vecera, 2012). It can be hypothesized that the two spots are being treated as one object in this vertical cue configuration, just like in the Egly et al. study

(1994), and there is an equal enhancement of attention at both the cued spots and the in-between location.

The fact that the results from this experiment failed to show splitting of the attentional spotlight in this vertical configuration, suggest that it is fundamentally more difficult to split attention within than across hemifields. A study by Kraft and colleagues (2005) shows that in a discrimination task, performance is always better when the stimuli are presented between hemifields than within the same hemifield. In other words, there is a benefit in discrimination performance when having to attend to simultaneous stimuli presented in different hemifields.

EXPERIMENT 3B

Mixed one and two cued spots in a horizontal configuration

Purpose

The aim of Experiment 3B was similar to 3A, except now the two cued spots were in a horizontal configuration. Thus, allowing for an examination of attentional splitting when stimuli are presented across hemifields. Specifically, this experiment concerned the following question: Is there a cost in response time performance when moving from attending to one cued location to two cued locations? This experiment allowed for a direct comparison of attention cost/benefit for a single focus of attention and two separate foci. The goal of this experiment was also to investigate whether cueing can result in two separate attentional areas, without any attentional enhancement occurring at uncued regions or in between two cued regions (as in experiment 2).

As was the case in the previous experiments, it was expected that the valid cue would reduce RT, while the invalid, as well as the in-between cues should increase RT. Moreover, it was expected that there will be no difference in RT for one and two cued spots. This would imply that there is no cost in performance when attending to two cued locations, rather than one location.

Method

Participants

The participants were nine subjects from Concordia University, all with self-reported normal (20/20) or corrected-to-normal vision.

Apparatus and Stimuli

The apparatus and stimuli were similar to the previous experiment (Experiment 3a) with one exception. When two spots were cued, the two spots on the top of fixation, or the two spots on the bottom of fixation flashed white. In this manner, the two cued spots formed a horizontal configuration (see Figure 3b.1, Figure 3b.2 and Figure 3b.3 for graphical depictions of the different configurations).

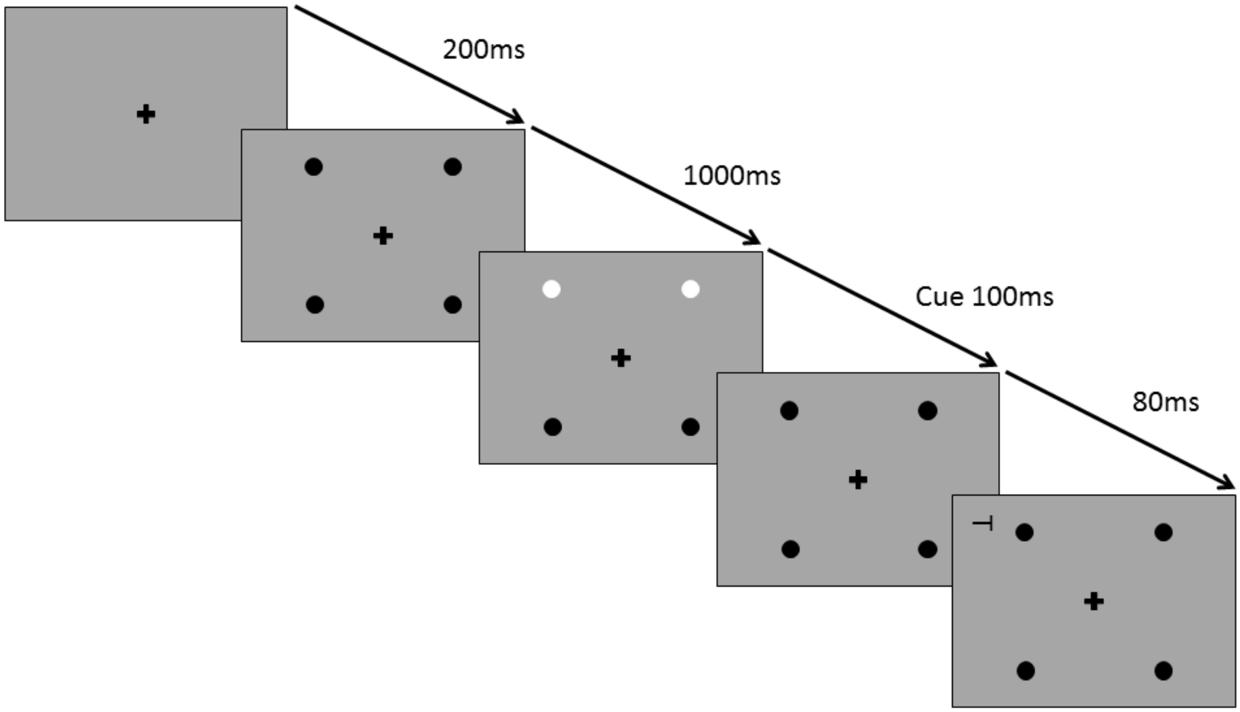

Figure 3b.1. Example of a valid two-cued spots trial. Here the discrimination target appears near a cued location, making this a valid cue trial.

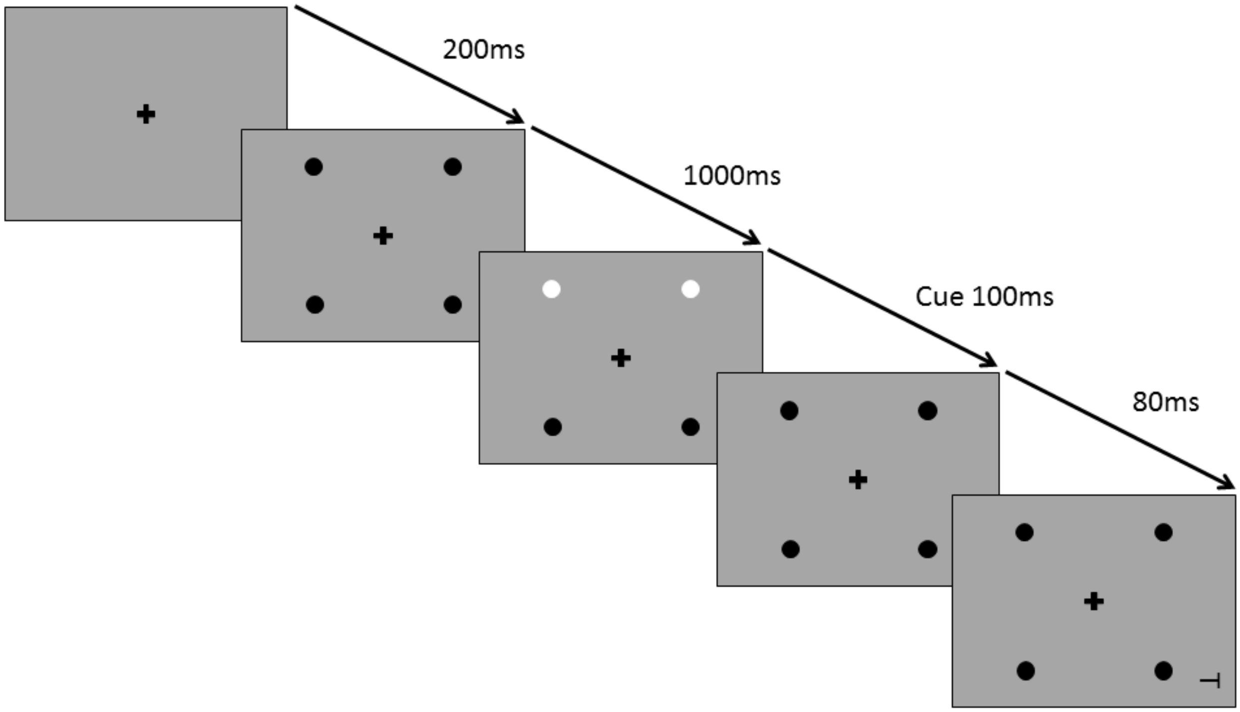

Figure 3b.2. Example of a invalid two-cued spots trial. Here the discrimination target appears near an uncued spot, making this an invalid trial.

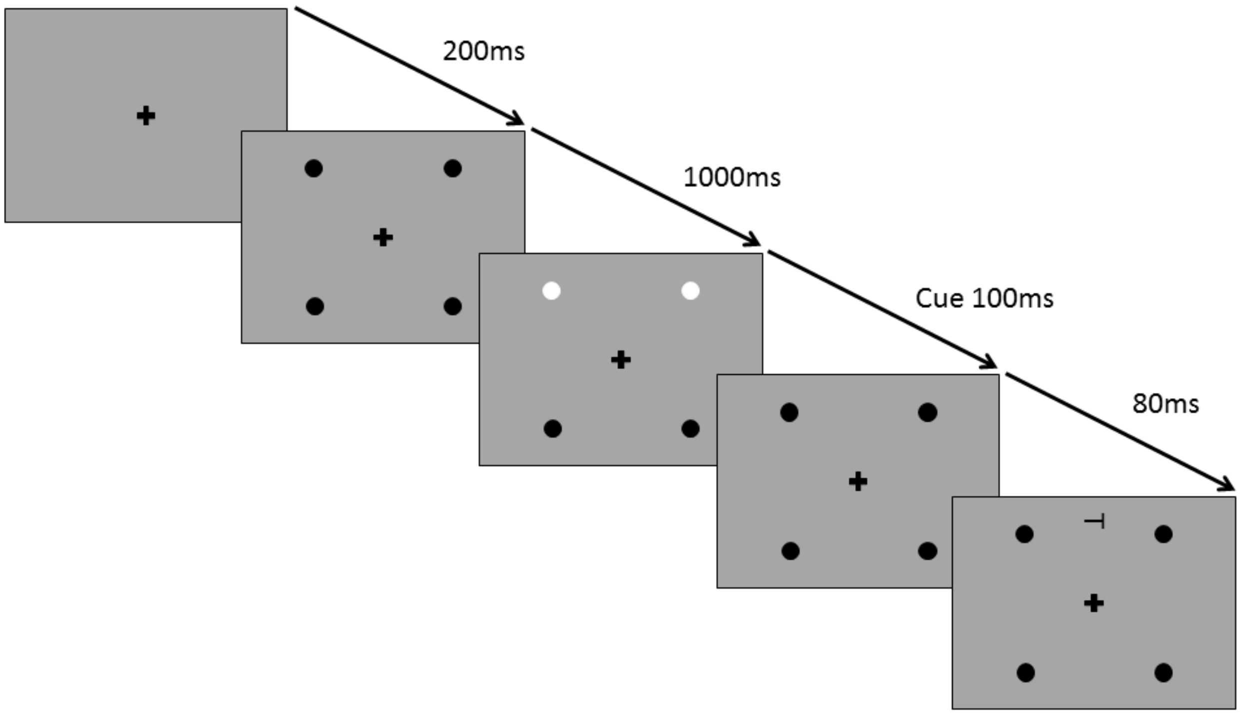

Figure 3b.3. Example of a in-between two cued spost trial. Here the discrimination target appears in between the two cued regions.

Design and Procedure

This experiment had a two-factor within-subjects design .The first independent variable is the number of cued spots, with two levels: one spot (level 1) and two spots (level 2). The second independent variable is the cue type with two levels: valid (level 1) and invalid (level 2). The dependent variable (response time, RT) was the time required to discriminate the target orientation (left or right). The response time was measured in milliseconds, and only correct trials were used. The observer was asked to respond as quickly and as accurately as possible. Presentation timings, reaction times and error rates were the same as in the previous experiments. Experiment 3B consisted of 672 trials, with the composition of trials being the same as in Experiment 3A.

Results

This experiment concerned the attentional selection of one versus two separate areas, arranged in a horizontal configuration. This experiment was concerned with the examination of the cost/benefit of performance when moving from a single focus of attention to two separate foci. In addition, to investigate whether cueing can result in two separate attentional areas, without any attentional enhancement occurring at uncued regions or in between two cued regions, two clearly defined and separate areas were cued. Figure 3b.4 depicts the results of the main analysis, and shows that the valid cue led to shorter RTs compared to the invalid cue, for both one spot and two spots. A two-way within-subjects ANOVA (spots x cue) on RTs for target discrimination was performed. A significant interaction between spots and cue type was found: $F(1,8) = 27.524$, $p = .001$, $\eta_p^2 = .78$. This result would suggest that cueing can affect the position of the spotlight, and most importantly, can change the location of the attentional spotlight. Examination of the difference scores can help explain this finding. The difference between valid ($M = 461.07$, $SD = 17.1$ and 95% CI [447.9, 474.2]) and invalid ($M = 491.61$, $SD = 23.1$ and 95% CI [473.2, 510.0]) for two spots is medium ($d = .41$), yet smaller when compared to the difference found for the one spot condition, with a very large effect size of .89 (Valid cue: $M = 450.02$, $SD = 23.4$ and 95% CI [432.1, 468.0]; Invalid cue: $M = 497.79$, $SD = 17.4$ and 95% CI [484.4, 511.2]). Also, the difference between one spot and two spots for the invalid cue is smaller ($d = .77$), with the upper confidence interval of the difference lying close to 0 (i.e., meaning no difference between the number of cued spots), compared to the difference score found for the valid cue condition ($d = 1.22$). See Table 3b.1 for all the difference scores for this experiment.

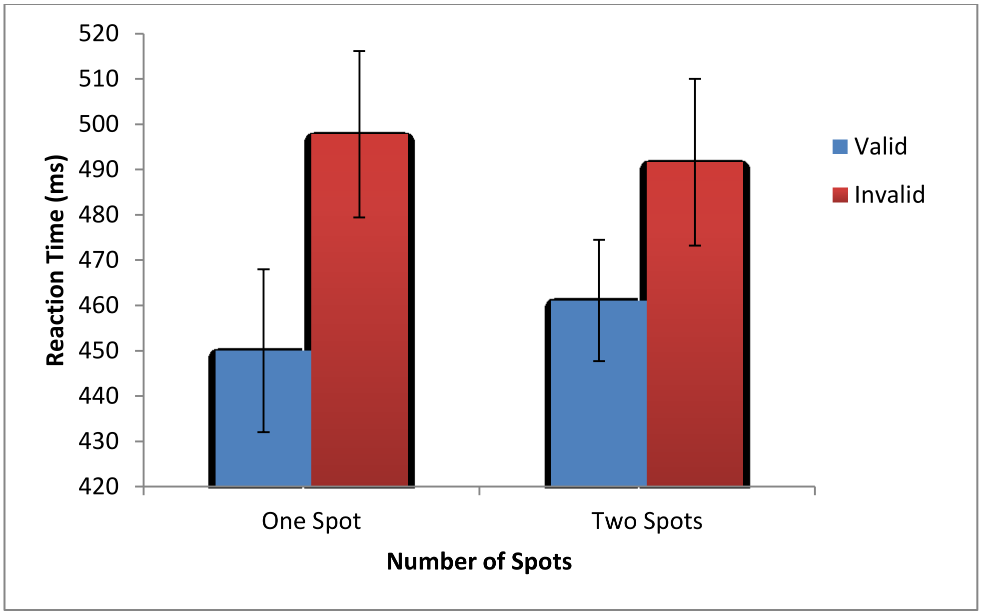

Figure 3b.4. Interaction effect of spots by cue on reaction times. Error bars represent 95% confidence intervals around the mean after normalization to remove between-subject variability (Loftus & Masson, 1994).

		Mean D.	SD	Lower	Upper	D
One	V-Invalid	-11.06	12.48	-20.64	-1.47	-0.89
Two	V-Invalid	6.20	15.09	-5.40	17.80	0.41
Valid	one-two	-47.78	39.13	-77.86	-17.70	-1.22
Invalid	one-two	-30.52	39.51	-60.89	-0.15	-0.77

Table 3b.1 Difference scores for all comparisons for the number of spots by cue type interaction for Experiment 3B.

To investigate whether cueing can result in two separate attentional areas, without any attentional enhancement occurring at uncued regions or in between two cued regions, two clearly defined and separate areas were cued. In order to examine the in-between condition, which is not present in the one spot condition, an analysis of the two spots condition was done separately. Figure 3b.5 depicts the results of the cue effect. The response time is plotted on the y-axis and the three types of cues are plotted on the x-axis. Figure 3b.5 shows that the valid cue led to the shortest RTs, while the in-between cue condition led to the longest RTs. A repeated-measures ANOVA on RTs for Cue Type (valid, invalid, and in-between) was performed. The cue type main effect was significant: $F(2,16) = 5.19$, $p = .041$, $\eta_p^2 = .39$.

The difference between the valid cue (*M* = 461.07, *SD* = 36.9 and 95% CI [432.7, 489.4] and in-between cue (*M* = 522.6, *SD* = 40.8 and 95% CI [491.2, 554.0]), was greater (*d* = .81) than the difference between the valid cue and invalid cue (*M* = 491.6, *SD* = 16.0 and 95% CI [479.3, 503.9], *d* = .77 and was also greater than the difference between the invalid cue and the in-between cue (*d* = .62). See Table 3b.2 for the difference scores for all comparisons for the effect of cue for this experiment.

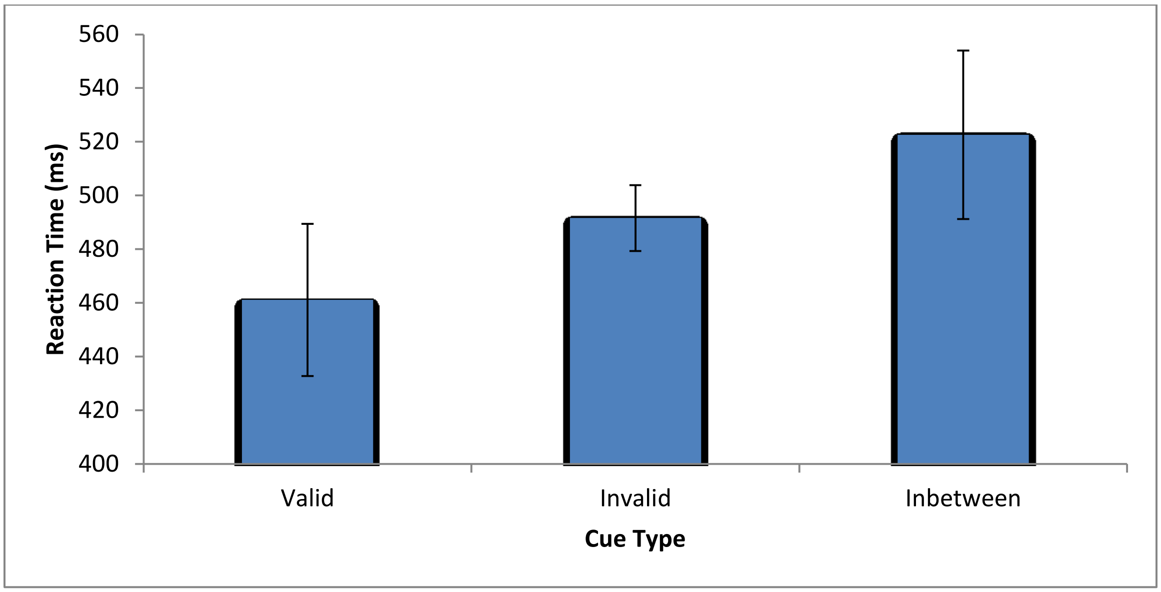

Figure 3b.5. Effect of cue type (valid, invalid, and in-between) on reaction times. Error bars represent 95% confidence intervals around the mean after normalization to remove between-subject variability (Loftus & Masson, 1994).

	Mean D.	SD	Lower	Upper	D
Valid-Invalid	-30.52	39.51	-60.89	-0.15	-0.77
Valid-Between	-61.51	76.13	-120.03	-2.99	-0.81
Invalid-Between	-30.99	49.84	-69.30	7.32	-0.62

Table 3b.2. Difference scores for all comparisons for the cue condition for two cued spots for Experiment 3B.

Discussion

The goal of Experiment 3B was the same as in 3A, except now the two cued spots were in a horizontal configuration. Thus, allowing for an examination of attentional splitting when stimuli are presented across hemifields, as opposed to within the same hemifield as was studied in Experiment 3A. Specifically, this experiment concerned the following question: Is there a cost in response time performance when moving from attending to one cued location to two cued locations? In Experiment 3B a direct comparison of attention cost/benefit for a single focus of attention and two separate foci was possible. The results from this experiment show a significant interaction between number of cued spots and cue type. Specifically, the difference between valid and invalid for two spots was much smaller than for one spot.

There was also a significant effect of cue type. Specifically, the valid cue condition led to shorter RTs compared to the invalid cue type. This result suggests that cueing can affect the position of the spotlight, and most importantly, can change the location of the attentional spotlight. Based on the difference scores, it can be concluded that that there is a cost of increasing the number of cued spots on RTs, but only for valid trials. Here again the explanation can be because of the mere number of valid trials compared to invalid trials, just like in the explanation for Experiment 3A. With so many more valid trials, participants learn to pay attention to the cue(s). Thus, their attention is more often than not placed at the cued regions. Therefore, when having to pay attention to two regions, rather than one, we observe an increase in RTs. Suggesting that more time is required to attend to two regions instead of only one. However, since there are fewer invalid trials, participants learn to pay attention to the cued region(s) while ignoring the other uncued regions. Therefore, when there are two spots to pay attention to, there is no increase in RT because participants have learned that the target is not likely to appear near an uncued region and they ignore those regions. Thus, there is no increase in RT going from one spot to two spots for the invalid trials.

To investigate whether cueing can result in two separate attentional areas, without any attentional enhancement occurring at uncued regions or in between two cued regions, two clearly defined and separate areas were cued. In order to examine the in-between condition which is not present in the one spot condition, an analysis of the two spots condition was done separately. The cue type main effect was significant. There was a large difference between the valid and invalid cues. There was also a very large difference between the valid and the in-between cues. In addition, there was a large difference between the invalid and the in-between cues. The in-between cue condition in this experiment led to a significant cost in performance (e.g., resulted in the longest RTs).

Since the two-spot condition replicates the vertical condition in experiment 2, we can compare the two experiments. When we do this, we find that the results from the current experiment agree with the results from Experiment 2. Specifically, the difference score effect sizes from the current experiment are in the same order as those in Experiment 2. For instance, in the current experiment the difference between valid and invalid had an effect size of .77. Moreover, the difference between valid and in-between had an effect size of .81. Finally, the difference between invalid and in-between had an effect size of .62. In Experiment 2, the difference between valid and invalid had an effect size of .47. Moreover, the difference between valid and in-between had an effect size of .65, and the difference between invalid and in-between had an effect size of .53. Based on this, it can be concluded that the largest difference was between the valid and the in-between cue conditions for both Experiment 2 and Experiment 3B.

Having observed that the in-between cue condition in this experiment led to a significant cost in performance, it can be concluded that the two cues were treated and perceived as two separate objects. In other words, two separate attentional beams were focused around them, with no activation in between the two cued regions. These two cues, which formed a horizontal configuration, did not lead to perceptual grouping as in previous studies (Egly, Driver, & Rafal, 1994; Mastropasqua & Turatto, 2013; Hollingworth, Maxcey – Richard, &Vecera, 2012). Another way to explain the cost in RT with the in-between cue condition is in terms of the cue-target distance effect observed by Hollingworth and colleagues (2012). They found that when the target was presented far from the cue, it led to increased RTs. This is similar to the result obtained in the present experiment. The target in the in-between cue condition is far away from the two cues and resulted in longer RTs compared to when the target was presented near the cue (valid cue condition).

EXPERIMENT 4

Cueing more than two locations

Purpose

One way to explore whether there are multiple attentional spotlights is to ask participants to track the movements of multiple objects (reviewed in Cavanagh & Alvarez, 2005). These experiments appear to show that participants can attend to four or five objects moving independently amongst other independently moving distractors (Pylyshyn & Storm, 1988; Yantis, 1992; Verstraten et al., 2000), although this number is dependent upon the speed of the moving dots, with increasing speed resulting in fewer objects being accurately tracked (Verstraten et al., 2000). For the purpose of this thesis, this could mean that observers can divide the spotlight into 4-5 independent attentional beams (Pylyshyn, 1989).

The aim of Experiment 4 was to expand on experiment 3A and 3B. Specifically, this experiment was concerned with addressing the question: Is there a cost in response time performance when moving from attending to one cued location to four cued locations? This experiment allowed for a direct comparison of attention cost/benefit for a single focus of attention and up to four separate foci.

As was the case in the previous experiments, it was expected that the valid cue would reduce RT, while the in-between cue should increase RT. Moreover, it was expected that there will be no difference in RT for one and four cued spots. This would imply that there is no cost in performance when attending to four cued locations, rather than one single location.

Method

Participants

The participants were nine subjects from Concordia University, all with self-reported normal (20/20) or corrected-to-normal vision.

Apparatus and Stimuli

The apparatus and stimuli were similar to the previous experiments. On half the trials only one spot was cued by flashing white. The remaining trials consisted of trials where all four spots were cued.

It was a valid cue condition, when the target appeared near one of the circles that flashed white. The in-between condition occurred when the target appeared in between two spots (see Figure 4.1 and Figure 4.2).

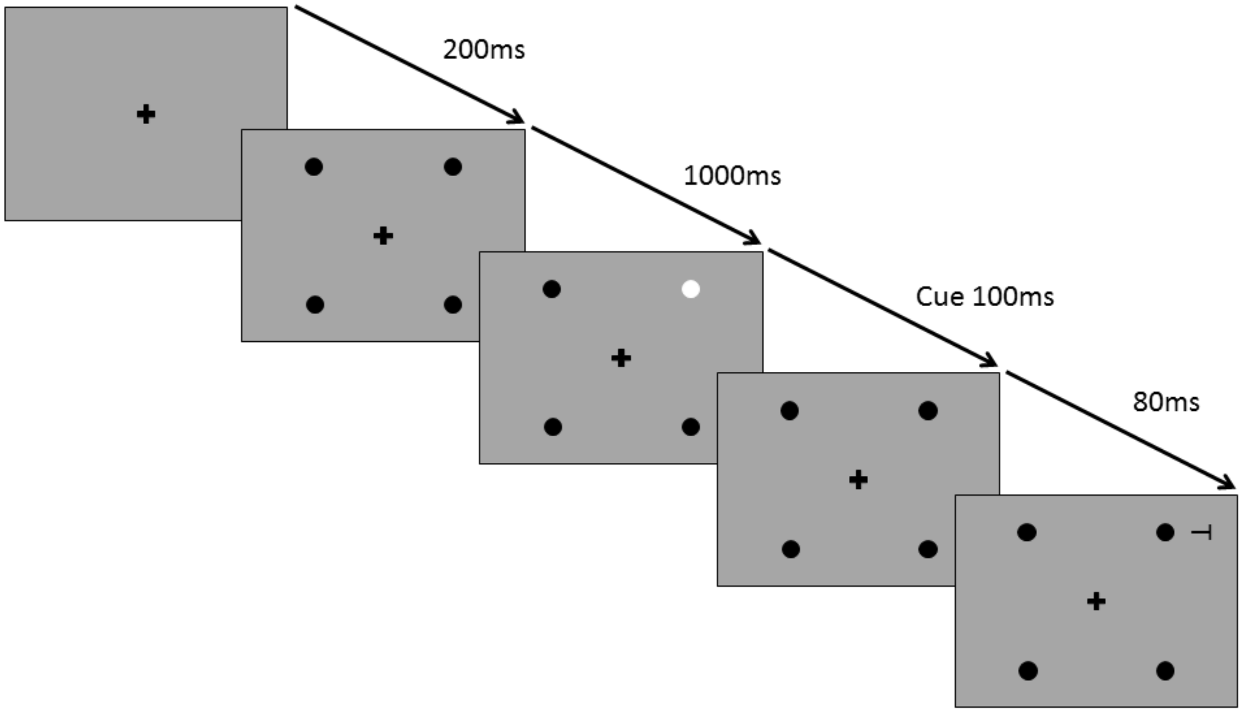

Figure 4.1. Example of a one-spot valid trial. Here the discrimination target appears near the cued spot, making this a valid trial.

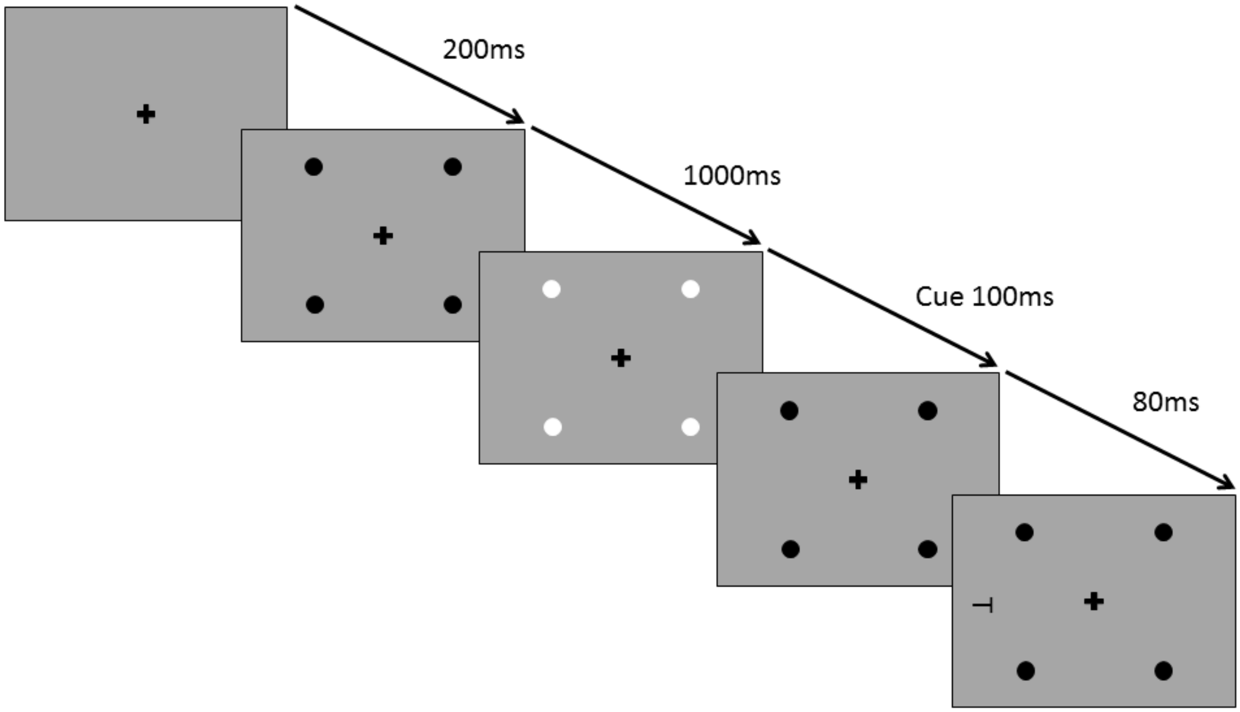

Figure 4.2. Example of a four-spots trial. Here the discrimination target appears in-between the cued spots, making this an in-between cue condition.

Design and Procedure

This experiment had a two-factor within-subjects design. The first independent variable is the number of cued spots, with two levels: one spot (level 1) and four spots (level 2). The second independent variable is the cue type with two levels: valid (level 1) and in-between (level 2). The dependent variable (response time, RT) was the time required to discriminate the target orientation (left or right). The response time was measured in milliseconds, and only correct trials were used. The observer was asked to respond as quickly and as accurately as possible. Presentation times, reaction times and error rates were the same as in the previous experiments.

Experiment 4 consisted of 640 trials and lasted approximately 30 minutes. The composition of the 640 trials was as follows: For the one cued spot condition, the target could be in 1 of 4 positions (quadrants of the screen), the target could be pointing to the left or right, the cue could be valid or in-between. There were 24 trials per location, for a total of 192 valid trials, of which half of the trials had the target pointing to the left and in the other half, the target was pointing to the right. There were a total of 128 in-between trial conditions. One quarter of them were presented on the top, on the bottom, on the left side and on the right side of two spots. Of these 128 trials, half of them had the target pointing to the right, and in the other half, the target was pointing to the left. For the four cued spots condition, there were 24 trials per location, for a total of 192 valid trials, of which half of the trials had the target pointing to the left and in the other half, the target was pointing to the right. There were a total of 128 in-between trial conditions. One quarter of them were presented on the top, on the bottom, on the left side and on the right side of two spots. Of these 128 trials, half of them had the target pointing to the right, and in the other half, the target was pointing to the left. Errors were infrequent (~5%) and were examined for speed-accuracy trade off, but none was found.

Results

This experiment concerned the attentional selection of one versus four separate regions. To investigate whether cueing can result in separate attentional areas, without any attentional enhancement occurring at uncued regions (in-between cued regions), one or four clearly defined and separate areas were cued. This experiment was also concerned with the examination of the cost/benefit of performance when moving from a single focus of attention to four separate foci. Figure 4.3 depicts the results, and shows that the valid cue led to shorter RTs compared to the in-between cue, for both one spot and four spots. A two-way within-subjects ANOVA (spots x cue) on RTs for target discrimination was performed. A significant interaction between spots and cue type was found, F(1,8) = 37.553, p = .000, η_p^2 =.82. This result suggests that cueing can affect the position of the spotlight, and most importantly, can change the location of the attentional spotlight. There was a significant effect of spots, F(1,8) = 34.443, p = .000, η_p^2 =.81. However, the difference between valid (*M* = 458.61, *SD* = 55.3 and 95% CI [416.1, 501.1]) and in-between (*M* = 521.28, *SD* = 62.8 and 95% CI [473.0, 569.5]) for four spots was smaller (*d* = 1.54), when compared to the difference found for the one spot condition, with an effect size of 2.06 (Valid cue: *M* = 408.67, *SD* = 76.9 and 95% CI [349.6, 467.8]; In-between cue: *M* = 533.13, *SD* = 69.0 and 95% CI [480.1, 586.2]).

Also, the difference between one spot and four spots for the in-between cue is smaller, with an effect size of .53, compared to the difference found for the valid cue condition, with an effect size of .85. See Table 4.1 for all the difference scores for this experiment.

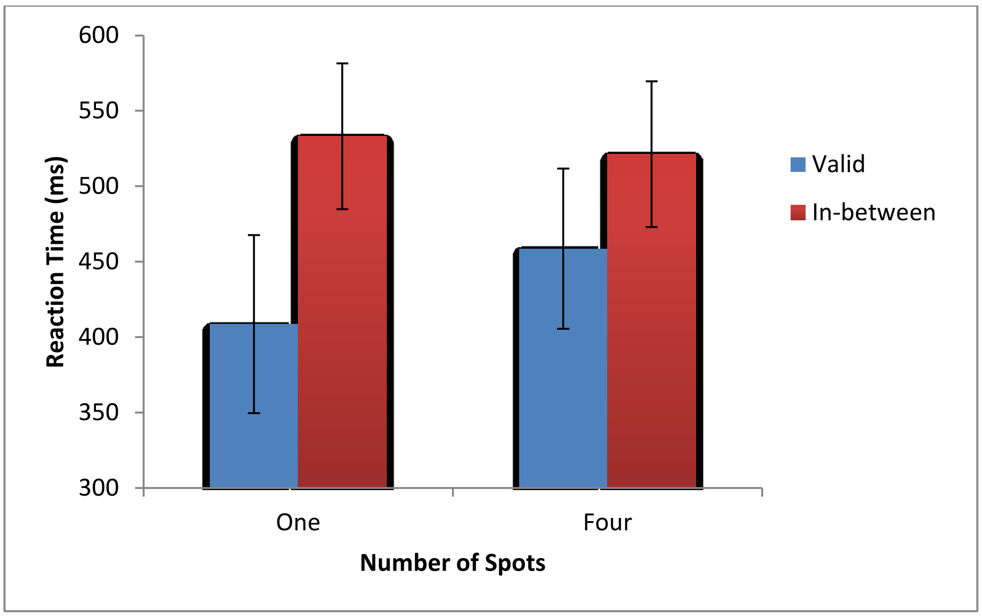

Figure 4.3 Interaction effect of spots by cue on reaction times. Error bars represent 95% confidence intervals around the mean after normalization to remove between-subject variability (Loftus & Masson, 1994).

		Mean D.	SD	Lower	Upper	D
one	Valid-Inbetween	-49.94	24.24	-68.57	-31.31	-2.06
four	Valid-Inbetween	11.85	7.72	5.92	17.78	1.54
Valid	one-four	-124.46	145.78	-236.51	-12.40	-0.85
Inbetween	one-four	-62.67	117.96	-153.33	28.00	-0.53

Table 4.1 Difference scores for all comparisons for the number of spots by cue type interaction for Experiment 4.

Discussion

The goal of this experiment was the same as Experiment 3A and 3B: to examine if there is a cost in response time performance when moving from attending to one cued location to now, up to four separately cued locations? In Experiment 4 a direct comparison of attention cost/benefit for a single focus of attention and four separate foci was possible.

The results from this experiment show a significant interaction between number of cued spots and cue type. Specifically, the difference between valid and in-between cues for four spots was much smaller than for one spot.

There was a large difference between the valid and in-between cues in both of the spot conditions, with the in-between cue condition resulted in longer RTs. From this result, it can be concluded that the four cues could have been perceived by participants as four separate objects. In other words, four separate attentional beams were focused around them, with no activation in-between the cued regions. As a result, when the target was presented in-between the cued regions, RTs were significantly longer to discriminate the target. Thus, resulting in a cost in performance for the task in the current experiment. Another way to explain the cost in RT with the in-between cue condition is in terms of the cue-target distance effect observed by Hollingworth and colleagues (2012). They found that when the target was presented far from the cue, it led to increased RTs. This is similar to the result obtained in the present experiment. The target in the in-between cue condition is far away from the cues and resulted in longer RTs compared to when the target was presented near the cue (valid cue condition).

The analysis also revealed a significant effect of the spot condition. This implies that participants search times were significantly longer when attending to four separate areas in comparison to just one cued location. It can be concluded that there was a cost on the performance that can be attributed to the increase in the number of cues. Based on this finding, it can be speculated that there is a limit to how many separate attentional foci can be activated simultaneously. Perhaps the limit has been reached, and it becomes costly for the participant to pay attention to four separate regions and perform a discrimination task. This result is similar to the one observed in Experiments 3A and 3B. Specifically, there was a cost in performance with the two spots condition. RTs were significantly longer when attending to two cued spots compared to a single cued spot, more so for the valid trials. In the current experiment, the same trend can be observed. RTs increase significantly when attending to four spots compared to only one spot, for the valid trials. Again, just like in Experiments 3A and 3B, we see a slight decrease in RTs for the in-between trials when attending to four separate cues compared to a single spot. It can be concluded from this that there is more cost in discrimination performance for the valid trials. Could valid trials be simply an easier task and can this be explaining the result? This is a likely explanation, whereby attention is left over during the valid trials and this results in a poorer discrimination performance, as compared to the in-between cue condition.

This experiment has demonstrated that as participants are instructed to pay attention to many locations (in this experiment, 4 separate locations), performance decreases. Thus, as the number of cued spots increases from one to four, the valid cue RT increases. Although participants can attend to four separate regions, they are not as good at target discrimination compared to the situation with only one spot or even two cued spots. The benefit of spatial cueing is decreasing however, the benefit is still present. A similar result has been found in the multiple-object-tracking literature (Cavanagh & Alvarez, 2005; Pylyshyn & Storm, 1988; Verstraten et al., 2000). These experiments appear to show that participants can attend to four or five objects moving independently amongst other independently moving distractors. However, this number is dependent upon the speed of the moving dots with increasing speed resulting in fewer objects being accurately tracked (Verstraten et al., 2000). In other words, to keep tracking performance at an acceptable rate, the speed of the moving dots must be reduced.

GENERAL DISCUSSION

The purpose of the thesis was to investigate how perceptual performance is altered when attention is directed to two or more non-contiguous locations simultaneously. This thesis presents four experiments that use a multiple spatial cueing paradigm, which to the best of my knowledge, has not been used by other investigators to investigate the potential splitting of attention into multiple separate spatial regions.

An important condition that must be met in order for attentional splitting to occur, is that there must be two or more separate areas of activation with no activation in between those areas. In addition, it would be interesting to find that there is no cost in performance (in terms of an increase in RT) when the one focus of attention is split into two (or more) foci of attention.

To investigate the possibility of splitting attention into two or more separate areas and the effect that would have in terms of performance and RT, four experiments were conducted. All of the experiments in this thesis were conducted using an exogenous spatial cueing paradigm. The cue was always stimulus-driven, and thus required bottom-up processing. In keeping with previous attention research, it was expected that RT to discriminate a target would be shorter in the valid cue condition (i.e., where the target is presented near the cue), when compared to the invalid or no cue condition. This hypothesis was tested in Experiment 1. In addition, it was expected that RT will be longer when the target appears in-between two different cued regions. This would imply that there is little or no activation due to attention in-between the two cued regions. This hypothesis was tested in Experiment 2. Experiment 3A and 3B allowed for a direct comparison of RT cost when attending to only one area and two cued areas. Thus, Experiments 3A and 3B compared RT for target discrimination when only one area is selected for processing versus two cued areas. It was expected that RT would be the same when attending to one or two non-contiguous regions. This would imply that attention can be separated to cover more than one area at the same time.

Another hypothesis was that there will be no difference in RT for target discrimination when participants are attending to one, two, or more separate regions. This would imply that there is no cost in RT when attending to two or more areas and that, more than one location can be selected at once. Experiment 4, involved cueing one of the four place holders that make up the visual stimulus, and cueing all four place holders and measuring differences in RT for target discrimination. It was expected that there would be no difference in RT when attention is placed in one region or four regions simultaneously. This would lend support to the premise that more than one non-contiguous area can be selected for processing at the same time.

The results from Experiment 1 support the hypothesis that the spotlight of attention can change location when multiple potential locations are present. The results obtained in this experiment, showed that there was a significant effect obtained when the cue was present, with significant differences between the valid and invalid cues, and between the valid and non-informative cues. Although the findings of Experiment 1 are in agreement with the previous studies of exogenously cued attention (Posner, 1980; Posner, 1995; Wolfe, 1994) the stimulus configuration (i.e., 4 potential cue locations) used in this study was novel. The reason why it was important to have more than the two potential locations was that the new stimulus allowed for the possibility of cueing more than two locations. This was an essential feature of the stimulus paradigm that is important to the current thesis. This new stimulus paradigm was used to answer questions that the standard two-cued location paradigm could not answer. For example, and of importance to this thesis, was how attention is selecting the different potential cue locations.

More specifically, is attention being split between the different locations as would be proposed by the attentional spotlight model (Posner, 1980)? In other words, can two separate areas be selected for processing at the same time? Or is attention operating across the entire stimulus, as has been proposed in the zoom lens model (Eriksen & St. James, 1986; LaBerge, 1983). This question was addressed in Experiment 2.

The goal of Experiment 2 was to investigate whether cueing can result in two separate attentional areas, without any attentional enhancement occurring at un-cued regions or in between two cued regions. The results of Experiment 2 showed that there was a significant cue effect, with differences between the valid and the invalid cues. This result suggests that cueing can affect the position of the spotlight, thus replicating the result of Experiment 1, but with two separate spatially cued locations. Moreover, the results from Experiment 2, showed that the in-between cue condition was most detrimental to the target discrimination performance when the cues were arranged in a horizontal configuration and encompassing both hemifields. When both cues were in the same hemifield, and formed a vertical configuration, the in-between cue condition had no effect on RTs and did not interfere with the discrimination task.

Furthermore, it was important to examine if a difference exists between the horizontal (i.e., two top cues and two bottom cues), and the vertical (i.e., two cues left of fixation and two cue right of fixation) cue configurations, since previous studies of attention have shown a hemispheric effect of attention (Harter, Aine, & Schroeder, 1982; Kraft et al. 2005; Ibos, Duhamel, & Hamed, 2009; McMains & Somers, 2004; Muller, Malinowski, Gruber, & Hilyard, 2003; Awh & Pashler, 2000). The results from experiment 2 revealed a cue configuration difference. Specifically, in the horizontal configuration, RT was significantly longer for the in-between region than for the cued regions. This increase in RT was not seen for the in-between condition in the vertical configuration. This finding would suggest that attention can be split across hemifields (i.e., in the horizontal condition), but cannot be split within the same hemifield (i.e., vertical configuration). This result replicates the same hemifield effect observed in previous studies (Kraft et al. 2005; Ibos, Duhamel, & Hamed, 2009; McMains & Somers, 2004; Muller, Malinowski, Gruber, & Hilyard, 2003). There is some evidence showing that the shape of the attentional window without cueing is naturally asymmetrical in the sense that the horizontal extent is larger than the vertical extent (Carrasco, McElree & Giordano, 2002; Sanders & Brück, 1991; Galera & von Grünau, 2003). Contrast sensitivity has also been shown to be better along the horizontal than the vertical meridian (Carrasco, Evert, Chang, Katz, 1995; Carrasco, Talgar, Cameron, 2001; Rijsdijk, Kroon, van der Wildt, 1980). The fact that the results of experiment 2 failed to show splitting of the attentional spotlight in the vertical configuration, suggest that it is fundamentally more difficult to split attention within the same hemifield than across different hemifields.

The purpose of experiment 3A was to measure the effects of valid and invalid cueing on RT for target discrimination when one and two non-contiguous regions are attended. Moreover, to investigate whether cueing can result in two separate attentional areas, without any attentional enhancement occurring at un-cued regions or in between two cued regions. In addition, this experiment was concerned with whether there is a cost in RT when attending to two separate locations, compared to a single location. In Experiment 3A the two cued spots formed a vertical configuration. The results from Experiment 3A revealed a significant interaction between number of spots and cue type. Specifically, the difference between valid and invalid for two spots was much smaller than for one spot. This finding can be explained by the perceptual load hypothesis (Lavie & Tsal, 1994).

According to Lavie and Tsal (1994), perceptual load is a factor in determining the locus of selection. They have presented evidence that perceptual load is one of the conditions influencing the processing of irrelevant information. They have proposed that early selection requires that the perceptual load of the task be sufficiently high to prevent available attentional resources exerting their effect on irrelevant information. In Experiment 3A, it is likely that attending to two cued regions is a more difficult task with greater perceptual load compared to attending to one cued location, and therefore no (or fewer) attentional resources were left over to process the target at an incorrect (or invalid) location. However, attending to only one cued location would be easier, and therefore there are attentional resources left over that can spill out and interfere with the discrimination task thereby leading to longer RTs for invalidly cued locations. It is important to exercise caution when interpreting the findings from Experiment 3A with the perceptual load hypothesis proposed by Lavie and Tsal (1994). Their explanation is only a hypothesis that has not been formally tested. One way to test the perceptual load hypothesis would be to measure frontal lobe activation by way of EEG. Another way is to use the technology of pupilometry. This area of research has revealed that as the task becomes more cognitively demanding, we can measure an increase in the pupil size. Therefore, by measuring pupil size, we can confirm that the task has in fact increased the perceptual load of the task.

In order to examine the in-between condition in Experiment 3A, which was not present in the one spot condition, an analysis of the two spots condition was done separately. The analysis revealed a large difference between the valid and invalid cues. There was also a large difference between the invalid and the in-between cues. However, a small difference between the valid and in-between cue conditions was found. The in-between cue condition failed to show a significant cost in performance (e.g., did not lead to the longest RTs).

This lack of cost in RT for the in-between cue condition could be due to Gestalt like perceptual grouping of the cued spots due to the similarity of stimulus onset (Egly, Driver, & Rafal, 1994; Mastropasqua & Turatto, 2013; Hollingworth, Maxcey – Richard, & Vecera, 2012). It is possible that the two cued spots were being treated as one object in this vertical cue configuration just like in the Egly and colleagues study (Egly et al., 1994), leading to an equal enhancement of attention at both the cued spots and the in-between location. The fact that the results from this experiment failed to show splitting of the attentional spotlight in this vertical configuration, suggest that it is fundamentally more difficult to split attention within than across hemifields. In addition, Experiment 3A aimed to investigate whether there is a cost in performance when attending to two cued locations compared to a single location. The results revealed no significant difference for one and two spots. This result suggests that there was no cost in RT performance when having to pay attention to one single spot and two spots simultaneously. Based on this result, it is safe to assume that participants can easily attend to two separate areas without any cost to their performance, and that attention is not split between the two regions. Instead, within the vertical configuration, attention appears to either spill over between the cued regions, or is spread out over the two regions, as has been proposed by the zoom lens model (Eriksen & St. James, 1986; Eriksen & Yeh, 1985).

The aim of experiment 3B was similar to that of experiment 3A, with the only difference between the two experiments being that the two cued spots were now in the horizontal configuration. This arrangement allowed for an examination of attentional splitting across hemifields. The results from this experiment revealed a significant interaction between number of spots and cue type. The RT difference between valid and invalid conditions, when attending to two spots was smaller than for the one spot condition. As was the case for Experiment 3A, this difference could be explained by the perceptual load hypothesis proposed by Lavie and Tsal (1994). It was also shown that there was no significant difference in RT when attending to one spot, or to two spots when presented simultaneously. Again, the assumption can be made that participants can easily attend to two separate areas without their attentional stores being taxed. To investigate whether cueing can result in two separate attentional areas, without any attentional enhancement occurring at un-cued regions or in between two cued regions, two clearly defined and separate areas were cued. In order to examine the in-between condition that is not present in the one spot condition, an analysis of the two spots condition was done separately. From the analysis, it was revealed that there was a very large difference between the valid and the in-between cues. The in-between cue condition in Experiment 3B led to a significant cost in performance (e.g., resulted in the longest RTs). Therefore, an assumption can be made where the two cues were treated and perceived as two separate objects. In other words, two separate attentional beams were focused around them, with no activation in between the two cued regions. This result fits well with the description of the spotlight of attention theory, and not the zoom-lens model. The two cues, which formed a horizontal configuration in Experiment 3B, did not lead to perceptual grouping as observed in previous studies of object attention (Egly, Driver, & Rafal, 1994; Mastropasqua & Turatto, 2013; Hollingworth, Maxcey–Richard, & Vecera, 2012).

Another possible explanation to the cost in RT within the in-between cue condition is in terms of the cue-target distance effect observed by Hollingworth and colleagues (2012). They found that when the target was presented far from the cue, it led to increased RTs. Using circular and semicircular tube-like objects, Hollingworth and colleagues varied the within-object distance between the cued location on an object and the target location. A spatial gradient across the attended object was revealed. That is, target discrimination performance was best at the cued location within an object, and discrimination performance decreased systematically as the within-object distance between the cue and the target increased. This finding was consistent with studies of spatial attention showing that after the presentation of a cue; attention is distributed in a graded manner, with highest sensitivity at the cued location and gradually decreasing sensitivity with increasing distance from the cue (Downing & Pinker, 1985; Henderson, 1991; Henderson & Macquistan, 1993; Mangun & Hillyard, 1988). This is similar to the result obtained in Experiment 3B of the current thesis. In the in-between cue condition, the target was far away from the two cues and resulted in longer RTs compared to when the target was presented near the cue (valid cue condition).

In the paradigm used by Hollingworth and colleagues (2012), the gradient of attention was limited to a relatively small region of the attended object and peaked at the cued location. The authors speculated that attention might not necessarily "fill" in the entire object, thereby leading to increased perceptual sensitivity across the entire object. That is, there may be regions of an attended object that receive little or no facilitation compared to other objects or locations in the visual field. If spatial attention is to be considered a limited pool of resources that can be distributed over the visual field, the size of the object could be an important factor in governing the extent to which attention "fills" an object and the density of the attentional distribution within the object. Consistent with this possibility, Davis and colleagues (2000) have observed a direct relationship between object size (i.e., area), and the efficiency of the perceptual processing of object features. Moreover, Hollingworth and colleagues argued that attention may not have come to "fill" the object because participants were cued to a spatially localized object region. If the entire object had been cued, a more uniform distribution of attention across the object would have been observed.

The goal of experiment 4 was to investigate whether cueing can result in four separate attentional areas, without any attentional enhancement occurring at uncued regions or in between cued regions, as well as to investigate if there is a cost in RT when attending to four separate locations, compared to a single location. As was the case with Experiment 3A and 3B, a significant interaction between number of cued spots and cue type was found. Specifically, the difference between valid and in-between cues for four spots was much smaller than for one spot. Here as well, this difference could be explained by the perceptual load hypothesis (Lavie, 1995). Although the ANOVA also revealed a significant effect of spots, the in-between cue condition resulted in the longest RTs for both the one spot and the four spots condition. From this result, it can be concluded that the four cues were treated and perceived as four separate objects.

In Experiment 4, it was also important to examine if a difference exists between the vertical and horizontal configurations in terms of the in-between cue condition on RTs. The analysis revealed that there was no difference in RT for the in-between cue condition for the two configurations. This difference that was observed in the previous experiments, was not found in Experiment 4.

When looking for commonalities within the results throughout all four experiments, a trend does appear in the effect that the number of spots have on the results. The difference between the valid and invalid cues when attending to a single cued spot is larger, with an effect size of 1.19, compared to the difference between these two cues when attending to two cued spots (effect size of .97). This finding could be explained using the perceptual load theory (Lavie & Tsal, 1994; Lavie, 1995). According to this theory, as the cognitive load of the task increases, there is less attention left over to spill onto and process irrelevant information. Based on this theory, it can be assumed that attending to two cued locations, as opposed to a single location, is a more challenging task. Therefore, the cognitive load increases, the participant's attention is focused onto these two cued locations, leaving little or no attention left over to spill onto the invalid condition and enhance performance. When comparing the in-between cue condition for two spots and four spots, no difference exists (d = .02). What can be concluded from this result is that attending to two or four locations is just as difficult, and therefore there is little attention left over to process the target that appears in this in-between cued location. In other words, all of the participants' attention is placed onto these two or four cued spots, and no attention remains to spill onto the location in between cued spots. The RT for the in-between cue condition is always longer compared to the RT for the valid cue condition.

The existing models of spatial attention, such as the spotlight (Posner, 1980; Posner, Snyder, & Davidson, 1980), zoom-lens (Eriksen & St James, 1986; Eriksen & Yeh, 1985), and gradient (LaBerge, 1983; LaBerge & Brown, 1986; LaBerge, Carlson, Williams, & Bunney, 1997) models make different assumptions about the size of the attentional field. Yet, most of them agree that this perceptual facilitation that is mediated by attention decreases monotonically with the distance from the focus of attention centered on the target. In one study (Downing & Pinker, 1985) observers were required to detect a spot of light that appeared in one of 10 outline boxes arranged horizontally on a computer screen. Participants were instructed to press a button as quickly as possible after one of the boxes was filled in. The digits 1-10 were displayed immediately above each box corresponding to the position of that box in the horizontal array. At the start of each trial, a number appeared at fixation indicating the likely location of the target that was about to appear (cued trials) or indicating that all positions were equally likely to contain the target (neutral trials). On 18% of the cued trials, no target appeared; these catch trials were included to ensure that subjects were responding to the stimulus and not anticipating its appearance. Of the remaining cued trials, the target appeared in the cued location 70% of the time and in one of the uncued locations 30% of the time. Participants were encouraged to focus attention on the cued location so as to minimize RT to detect the target. The results revealed a V-shaped function surrounding the attended location, such that targets appearing closer to the cued location were detected more rapidly than targets appearing farther from the cued location. The authors suggested that the size of the cueing effect depended not on the physical distance between cue and stimulus, as one might expect, but on the "cortical distance" between the two points. Since more visual cortex is devoted to processing the center visual field, it makes sense that distance effects were much larger when the two points were near the center and the effect was smaller when the two points were in the periphery. Interestingly, the largest effect of the cue occurred when the two points were on opposite sides of the vertical midline. Psychophysical data (e.g.: Downing & Pinker, 1985) show that attentional enhancement is distributed as a gradient around the attended location with decreasing effects as distance increases.

In the current thesis, the same type of finding is shown with the in-between cue condition for the horizontal configuration, with an increased RT, showing a decreased benefit of attention, as the target is further away from the cued regions. The in-between cue condition resulted in significantly longer RTs for the horizontal configuration in Experiments 2 and 3B. For the vertical configuration, there was no cost in discrimination performance with the in-between cue condition in both Experiments 2 and 3A. This finding is similar to the result reported in the Downing and Pinker (1985) study, whereby the largest effect of the cue occurs when two points are on opposite sides of the vertical meridian.

Results from the current thesis also revealed a cue configuration effect, which is line with previous studies of attention showing hemispheric effects (Alvarez & Cavanagh, 2005; Alvarez, Gill, & Cavanagh, 2012; Harter, Aine, & Schroeder, 1982; Kraft et al. 2005; Ibos, Duhamel, & Hamed, 2009; McMains & Somers, 2004; Muller, Malinowski, Gruber, & Hilyard, 2003; Awh & Pashler, 2000). Meaning that, there was a difference between the horizontal (i.e., two top cues and two bottom cues), and the vertical (i.e., two cues left of fixation and two cue right of fixation) cue configurations. The in-between cue condition was detrimental in RT for the horizontal cue configuration, but not for the vertical configuration. Based on this, it can be concluded that the two cues were treated and perceived as two separate objects in the horizontal cue configuration. Thus two separate attentional beams were focused around them, with no activation in between the two cued regions. These two cues, which formed a horizontal configuration, did not lead to perceptual grouping as in previous studies (Egly, Driver, & Rafal, 1994; Mastropasqua & Turatto, 2013; Hollingworth, Maxcey – Richard, &Vecera, 2012).

However, one caveat with the present study involves the positioning of the cued spots. Specifically, the spots are not equally distant from each other. The cued spots arranged in the vertical configuration are closer to each other than the two cued spots arranged in a horizontal configuration. This spatial topography may result in more attentional overlap for the vertical cue configuration, compared to the horizontal configuration. Could this be contributing to the attention spilling effect for the vertical cue, in accordance to the zoom-lens model? Future studies will need to equate the distance between the spots to allow for a full interpretation of the findings.

A related point is that we may not be equally sensitive across the entire visual field or across the vertical and horizontal meridian. Research has indicated that we are more sensitive along the horizontal meridian. As a result, crowding occurs more along the vertical meridian

(Pelli, Tillman, Freeman, Su, Berger, Majaj, 2007). This is related to the spilling of attention that is found in Experiment 3A with the vertical cue configuration.

Perceptual grouping suggests that attention selects perceptual groups that result from the pre-attentive segmentation of the visual field via Gestalt grouping principles (e.g., Duncan, 1984). The two cued spots or four cued spots in the current thesis, flashing together were not being treated as a single object, and the observer must make an inference that they are one. This may explain why we do not see the same object effect as observed in the perceptual grouping research literature (Egly, Driver, & Rafal, 1994; Mastropasqua & Turatto, 2013; Hollingworth, Maxcey – Richard, &Vecera, 2012). In the perceptual grouping papers reviewed (e.g., Egly et al., 1994; Hollingthworth et al., 2012, Mastropasqua & Turatto, 2013), the stimuli that are used are physically defined objects, being either a rectangle or arch-shaped objects. In the current thesis, the cued object can only be defined by Gestalt grouping heuristics, such as synchrony of onset, with the two spots or four spots flashing together. In all the papers reviewed, the cue was an exogenous one, it contained a physical boundary. The cue in the current thesis requires making an inference therefore it may affect how attention groups these objects.

Another way to explain the results from the current thesis is by way of the multiple spatial indexing proposed by Wright (1994). Wright and Ward (1993) have claimed that when stimulus-driven shifts occur, a unitary focus is shifted reflexively to the location of the strongest index signal and perhaps as many as four stimuli can be indexed. According to Wright and Ward (1993), indexes are not attentional resources per se. Rather, their role is to act as anchor points for shifts of a unitary attentional focus. Therefore, indexes provide location information only and can do so independently of attentional focus. The authors believe that given the nature of multiple spatial indexing, this operation allows us to explain attention shift findings involving more than one location, without resorting to proposals of attentional splitting.

Mechanisms that may explain the results of the current thesis

Neuronal Model of Attention

Neuronal responses do not operate in an all-or-nothing manner. Rather, they are gradual responses with a gradient characteristic. Attention is a modulating mechanism. Several studies have shown that attention can alter visual cortical receptive fields (Busse, Katzner, & Treue, 2008; Pestilli, Viera, & Carrasco, 2007; Morrone, Denti, & Spinelli, 2004; Motter, 1993; McAdams, C. J. & Maunsell, 1999). For example, when two objects are presented in a neuron's receptive field and attention is directed to one of the objects, the neuron's receptive field contracted around the attended stimulus, causing the unattended stimulus to fall outside the new contracted receptive field (Moran & Desimone, 1985). This effect has since been confirmed by other studies (Luck, Chelazzi, Hillyard, & Desimone, 1997; Lee & Maunsell, 2010; Ghose & Maunsell, 2008). Together, these findings suggest that rather than the receptor field having a fixed size, the receptive fields of neurons are dynamically changed via attention. However, these results could also be explained by a shift of the receptive field towards the attended stimulus (Connor, Gallant, Preddie, & van Essen, 1996; Anton-Erxleben, & Carrasco, 2013). It has been reported that receptive fields are about 5% smaller when attention is directed to one of the stimuli inside the receptive field compared with a neutral condition without attention inside the receptive field (Anton-Erxleben, Stephan, & Treue, 2009; Womelsdorf, Anton-Erxleben, Pieper, & Treue, 2006). When attention is allocated to a stimulus next to the receptive field, the receptive field expands by about 14% compared with the neutral condition (Anton-Erxleben, Stephan, & Treue, 2009). The changes in receptive field size are accompanied by a shift of the center of the RF towards the attended stimulus (Anton-Erxleben, & Carrasco, 2013). The shift is still measurable when the attentional focus and the receptive field lie in opposite visual hemifields, but declines with distance between the attended stimulus and the receptive field (Womelsdorf, Anton-Erxleben, Pieper, & Treue, 2006). This implies that both the receptive field size and location can be modulated by attention (Anton-Erxleben, & Carrasco, 2013).

In line with these single-unit electrophysiological studies, several fMRI studies have shown that attention can change neuronal activity within the early visual areas, specifically, areas V1–V4 (Datta & DeYoe, 2009; Brefczynski, Datta, Lewis, & DeYoe, 2009; Fischer & Whitney, 1999). A study by Fischer and Whitney (1999), measured the spatial spread of fMRI BOLD responses to stimuli at adjacent spatial locations. The direction of attention to a nearby location led to a decrease in the spatial overlap of the responses to each stimulus location. Based on this result, the authors concluded that there was a narrowing of spatial tuning within the neurons. Fischer and Whitney (1999) interpreted this finding so that this narrowing of spatial frequency selectivity can be explained by the narrowing of the receptive fields within single cells.

Attention is thought to dynamically modulate the receptive field by selectively increasing the weight of those inputs representing the attended stimulus, and thereby increases inhibition of the neighbouring inputs (Anton-Erxleben, & Carrasco, 2013). Moreover, the strength of the attentional modulation follows a Gaussian distribution, with the strongest modulation at the attentional focus, and weaker modulation everywhere else. It has been proposed by Anton-Erxleben and Carrasco that attention results in a Gaussian receptive field distribution that is narrower and shifted towards the attentional focus. Therefore, information from the attentional focus is selectively routed to higher cortical areas. This leads to a strengthened representation of information from the attended location compared with information from the unattended locations (Anton-Erxleben, & Carrasco, 2013).

From the results observed in the psychophysical experiments in the current thesis, plus the hemifield effects observed by others (Harter, Aine, & Schroeder, 1982; Kraft et al. 2005; Ibos, Duhamel, & Hamed, 2009; McMains & Somers, 2004; Muller, Malinowski, Gruber, & Hilyard, 2003; Awh & Pashler, 2000), here I propose a simple model whereby attention works to modulate receptive fields of neurons but more so of neurons between hemifields, such as in the horizontal configuration. Based on my readings from the electrophysiological literature, I believe that within the same hemifield, attention does not have a strong enough effect on neurons to narrow their responses (Womelsdorf et al., 2006). This results in an increase in neuronal selectivity overlap. The results from the current thesis, suggest that when attention is split across hemifields, there is less overlap between the receptive fields, thus increasing the spatial selectivity. Therefore, it can be theorized that the attentional tuning curves are narrow for the horizontal cue configuration, as compared to the vertical cue configuration when attention is applied. With the vertical cue configuration, the results are more in line with the zoom-lens model of attention, where the size of the attentional lens can vary. Figure 5 shows a visual depiction of the model of how attention may modulate perception differently within and between hemifields, which could explain the results in the current thesis. Under normal vision with attention not being focused on a particular object, attention does not affect the receptive field size or location (blue lines). However, when attention is focused on two objects across hemifields, then attention causes the receptive field size to shrink (red lines). This shrinking of the receptive field leads to less overlap and a more precise neuronal selectivity.

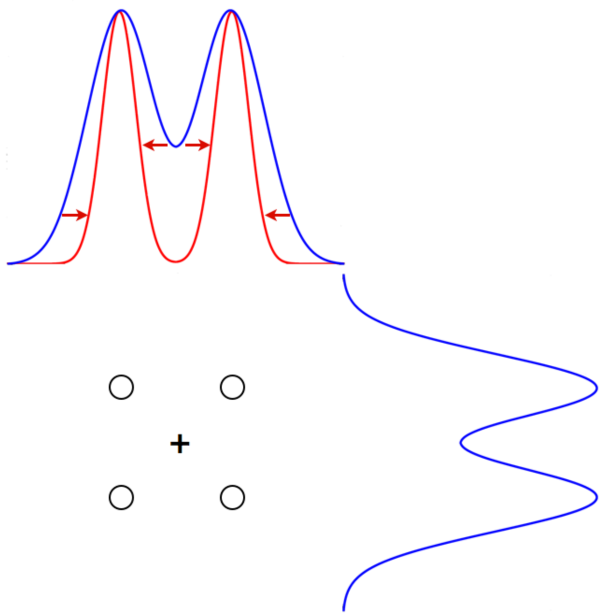

Figure 5. Schematic representation of the narrowing of attentional tuning curves for horizontal and vertical cue configurations. When attention is not focused on any region, then the receptor fields encoding the stimuli will overlap (blue curves). However, when attending to two cues in a horizontal configuration (in red), the tuning curves become more narrow in the horizontal configuration, but remain the same in the vertical configuration.

Thus, if a discrimination target is presented within the hemifields, because the receptive fields in the two vertical cued stimuli still have considerable overlap, then the RT is faster than in the invalid condition (as shown in Exp.3a). However, when the discrimination target is shown in-between the two horizontal cues (i.e., across hemifields), then attention modulates the size of the receptive field, causing it to shrink inward towards each cue location. This decreases the overlap between the receptive fields, so that the response times to the discrimination target are longer, and similar to the invalid condition (as shown in Exp.3b).

Another explanation of the perceptual enhancement that is observed with spatial cueing in the current thesis is by relying on task-specific spatial frequency channels. Solomon (2004) demonstrated that it does not matter if there are 1 or 8 cued locations. Rather, direct spatial cueing enhances visual sensitivity. Since 8 spatially-separated cues are as effective as a single cue, then enhancement is most likely not due to attention or the splitting of attention (Solomon, 2004). An alternative solution that would illicit the same result has been proposed by Lu and Dosher (2000). They proposed that the cue serves to amplify signals elicited by the target, which is also supported by the attention physiology literature reviewed in the introduction. This amplification of signals is most likely due to switching from a poorly suited spatial frequency or orientation channel to one that is more appropriate for the task. Therefore, rather than analyzing the entire image with all spatial frequency channels, we only select the one that is better suited for the task. This would provide a simpler solution for the visual system to implement than the traditional model of splitting of attention.

Psychophysical Models

Although the current thesis uses a multiple spatial cueing paradigm to explore multiple attentional spotlights, another way is to ask subjects to track the movements of multiple objects (reviewed in Cavanagh & Alvarez, 2005). Multiple object tracking is an experimental technique used to study how our visual system tracks multiple moving objects. These experiments appear to show that subjects can allocate attention to four or five objects moving independently amongst other independently moving distractors (Pylyshyn & Storm, 1988; Yantis, 1992; Verstraten et al., 2000), although this number is dependent upon the speed of the moving dots, with increasing speed resulting in fewer objects being accurately tracked (Verstraten et al., 2000). This implies that observers can divide the spotlight into 4-5 independent attentional beams (Pylyshyn, 1989).

Multifocal attention assumes that each moving target attracts an independent focus of attention, and that each focus of attention is directed to follow the targets as they move. At the end of the trial, participants will be attending to the same items that they began with, even though now, they have moved to different locations. Moreover, observers can identify them as members of the original set. This strategy relies on classic properties of attention, but requires that attention can be allocated to more than one focus.

In addition to the number of targets, several other factors can increase the difficulty of the tracking. When targets and distractors are too close, it becomes difficult to separate the targets and maintain tracking. This difficulty in selection of an individual item from a dense array, despite the items being clearly visible, has been attributed to the coarse acuity of attention (He, Cavanagh, & Intriligator, 1997; Intriligator & Cavanagh, 2001), or to obligatory feature averaging (Pelli, Palomares, & Majaj, 2004; Parkes, Lund, Angelucci, Solomon, & Morgan

2001). Due to these spacing limits on selection, tracking becomes difficult if not impossible with displays spanning less than about 1/16th of a degree (Intriligator & Cavanagh, 2001) where the dots are seen but impossible to track.

In theory, three separate models of attention can be used as potential mechanisms for the results obtained through the research for this thesis. The first is classically known as the spotlight of attention model. According to this model, visual attention operates like a spotlight illuminating only the object or objects of interest (Posner & Cohen, 1984). According to Posner, Snyder and Davidson (1980) selective attention is like "a spotlight that enhances the efficiency of the detection of events within its beam" (p.172). Theories of detection and visual attention have emphasized that the spotlight of attention helps to process the information that falls within its beam faster and more accurately (Posner, 19080; Eriksen & Hoffman, 1972; Julesz, 1984; Yeshurun & Carrasco, 1998), and the remainder of the visual field is partially filtered out or suppressed. In line with the spotlight model, it can be speculated that two or even four separate spotlights exist to process and "illuminate" the two or four cued spots in this thesis.

The results of the current thesis can also be interpreted in terms of the zoom-lens model. The zoom lens model of visual attention proposes that the attended region can be adjusted in size, and predicts a trade-off between its size and processing efficiency because of limited processing capacities. Rather than a beam of attention of a set size, it has been argued that we zoom in and out depending on the task (Eriksen & St. James, 1986). According to this model, only one large region of attention exists and this region varies in size depending on the size of the attended location or object. Therefore, if the observer is attending to two or four cued spots, then the beam of attention increases to incorporate all cued spots and everything else in between them. The zoom-lens model may explain the results observed with the in-between cue condition for the vertical configuration in both Experiments 2 and 3A. In the vertical configuration, the zoom-lens model is operating and focusing out to cover the two cued regions as well as the region in between them. Thus, no cost in RTs is observed with the in-between cue condition because the area of attention has expanded to include the in-between region, and this area receives the benefits of attention, which aids to process targets for discrimination.

Another model can also be proposed to explain the current results. This model consists of overlapping beams of attention with “fuzzy” borders. Based on the results observed in the thesis, I believe that this model is the most appropriate, and likely explanation for the results in this thesis. There is obviously attentional enhancement at the cued locations. However, attention does not operate like a square wave function with clear on and off attentional regions. Attention should be viewed more as a sine wave function with a gradual decrease of attentional enhancement as the target moves further away from the cued region. Moreover, with two or more cued regions, we end up with overlapping spotlights of attention with the most enhancement or attentional facilitation at the cued regions and less facilitation the further away the target appears from the cued regions.

In my opinion, the overlapping beams of attention, is the most complete and likely explanation for the results revealed in this study. This model is the most complete explanation, as it can account for the results of the in-between cue condition for all experiments, and for both the vertical and horizontal cue configuration. According to this model, the beams of attention overlap more and have fuzzier borders for the vertical configuration, as compared to the horizontal cue configuration. Therefore, when the target appears in-between the two cued regions, no cost in RT is observed and the observer can easily perform the target discrimination task. With the overlapping beams of attention, we see attentional enhancement and facilitation in the cued regions but also in-between these regions. Whereas with the horizontal cue configuration, we observe more edge defined attentional spotlights with no overlapping beams of attention. Thus, no attentional facilitation can be observed in the region between the cued regions. Therefore, with the in-between cue condition, we observe increased RTs for target discrimination.

The existing models of attention, such as the spotlight, the zoom-lens and the gradient, all agree that the perceptual facilitation that is mediated by attention decreases with the distance from the focus of attention as the target increasing. However, some studies have reported regions of perceptual suppression surrounding the attentional window or, the region of attentional enhancement (Bahcall & Kowler, 1999; Caputo & Guerra, 1998; Cutzu & Tsotsos, 2003; Slotnick, Hopfinger, Klein, & Sutter, 2002). Researchers have also provided physiological evidence for surround inhibition, showing that neural activity in early visual areas coding for locations nearby an attended location was suppressed (Müller & Kleinschmidt, 2004). The authors suggested a Mexican hat-like distribution of attentional modulation. With this type of distribution, processing of stimuli close to the focus of attention will be enhanced, and the facilitation will level off with increasing distances of the stimuli from the center of attention.

In a study by Müller, Mollenhauer, Rösler, & Kleinschmidt (2005), subjects had to discriminate target letters that were presented at a fixed location on an imaginary hemicircle centered at fixation. With the target letter, distractor letters were presented at various positions on the hemi-circle. The letters could either be neutral, compatible or incompatible with the target. The authors investigated how the distance between the target and incompatible distractor letters would modulate behavior. They calculated the response time differences of trials with incompatible and neutral distractors (linked with no, or a conflicting response with respect to the target), and plotted them as a function of distance. In the case of a Mexican hat distribution, the authors expected the response time differences to be largest for nearby distractors, and then drop to zero in the inhibition zone, then increase and finally taper off. The results supported the Mexican hat-like distribution, where the distractor letters inducing a response incompatible to the one required by the target led to the longest response times when they were closest to the target letter. This finding of strongest interference and suppression from incompatible distracting stimuli when they are closest to the target has been reported in previous studies (Eriksen & Hoffman, 1973; Eriksen & St James, 1986; Eriksen, Pan, & Botella, 1993). Results from the current thesis would fit the Mexican hat-like distribution, even with multiple regions of attention. As the distance of the target increases from the cued spot, there is a decrease of the perceptual facilitation.

Moreover, with two or more cued spots, as the distance of the target to the cued spots varies, this leads to overlapping beams of attention. However, these beams do not have sharp boundaries, as they are flexible in shape (Panagopoulos, von Grünau, & Galera, 2004), and size (Julesz, 1984). Results from the current thesis support the idea of overlapping areas of attentional enhancement and suppression, with the overlapping regions changing as a function of distance from the cued spots to the target.

Bayesian decision theory (Kersten & Yuille, 2003; Maloney & Zhang, 2010) could also be used to explain observer responses, Bayesian decision theory is a statistical approach, that quantifies trade-offs between various decisions using probabilities and costs that accompany such decisions. Suppose that participants know that 80% of the trials are valid, and the rest are invalid. If this is the only information they have in order to make their decision, then they will want to classify the trial as valid. The a priori information in this case is the probability of a trial being either valid or invalid. So the probability of a valid trial, P(valid) = 0.8 (or 80%). If we respond valid on most trials, we will ensure that we get 80% correct. However, in reality, the participants do not know the probabilities of the number of valid/invalid trials. However, human participants have been shown to build internal representations of priors and likelihoods (Kording & Wolpert, 2004 Beierhold, Quartz, & Shams, 2009; Vilares, Howard, Fernandes, Gottfried, & Kording, 2012). Higher proportion of valid trials leads to higher likelihood of valid trials, thus internal participant representation would be biased towards valid. Therefore, task performance may be due to the experienced probability of the stimulus being valid/invalid/in-between. In all experiments, the probability for valid trials was greater than the probability for invalid trials, and even greater than the probability for the in-between trials. Since the in-between trials are infrequent (thus low probability), participants have no representation of them and therefore behave like they do for the invalid cue in some cases, but with a higher degree of variability.

Another way to interpret the results of experiments with partially valid precues, is by making certain assumptions about how observers interpret the cue probabilities. For example, Palmer, Ames, and Lindsey (1993) were rather dismissive of partially valid precues. They were also critical of effects on measure of sensitivity using the ‘‘dual-task’’ paradigm, in which performance when target detection was the primary (e.g. first-reported) task is compared with performance when target detection was a secondary task. They concluded that effects measured in this way might reflect different rates of memory decay rather than different sensitivities per se. Instead, Palmer et al. (1993) advocated the use of totally valid precues in all conditions.

Limitations of current thesis

The main limitation of the current thesis is that there is no in-between cue condition, when attending to one single spot for Experiments 1, 3A and 3B. This does not allow for direct comparisons of the in-between cue condition for the experiments aforementioned. It would be interesting to study how the in-between cue condition would work in such situations and future experiments could address this.

Another limitation is that it is not known with certainty if the participants in this study truly maintained fixation throughout the experiments. An obvious remedy for this is to have the experiment set up with an eye-tracker and monitor eye movements. Using the eye-tracker, if the participant moves their eyes beyond fixation (+/- 1 degree), then the trial could be marked as an error or null trial, and re-cycled later in the experiment.

Another limitation involves the use of the cognitive/perceptual load hypothesis to explain some of the results in this thesis. Unfortunately, this is just a hypothesis and has not been experimentally tested. One way to test such a hypothesis is to use the technology of an eye-tracker. With an eye-tracker, the researcher can investigate how fixations (i.e., pauses in eye movement), saccades (i.e., rapid, ballistic eye movements), and pupil dilation responses (i.e., changes in pupil sizes) are related to the information on the screen and behavioural choices during an experiment. The hypothesis of cognitive load can potentially be confirmed via measurement of pupil size with the aid of eye tracking. This is because pupil dilation responses indicate emotion, arousal, stress, pain, or cognitive load (Wang, 2009). Since images of the pupil are recorded, the eye-tracker is able to measure pupil dilation by either counting the number of pixels of the pupillary area or fitting an ellipse on the pupil image and calculating the length of the major axis (Klingner, Kumar, & Hanrahan, 2008).

In principle, pupillary responses could be used to measure differences in cognitive load under various tasks. As an example, in one study pupillary dilation responses were used as an indication of cognitive load during syntactic processing (Just & Carpenter, 1993). Subjects were given object-relative sentences ("The reporter that the senator attacked admitted the error") that involved a larger load on short-term memory, and the less cognitive demanding subject-relative sentences ("The reporter that attacked the senator admitted the error"), and were asked true-false questions later to test their comprehension of the sentences. The authors concluded that object-relative sentences induced larger pupillary responses (0.25mm vs. 0.21mm), and increased latency to peak by 116ms. Consequently, if the perceptual load with the spatial cueing paradigm does increase with the number of cued locations, we would expect to see an increase in the pupil size as we increase the number of cued locations from one spot to two (or more spots).

Yet another limitation could be that the distances between the spots, in the experiments for the present study were chosen arbitrarily. Perhaps if the spots were closer together the effect size would decrease. Meaning that, attention would have to exert a much larger effect in order to successfully narrow the attentional tuning curves. With the current state of the thesis, it is not known, nor can it be known how the results would change with changes in spots density by moving the spots closer to fixation or further apart.

Future directions

To address some of the limitations with this study, several experiments can be proposed. All of these experiments have the same goal: to study and provide further evidence of the existence of multiple beams of attention under the right circumstances.

Proposed Experiment 1

This experiment is concerned with the study of variations in spot density. We can suspect that if spots are moved further apart than what they were in present thesis, it may be easier to split attention even in the same hemifield. The reasoning behind this is that even a small variation in receptive field size or attentional size, would decrease the overlap between the two attentional areas. The further the two spots are apart, the smaller the attentional overlap will be and therefore, a small change in receptive field size caused by attention could lead to a large modulating effect by attention on the overlap. This would imply that even within the same hemifield, attention would have a large modulating effect on neurons to narrow their responses and reduce the neuronal selectivity overlap. Thereby, allowing for multiple attentional beams.

Proposed Experiment 2

This experiment proposes to use gaze-contingent stimuli presentation. The gaze-contingency paradigm is a general term for techniques that allow for a change in the display on a computer screen as a function of where the viewer is looking. Gaze-contingent techniques are part of the eye movement field of study in psychology (Land & Tatler, 2009). In gaze-contingent paradigms the stimulus display is continuously updated as a function of the observers' current gaze position. The gaze-contingent techniques aim to overcome limitations with the simple eye-movement recording. For instance, it is not possible to exactly know which visual information the viewer is processing based on the fixation locations. By controlling precisely the information projected in different parts of the visual field, the gaze-contingent techniques permit to disentangle what is fixated and what is processed.   In the current thesis, a short SOA was used to avoid eye-movements. However, if stimuli were gaze-contingent, then the SOA could increase.

Therefore, we might see more of a modulating effect of attention. The technology of eye-tracking can also be used as a tool to study and measure pupil size since this has shown to be affected by the attentional load of the task (Wang, 2009). Moreover, an eye-tracker can be used to determine if participants made an eye movement from fixation, and this would null the trial.

Proposed Experiment 3

What happens when the target location between the spatial cue and the in-between cue condition is varied? By varying this distance, to place the in-between condition closer towards one of the cued locations, we can investigate if there is an effect of distance, and how this affects selective attention, and most importantly multifocal selective attention. This would allow us to explore the properties of spatial attention, and better understand the overlapping regions or separation of receptive fields between two or more cued locations. This proposed experiment would also allow for the investigation of the theoretical model of overlapping beams of attention with fuzzy borders.

Proposed Experiment 4

Do the current thesis results apply to other tasks (or paradigms)? One such paradigm that could be explored is the Line Motion Illusion (Schmidt, 2000; Bavelier, Schneider, & Monacelli, 2002; von Grünau, Dubé, & Kwas, 1996; von Grünau, Racette, & Kwas, 1996; Hikosaka, Miyauchi, & Schimojo, 1993). Visual attention enhances our perceptual sensitivity (Carrasco, Penpeci-Talgar, & Eckstein, 2000; Pestilli & Carrasco, 2005; Treue, 2004) and research indicates that its effects can be observed at the earliest stages of cortical processing (Posner & Gilbert, 1999; Rees, Backus, & Heeger, 2000). Researchers have speculated that visual attention accelerates the processing of attended stimuli as early as the primary and secondary cortices (von Grünau, Racette, & Kwas, 1996; von Grünau, Saikali, & Faubert, 1995; Hikosaka, Miyauchi, & Shimojo, 1993; Schmidt & Klein, 1997).

The line motion illusion has been taken as support of the view that visual attention increases the speed of processing at the earliest stages of visual processing. When a static line is presented near a brief cue, participants report motion within the line from the cued end, towards the un-cued end. Researchers have suggested that endogenous and reflexive attention can induce the line motion illusion (Schmidt, 2000; Bavelier, Schneider, & Monacelli, 2002). The line motion illusion can be used to provide a different and direct measurement of attention, as well as to study multifocal attention. Since the perception of motion in the line motion illusion is away from the attended area, one can hypothesize that if the observer is actually attending exclusively to the cued area, he/she will report illusory motion away from only that area.

The line motion task can be used to investigate whether RT will be significantly longer when the target appears between two cued regions. It would be expected that if the line is presented at one of the two cued areas, then motion will be perceived as moving away from the cued location. However, if the line is presented near an area in between the two cued regions, then there should be no biased motion perceived. This would suggest that attention is not placed in between the cued locations, thus there would be no activation in that area. Moreover, this result would imply that the attentional beam was successfully split to cover non-contiguous regions.

Significance of thesis

To understand perception as it happens in the real world, we need to go beyond just considering how we perceive isolated objects. We need to consider how observers seek out stimuli, and how they perceive some things and not others. What one sees is determined by what one attends to. At any given time, we are bombarded by far more perceptual information that can be effectively processed. To cope with this potential overload, the brain is equipped with a variety of attentional mechanisms. Attention is selective: We can attend to some things and ignore others.

The research conducted for this thesis has important implications for understanding how the brain processes visual information, and the role that attention plays within visual search. This is of practical importance, since within most natural scenes there are many distractor objects, so that it becomes necessary for the visual system to select only places or objects of interest to be processed. In this context, detailed knowledge about the spatial characteristics of the spotlight can contribute much to our understanding.

The thesis was concerned with the following question: when moving beyond two potential stimuli locations, is there a limit of how many locations we can attend to? In addition, how does visual attention behave at multiple locations? The problem with addressing these questions with the classic cueing paradigm (Posner et al., 1980), is that the stimulus locations are limited to only two spatial locations (i.e., left and right), of which only one can be cued at any time. Since the main aim of this thesis was to investigate cueing at multiple locations (i.e., greater than two), and cueing more than one location at a time, a new stimulus paradigm was developed. This new stimulus consisted of four possible cue locations, with each potential location located in 45 degree increments (45, 135, 225, 315 degrees) at the same eccentricity.

With this new cueing paradigm, the same cueing effect results were obtained as previously reported by Posner and colleagues (1980). Meaning that, the location of the spotlight can change with spatial cueing. In addition and of importance to this thesis, the spotlight of attention can change location when multiple potential locations are present. The results obtained throughout this thesis revealed a significant cue effect. An interesting cue configuration result was revealed in this study. It was much easier to split attention across hemifields as opposed to within the same hemifield. This result was evident by looking at the cost in RT when the target appeared between two cued spots. RT was significantly longer for the in-between cue condition only when the cues formed a horizontal cue configuration, not the case with the vertical configuration.

The results of the current thesis have revealed that when observers' attention moves from attending to one single spot, to two simultaneous spots, and even to four simultaneous spots, the benefit of cueing a spatial location decreases. However, the benefit is still present. That is, as participants are instructed to pay attention to many locations (up to four separate locations), discrimination performance decreases. Thus, as the number of cued spots increases from one to four, the valid cue RT increased. Although participants can attend to four separate regions, they are not as good at target discrimination compared to the situation with only one spot or even two cued spots. Based on this, it can be concluded that the benefit of spatial cueing is decreasing as the number of spots is increased. However, even though the benefit of the cues is decreasing, it is still present when four spots are cued (when compared to the invalid condition).

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Appendix A

Summary Table for Cueing one spot – A single focus of attention

(Experiment 1)

Table A

Analysis of Variance Results for cueing a single focus of attention with cue type (Valid, Invalid, and Non-informative)

Source	*SS*	*df*	*MS*	*F*	*p*	η_p^2
<u>Within-Subjects</u>						
Cue Type	.019	2	.010	16.10	.000	.59
Error	.013	22	.001			

Appendix B

Summary Tables for cueing two spots – Two foci of attention

(Experiment 2)

Table B1

Analysis of Variance Results for cueing two foci of attention with cue type (Valid, Invalid, and In-between)

Source	*SS*	*df*	*MS*	*F*	*p*	η_p^2
<u>Within-Subjects</u>						
Cue Type	2260.04	2	1460.042	3.697	.04	.24
Error	7335.98	24	394.936			

Table B2

Analysis of Variance Results for cueing two foci of attention with the two factors of configuration (Horizontal and Vertical) and cue type (Valid, Invalid, and In-between)

Source	*SS*	*df*	*MS*	*F*	*p*	η_p^2
<u>Within-Subjects</u>						
Configuration (A)	4134.81	1	4134.81	4.786	.05	.29
Error	10367.502	12	863.959			
Cue (B)	4520.082	2	2920.084	3.697	.05	.24
Error	14671.972	24	789.871			
A x B	8799.422	2	5531.406	8.975	.003	.43
Error	11764.886	24	616.294			

Appendix C

Summary Tables for mixed one and two cued spots in a vertical configuration

(Experiment 3A)

Table C1

Analysis of Variance Results for mixed one and two cued spots in a vertical configuration with the two factors of spots (One and Two) and cue type (Valid and Invalid)

Source	*SS*	*df*	*MS*	*F*	*p*	η_p^2
<u>Within-Subjects</u>						
Spots (A)	2.132E-05	1	2.132E-05	.351	.568	.037
Error	.001	9	6.081E-05			
Cue (B)	.018	1	.018	20.694	.001	.697
Error	.008	9	.001			
A x B	.001	1	.001	9.276	.014	.51
Error	.001	9	.000			

Table C2

Analysis of Variance Results for cueing two foci of attention with cue type (Valid, Invalid, and In-between)

Source	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Within-Subjects						
Cue Type	.007	2	.005	14.144	.001	.611
Error	.005	18	.00			

Appendix D

Summary Tables for mixed one and two cued spots in a horizontal configuration

(Experiment 3B)

Table D1

Analysis of Variance Results for mixed one and two cued spots in a horizontal configuration with the two factors of spots (One and Two) and cue type (Valid and Invalid)

Source	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Within-Subjects						
Spots (A)	5.305E-05	1	5.305E-05	.317	.589	.038
Error	.001	8	.00			
Cue (B)	.014	1	.014	9.065	.017	.531
Error	.012	8	.002			
A x B	.001	1	.001	27.524	.001	.775
Error	.000	8	2.434E-05			

Table D2

Analysis of Variance Results for cueing two foci of attention with cue type (Valid, Invalid, and In-between)

Source	*SS*	*df*	*MS*	*F*	*p*	η_p^2
<u>Within-Subjects</u>						
Cue Type	.017	2	.014	5.190	.041	.393
Error	.026	16	.002			

Appendix E

Summary Tables for mixed one and four cued spots

(Experiment 4)

Table E1

Analysis of Variance Results for mixed one and four cued spots with the two factors of spots (One and Two) and cue type (Valid and In-between)

Source	*SS*	*df*	*MS*	*F*	*p*	η_p^2
<u>Within-Subjects</u>						
Spots (A)	3264.100	1	3264.100	34.443	.000	.81
Error	758.136	8	94.767			
Cue (B)	78782.556	1	78782.556	4.540	.066	.362
Error	138832.375	8	17354.047			
A x B	8591.361	1	8591.361	37.553	.000	.824
Error	1830.249	8	228.781			