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SPATIOTEMPORAL CHARACTERISTICS OF INTERACTION BETWEEN EXOGENOUS AND ENDOGENOUS ORIENTING OF VISUAL ATTENTION

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

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*****

The Ohio State University 1999

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ABSTRACT

The location-precuing paradigm establishes two distinguishable forms of spatial cueing: an endogenous cue, a centrally presented indicator, that directs attention to a peripheral location in a goal-driven fashion; and an exogenous cue, a peripheral onset stimulus, that draws attention in a stimulus-driven fashion. Attention gradients, a phenomenon that attention effects on the unattended locations decline with increasing distance from the attended location, is found whether exogenous or endogenous cues are administered under different experimental settings. However, it is argued from the perspective of limited capacity that there may be a differential effect of exogenous and endogenous cues in the allocation of spatial attention. Experiments 1 and 2 examined this issue. Using EOG electrodes to monitor eye movements, the allocation of spatial attention is measured with response times to recognition of the targets that are presented at different locations following a cue. The results showed that as opposed to endogenous orienting, there was no distance effect found in exogenous orienting. Experiment 2 further examined whether the abrupt-onset feature or luminance of an exogenous cue was responsible for triggering the orienting response. The results showed that the reaction time costs of the uncued locations for the bright cue was about the same as for the dim
cue. The findings suggest that the dynamic changes of a peripheral flash, rather than luminance of the flash, may trigger the orienting system.

Presumably, a peripheral onset may override an endogenous cue. Past research concluded that whether an abrupt-onset distractor could override an endogenous cue depended on spatial certainty of the endogenous cue. Yet the underlying competitive mechanisms are still not clear. In three experiments, we manipulated the cue-to-distractor SOA (stimulus onset asynchronies) and spatial distance between cued and distractor locations, assuming that competition between distractor and cue can occur in two stages: location coding and attention allocating. Following a central cue, an abrupt flash occurred in any location other than the centrally cued location. The reaction times to identification of the target were measured. The interruption effect of a peripheral flash is indexed by the extent to which this identification process is slowed down relative to the distractor-absent condition.

Experiment 3 found that when the cue-to-distractor SOA was over 200 ms, the nearest distractor produced the largest interruption. Experiment 4 found an asymmetrical pattern of interruption effects across different visual fields when the cue-to-distractor SOA was 100 ms. Experiment 5 found that when the cue-to-distractor SOA was only 84 ms, the farthest distractor produced the largest interruption. In conclusion, the extent to which an abrupt-onset distractor will override a central cue depends on interaction of the cue-to-distractor SOA and spatial distance between the cued location and the distractor, which has significant implications for the theories of visual search.
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CHAPTER 1

INTRODUCTION

1.1 Brain capacity and visual attention

Information abounds in our surroundings; information-processing capacity is, however, limited for the brain. Limited capacity is a sufficient reason for perceptual systems to select which object and/or region of space to process first (Tsotsos, 1997). As Tsotsos (1990) has demonstrated, the computational complexity of a visual search task without knowing where to start is far beyond the brain's capacity. The general purpose of selectivity is to protect the brain's limited capacity system from informational overload (Allport, 1989). If the brain's capacity were sufficient to process all information that arises from every sense organ at one time, then attention would not be necessary. Therefore, the function of attention is to decide which information will be selected for high priority processing and further to control the availability of the brain's capacity. Attended objects or locations make demands on processing capacity, whereas unattended ones may or may not, to various degrees, have the allocation of processing capacity.
Take vision, for instance. It seems impossible for people to recognize everybody at a party at the very first look. Obviously, people can not recognize every object in every region of space at one time. The visual systems accomplish object recognition by selectively gazing on a relevant (or salient) portion of image or region and processing the feature information just within this portion, then moving on to another relevant portion. The faculty that executes this selective mechanism is called visual attention.

1.2 Location-precuing paradigm

Experimental evidence gathered from different paradigms, such as visual search and location-precuing paradigms, has suggested that the algorithm of spatial selection is to enhance the processing of relevant locations and/or to inhibit the processing of irrelevant locations. Early evidence of spatial attention is shown from the location-precuing paradigm (Posner, 1978). In this paradigm subjects' attention is directed to one specific location at either left or right of a fixated point by an arrowhead cue presented at the fixated point, which indicates the likely target location, or by an abrupt brightening of a peripheral location. Hundreds of milliseconds after the cue, a target appears either in the cued location (a valid condition) or its opposite location (an invalid condition). The baseline condition is when a cross is presented at the fixated point, serving as a warning signal and not indicating any target location (a neutral condition).

It has been well established that reaction times (RTs) to the target are faster in a valid condition than in a neutral condition. This RT difference is called the benefit of precuing, and it results from enhancement of cued locations. In contrast, RTs are slower in an
invalid condition than in a neutral condition. This RT difference is called the cost of precuing, and it results from inhibition of uncued locations.

In the location-precuing paradigm, two sources of spatial selection—exogenous and endogenous cues—are used to direct covert orienting which refers to the allocating of attention to a peripheral location without concomitant eye movements. The differences between exogenous and endogenous orienting lie in the selective mechanism and time courses.

An endogenous cue is a symbolic indicator (e.g., an arrowhead or a line) presented at the center of the display (also referred to as a central cue), indicating the very likely location of the forthcoming target in the periphery. The facilitation effect of the valid cue on the target detection must be ascribed to the perceptual goal generated endogenously because the target never appears at the center of the stimulus display. In contrast, an exogenous cue is an abrupt brightening of the outline of one location in the periphery (also referred to as a peripheral cue), which is randomly associated with the target location. The shift of attention and processing benefits for the cued location may be initiated by the sudden stimulus onset because subjects are given no reason to expect the target at the cued location.

In addition, the endogenous cue needs to be perceived and decoded to determine which location it indicates, whereas no such translation or decision process is required for the exogenous cue. This distinction may result in the difference between central and peripheral cues in the time course of their facilitation effect on task performance. For
example, Cheal and Lyon (1991) found that an exogenous cue produced an optimal performance on the target discrimination when the interval between the onset of the cue and the onset of the target (stimulus onset asynchronies; SOAs) was within 100 ms, whereas an endogenous cue required approximately 300 ms to produce an optimal performance.

1.3 Stimulus-driven vs. goal-directed selectivity

The theoretical and empirical distinctions indicate that the determining force of selection can be goal-directed or stimulus-driven (Egeth and Yantis, 1997). In stimulus-driven attention, selection is determined by the properties of the stimulus itself even if they are irrelevant to the current goal of the tasks. In goal-directed attention, observers’ knowledge and goals determine where and/or what to select. It is also implied that exogenous orienting is an automatic process (or a bottom-up process), whereas endogenous orienting is a voluntary process (or a top-down process).

1.3.1 Distance effects in spatial selection

A question of interest arising from this distinction is: what is the differential effect of exogenous and endogenous cues on the processing of uncued portions of the visual field? A general approach to this question is that following the cue, a target is then presented at different spatial separations from the cued location. The allocation of spatial attention is measured with response times to recognition targets at different locations. For example, Hughes and Zimba (1985) examined a central cue and found small, but uniform, benefits
associated with all the target locations within the expected hemifield and larger, uniform costs associated with all target locations occurring within the unexpected hemifield.

On the other hand, Downing and Pinker (1985) found that the magnitude of costs was a linear function of spatial separation between expected and unexpected locations when a central cue was used. The allocation of attention to the unexpected locations declined with increasing distance from the attended location. This result suggested that attention selection operated like a gradient centered at the cued location. This is also referred to as a distance effect in the spatial distribution of attention. In addition, Henderson and Macquistan (1993) tested an exogenous cue in a different stimulus display. They also found a gradient of attention surrounding the cued location.

Shaw (1984) has argued that the distance effects (indexed by response times) may result simply from the change of the response criterion because the response criterion varies inversely with the likelihood of the target. The most likely target location will have the lowest response criterion and thus the fastest response. Nonetheless, the distance effects of spatial selection on perceptual sensitivity have also been observed. For example, Downing (1988) found a gradient of sensitivity (d') distribution following an endogenous cue. In addition, Mangun and Hillyard (1988) also found that the amplitudes of the P135 and N190 brainwaves decreased progressively as attention was directed to the locations increasingly distant from a lateral stimulus.

In sum, it seems that the distance effect is quite robust across different approaches under different stimulus displays and tasks. Generally, this line of research suggests that
the extent to which the unattended locations are processed decreases with increasing separation from the attended location no matter what type of cue is involved.

The distance effect also implies that the closer to the attended location the distracting stimuli are, the more interference they will cause. This reasoning has been demonstrated in the response-competition paradigm. For example, Eriksen and Hoffman (1973) found that reaction times to a designated target letter were slowed by the presence of neighboring irrelevant letters associated with the wrong response. More importantly, this interference effect rapidly diminished as noise letters associated with the wrong response were moved farther away from the target. This evidence applies to goal-directed visual selection because perceptual goal settings must be established before the target is presented.

However, this implication may not be applied to stimulus-driven selection because it has been found that the noise stimuli will not affect the search time for a target with a distinctive feature no matter how far the noise is from the target. Under these circumstances, observers’ attention seems to be allocated to a restricted region surrounding the target when they are required to look for a target containing a unique distinguishing feature relative to neighboring distractors. Feature search is a bottom-up process. This evidence suggests that there may not be a distance effect in stimulus-driven visual selection.

The limited-capacity perspective holds that the total amount of resources in the brain is fixed. If process A has taken up most of them, then process B will have less to use. Because exogenous orienting to a cued location is an automatic process (capacity-free),
other uncued locations may still be attended to some extent. Relatively, because endogenous orienting to the expected location is a voluntary process (capacity-consuming), other unexpected locations may have no allocation of attention at all and may even be inhibited. According to the evidence from visual search and response-competition paradigms, we speculate that there may well be a differential effect of exogenous and endogenous cues on attentional allocation over uncued locations. A prediction of this hypothesis is that RT costs of the uncued locations in endogenous cueing should be significantly larger than in exogenous cueing. The second prediction is that no distance effect will be found in exogenous orienting as opposed to endogenous orienting.

1.3.2 Competition between stimulus-driven and goal-directed selectivity

Another question of interest is: how will exogenous and endogenous cues compete with each other for control of attention if they both direct attention to different locations? Presumably, exogenous orienting may override endogenous orienting if both processes are put together against each other because exogenous orienting is more automatic (Jonides, 1981). Following this approach, Muller and Rabbitt (1989) found that a subsequent peripheral flash could interrupt the endogenous cue that is only 50% valid. However, Yantis and Jonides (1990) found that an abrupt-onset stimulus did not necessarily capture attention when attention was directed to a specific location by an endogenous cue 200 ms prior to the abrupt onset. Theewues (1991) also found that when attention was in focused mode (a central cue with 100% predictive validity appeared prior
to the target), abrupt-onset at nontarget locations did not affect performance, relative to the baseline condition. Nonetheless, when attention was not focused on a specific location, which was also referred to as a diffuse mode (i.e., a central cue appeared posterior to the target), abrupt-onset at target locations facilitated performance, whereas abrupt-onset at nontarget locations slowed down performance, relative to the baseline condition. This finding suggested that the peripheral abrupt-onset could capture attention only when attention was in diffuse mode.

Taken together, it seems that whether the abrupt-onset distractor can overrule the endogenous cue depends on the extent to which attention has been engaged. From the information-processing perspective, the competition between exogenous and endogenous cues can possibly occur at two stages. The first stage can occur as early as in location coding because the directionality of the endogenous cue must be decoded before the shift of attention. When the subsequent exogenous cue arrives at this stage, its interruption effect on the previous endogenous cue may be simply due to the failure of location coding of endogenous cues. As a result of this interruption, attention must be in diffuse mode at one moment and then be captured by the exogenous cue. After realizing that the target is occurring somewhere else (i.e., attention has been distracted), observers then shift their attention back to the target location. If reaction times increase with the distance of the attention shift, performance on target identification will be faster when it is near the exogenous cue than when it is far from the exogenous cue.

The second stage occurs during attention focusing. As described earlier, at a given moment in time the distribution of focused attention directed by an endogenous cue is a
gradient surrounding the cued location. The farther away from the cued location the
distractor is, the less amount of attention the distractor will be allocated. If this is true, it
is more probable for an irrelevant abrupt-onset cue to distract attention when it is near the
digenous cue than when it is far from the endogenous cue.

In addition to the distance effect involved in the attentional distribution, we speculate
that there may well be a distance effect in the interaction of exogenous and endogenous
cues. In other words, the interruption of an endogenous cue by an irrelevant exogenous
cue depends on the distance between two locations where those two types of cues indicate
respectively. This prediction also makes ecological sense. From the ecological
perspective, the exogenous cue (e.g., a sudden movement or a flash) usually represents a
potential danger to animals. It is reasonable to think that the extent to which this
exogenous cue will interrupt endogenously attentive ongoing behavior (e.g., catching a
bug) may depend on how far away the potential danger is and how deeply the
endogenously attentive behavior has been engaged in. In other words, this distance effect
varies with whether attention is in diffuse or focused mode.

1.4 A computational approach to visual attention

The information-processing approach has led many researchers to propose some
metaphors of attention, such as a filter (Broadbent, 1958), a spotlight (Eriksen and
Hoffman, 1973; Posner, 1980), and a zoom lens (St. James and Eriksen, 1986). In those
metaphors, the mechanisms of selective attention are expressed as the regulation of
information flow through those cognitive devices. Take the example of a spotlight.
Information that is included in the spotlight will be processed actively, while information excluded outside the spotlight will be ignored or actively inhibited. The zoom lens model further adds one feature of flexibility to the spotlight to make it able to either focus on a limited region or expand to a larger portion of the visual field. To accommodate the distance effect described earlier, Cheal (1997) proposed the variable and permeable filters metaphor in which each filter is the composite of excitatory and inhibitory effects. The actual flow of information is determined by relative amounts of excitation and inhibition. If the summation of excitation (positive) and inhibition (negative) in each filter for a specific location turns out positive, information processing in that location will be enhanced. In contrast, if the summation is negative, information processing in that location will be inhibited. Therefore, any pattern of attention effects across the visual field can be accounted for by using as many filters as necessary. However, this metaphor seems to be unfalsifiable. In summary, these metaphors do not seem to explain what computational mechanisms in the brain actually accomplish the spatial selection.

However, the computational approach (Mozer, 1991; Tsotsos, 1993) provides an alternative conceptual framework to revisit the nature of visual attention. This approach concerns the computational aspect of attention and attempts to implement the information processing models of attention with massive neuron-like processing units in the interconnected network. This approach is to construct models at a level that is possibly realized both computationally and neurobiologically.

Among many different models, attention is also described and implemented in different ways. Mozer (1991) proposed a connectionist model of visual attention that is
independent of the visual information processing system. The attention mechanism (AM) network is a set of units arranged in a retinotopic map in one-to-one correspondence with the units that interpret the visual features and thus represent a feature map. Activity in an AM unit serves to gate the flow of activity from the lowest feature map to the upper level. Generally, attentional selection results from the AM network that constructs a variable-diameter spotlight on the retinotopic representation. Within that spotlight the sensory information is preferentially processed. Attention selection occurs by biasing processing, not actively inhibiting activation from the unattended locations. Nonetheless, Tsotsos (1993, 1994) described a model of visual attention within the visual processing system. Attention selection operates via inhibiting irrelevant connections throughout the whole visual processing system.

As some theorists of attention have suggested (Bundesen, 1990; Logan, 1996), selectivity may well be the result of a combination of stimulus-driven and goal-directed processes. Stimulus-driven selection may be dependent on observers' goals for the current tasks (Folk, Remington, and Johnston, 1992). On the other hand, stimulus-driven processes may interrupt goal-directed processes (Muller and Rabbitt, 1989). Yet these connectionist models do not seem to describe explicitly how stimulus-driven and goal-directed processes interact with each other.

In this research, a connectionist model is built, adapted from Tsotsos' model, to describe how bottom-up and top-down influences are implemented and to predict the nature of interaction between stimulus-driven and goal-directed selection.
1.5 Confounding in visual attention research

Attentional effects can be confounded by two other factors: eye movements and visual acuity. First, the relationship between attention and eye movements is very complicated. Observers may move their eyes to where they are attending; this is called “overt orienting” as opposed to “covert orienting”, which will be explored in this study. Without controlling eye movements, observers will spontaneously move their eyes to the cued location and wait for the target. Therefore, the dependent measurement of reaction times will simply reflect the duration of time during which the eyes move from the cued location to the target (saccadic movements). The distance effect will simply reflect the spatial separation between the cued location and the target. To exclude this confounding, we monitor subjects’ eye movements using EOG (electro-oculograms) electrodes.

Second, targets in foveal vision are always recognized more quickly than in peripheral vision. This is called the visual acuity effect. As the location is farther away from fixation, it is more peripheral to the foveal acuity. Therefore, if each location had a different distance to the fixated point, the visual acuity effect might confound the attentional effects. The gradient of attention can be due to confounding of the target locations with retinal acuity. To avoid this confounding, the stimulus display is arranged along an imaginary semicircle in which each possible target location is equally distant from the fixation center.
1.6 Purposes of research

Much previous research into spatial attention has been more or less contaminated by the two confounding factors described above. The worst is that the confounding can lead to the most important conclusion in this line of research, which is the distance effect in the spatial distribution of attention. In this study, we aim to control confounding and answer the following questions. Is there a differential effect of exogenous and endogenous cues on the processing of uncued portions of the visual field? In addition to cognitive metaphors, what model can explain this difference computationally? Can the irrelevant exogenous cue interrupt the endogenous cue? What is the factor determining when this interruption will or will not occur? What is the computational mechanism underlying this interaction?

More specifically, there are three main goals in this study. First, we want to test the prediction regarding the differential effects of exogenous and endogenous cues on the spatial distribution of attention across the uncued regions, which is no distance effects in exogenous orienting as opposed to distance effects in endogenous orienting. Second, we want to test the prediction regarding competition between central cue and abrupt-onset distractor, which is not only that interruption of the distractor depends on spatial separation between cue and distractor, but also that this distance effect in interruption depends on whether attention is in diffuse or focused mode. Third, we want to build a connectionist model to simulate the data derived from those tests and hopefully to capture the computational aspects of the neural mechanisms underlying spatial attention.
1.7 Organization of this dissertation

This research consists of five experiments. Experiments 1 and 2 examine how visual attention is distributed when directed by exogenous and endogenous cues. Experiments 3-5 test the predictions regarding the competition between endogenous and exogenous cues presented successively.

A detailed literature review is presented in Chapter 2, including three main topics: spatial distribution of attention, interaction of exogenous and endogenous control of attention, and a connectionist model approach to visual attention.

Experiments 1 and 2 are presented in Chapter 3 and 4, respectively. Experiments 3 and 4 are presented in Chapter 5. Experiment 5 is presented in Chapter 6. Finally, Chapter 7 presents a summary of the major findings, general discussions, and conclusions of this research.
CHAPTER 2

LITERATURE REVIEW

2.1 Spatial distribution of visual attention

Posner, Nissen, and Ogden (1978) first established the location-precuing paradigm to demonstrate that a symbolic cue indicating a likely target location could draw observers’ attention to that particular location, making the target detection faster at that location than at other uncued locations. In their experiment, a symbolic arrowhead was presented at the fixated point, pointing to either the left or the right of fixation and predicting the upcoming stimulus with 80% of likelihood. After variable time intervals, a stimulus, “X”, appeared 0.5° to the left or the right of fixation. The results showed that response times to the stimulus in an expected position were faster than to the same stimulus at an unexpected position. It seemed that directed attention was focused in a spatially restricted region (less than 1°).

Hughes and Zimba (1985) adopted this precuing method to explore how wide attentional focus could be across the visual field. In contrast to Posner et al.’s (1978) finding, they proposed the meridian boundary model. According to this model, rather than
restricted locations, attention was directed to large regions of the visual field, where regions were visual hemifields or visual quadrants defined in terms of the vertical and/or horizontal meridians.

In their study, subjects were required to direct their attention by following a central cue to the locations at either a 2° or a 6° visual angle from fixation. The subjects made a simple response to a probe (a luminance onset) occurring at either the cued location 89% of the time, the opposite location across the vertical meridian, or several other locations along the horizontal meridian within the same or different hemifield of the central cue. Hughes and Zimba found small, but uniform, benefits associated with all the probe locations within the expected hemifield and larger, uniform costs associated with all probe locations occurring within the unexpected hemifield. This pattern indicated a sharp transition from costs to marginal benefits across the midline (i.e., vertical meridian). This is referred to as the meridian effect.

Hughes and Zimba believed their results showed that directed attention could not be allocated to a specific location; rather, it would activate the whole visual hemifield. However, since the cost and benefit of RTs for each probe location was based on the ratio of RTs for uncued trials over RTs for cued trials, this index might not be sensitive enough to show the RT difference over spatial distance separated from the expected location. In addition, they didn’t present catch trials, so that subjects tended to anticipate responses and thus had very quick response times (most of data were below 300 ms). Therefore, the data may not have enough sensitivity to reveal the difference of attention effects on each probe location.
Klein and McCormick (1989) tested the meridian boundary model. They precued subjects endogenously to attend to one of the corners in an imaginary square centered at fixation. Suppose an arrow cue pointed to the upper left of the square. An invalid location could be one of the following three types: (A) the lower left that was within the same hemifield as the cued location (across a horizontal meridian), (B) the upper right that was within a different hemifield from the cued location (across a vertical meridian), and (C) the lower right that was the opposite location diagonally across from the fixation point.

If an entire visual hemifield was activated, as Hughes and Zimba (1985) had proposed, then a simple reaction time to a luminance increment in location A would be similar to valid RT and faster than that in location B and C, both of which should be equivalent. The results showed that all three invalid locations behaved similarly. This pattern strongly contradicted the hemifield activation hypothesis. Further, Klein and McCormick proposed a midlocation placement strategy to explain what they found in an experiment in which they fixed the invalid location in one block of trials.

The midlocation placement strategy assumes that locating attentional focus depends on the angular difference between valid and invalid locations. If valid and invalid locations are in the same direction (e.g., above or left), then attention focus is located in the middle location between the two. When an invalid location is moved towards the diagonal opposite of a valid location, attentional focus would be moved towards the valid location and further away from the invalid location (C). Because invalid location A or B is fixed in one block of trials, subjects might just attend to a midlocation between the cued and potentially invalid locations. According to this hypothesis, it was predicted that the
benefit for the valid location would be reduced and the RTs for invalid location A would be equivalent to the RTs for invalid location B, but faster than invalid location C. The results were consistent with the prediction of the midlocation placement hypothesis that attentional focus could be located at the midlocation no stimulus was located.

Unlike the midlocation placement hypothesis, the attentional gradient model proposes that attention is distributed like a gradient centered at the attended location (or precued location). Accordingly, the effects of attention on response performance decline with increasing distance from the attended location. It is also referred to as the distance effect. Obviously, the distance effect has been found in Klein and McCormick’s results.

Downing and Pinker (1985) first demonstrated the conceptualization of attention gradients. In one experiment, subjects had to detect a luminance increment that occurred in one of ten boxes located at either left or right of the fixated point on the horizontal meridian. The eccentricity of boxes varied from 1.25° to 11.25°. A digit cue (from 1 to 10) presented at fixation identified one of ten boxes as a high-probability location and the remaining nine boxes served as low-probability locations. Downing and Pinker found that the magnitude of RT costs on the unexpected locations was a function of the distance separating the expected from unexpected locations. They suggested that the allocation of attention to a spatial location produced a gradient of attention whose peak was centered at the expected location.

Egly and Homa (1991) also provided data consistent with graded attention. Nonetheless, their study was different in some points from Downing and Pinker’s (1985). First of all, Egly and Homa used a two-dimensional stimulus display with four possible
target locations positioned at the corners of an imaginary square. Thus, each location had the same retinal acuity. Secondly, subjects directed their attention by following an exogenous cue combined with the knowledge of probability of the target location to discriminate the letter “L” from the letter “R”. Thirdly, because there were no neutral trials, the cost of invalid trials was based on invalid RTs minus valid RTs.

The results showed that the RT costs for all three invalid locations were a linear function of retinal distance from the cued location. The reaction times to two invalid locations with equal distance from the valid location were equivalent. In their latter experiments, even though one invalid location was fixed in the same block of trials, the results still showed a similar linear trend over retinal distance. Apparently, their findings were similar to Klein and McCormick’s (1985). The RT costs for the invalid locations are mediated by distance, instead of the vertical meridian.

Henderson and Macquistan (1993) examined exogenous orienting. In their study, the stimulus display had eight possible target locations arranged around an imaginary octagon with a radius of 9° visual angle, in which any two adjacent locations have equal distance (7° visual angle). After a peripheral flash was presented, subjects had to complete a letter-discrimination task (“X” or “O”). The cost for each invalid location was based on a reference to neutral trials. The results showed that performance in the cued location was the fastest (and the most accurate), followed by the closer invalid location (whether they were inside- or outside-quadrant locations), and worst at the farthest invalid location (diagonal invalid). As they suggested, the findings supported the gradient model of attentional allocation.
The only shortcoming in the study is that they did not monitor subjects' eye movements instrumentally. Although the interval between cue onset and target offset was only 150 ms, during which subjects probably could not have gained any advantage by executing a saccade to the cued location (entailing more than 200 ms), it is still not certain whether subjects moved their eyes or not during the trial. When eye movements are not controlled, subjects tend to move their eyes to the peripherally flashed location. If so, the pattern of the attentional gradient can possibly be revealed merely by the visual acuity effect because as the target location is farther away from the cued location (assuming eyes are moved to the cued location), it is more peripheral to the foveal acuity. Therefore, it is very probable that this gradient is due to confounding of the target location with retinal acuity.

Handy, Kingston, and Mangun (1997) recorded subjects' EOGs and discarded the trials that contained eye movements or blinks to study the attention distribution across the visual field. In their study, subjects directed their attention to one location by following an arrow cue presented at the fixation point and then responded to a luminance onset. There were six possible target locations arranged along an imaginary semicircle in the upper visual field, 6.0° visual angles from fixation. Both accuracy and reaction times were measured. The analysis of RT cost and benefit for the target detection in each location showed that attention was very narrowly focused on the specific cued location. If the data point of the valid-cued location was excluded, the rest of curve did not indicate that RT costs increased monotonically with increasing target distance from the cued location. It
appeared that beyond 2.5° from the attended location, there was little or no modulation in target detection latency.

In their Experiment 3, unlike in the previous experiment, targets were suprathreshold and not masked. The catch trials were reduced from 50% to 9.5%. The results showed a much broader RT gradient pattern. Even though the data point of the attended location was excluded, there was still a significant attentional effect in the rest of the curve. Evidence from these two experiments suggests that perceptual factors can influence the spatial distribution of attention. Specifically, as perceptual demands increase (e.g., via decreased target saliency), attention becomes more narrowly allocated in order to focus greater attentional resources on the expected target location.

In summary, the findings from different tasks and stimulus displays seem to be inconsistent, but most researchers generally agree that the effects of attention on response performance decline with increasing distance from the attended location. This conclusion is based on the reaction times as a dependent measure. On the other hand, the distance effects (indexed by response times) may result simply from the change of the response criterion because the response criterion varies inversely with the likelihood of the target location (Shaw, 1984).

According to the signal detection theory, there are two stages of information processing involved in the target detection. First, sensory evidence in one channel is accumulated regarding the presence of the target. Second, observers adopt a decision criterion, whether it is liberal or conservative, to determine whether this evidence is sufficient for the detection response. Compared to the uncued locations, the decision criterion will be more
liberal towards the cued location because the target is most likely to occur at that location. As a result, the response to the target at the cued location will be faster relative to other uncued locations because less sensory evidence needs to be accumulated from the cued location.

Instead of simply measuring reaction times, the distance effect of spatial selection in perceptual sensitivity has also been observed. In Downing's (1988) experiment, twelve possible target locations marked by boxes were arranged along on an imaginary circle with a 7° diameter. After an arrow cue pointed to one location, subjects were randomly probed to perform a detection task in which the stimulus could occur at one of four locations including the expected location. The performance was indexed by perceptual sensitivity (d') according to the signal detection theory. The results showed that sensitivity was maximally enhanced at the expected location and gradually decreased with increasing distance from that location.

In addition, from electrophysiological evidence, Mangun and Hillyard (1988) also found that the amplitudes of the P135 and N190 brainwaves decreased progressively as attention was directed to locations increasingly distant from a lateral stimulus. Also, the spatial gradients of P1/N1 amplitudes were paralleled by changes in d' scores. Because the modulations of P1/N1 components index an early attentional process that regulates the amount of sensory information flowing to higher perceptual centers (e.g., visual cortex), the distance effects in spatial selection may reveal a mechanism operating (filtering or gating) at the early stage of visual information processing.
Although the distance effects reviewed previously are all revealed from the location-precuing paradigm, in which the target appears without accompanying any distracting stimulus, it is reasonably assumed that the closer to the attended location the distracting stimulus is, the more interference it will cause. Many studies using the response-competition paradigm have also supported this assumption.

The response-competition paradigm consists of experiments performed to study the extent to which nontarget noises are processed along with the target stimuli. For example, in viewing a three-item display, such as YXY or XYX, subjects are required to respond to the center stimulus by pressing the left key if it is X or the right key if it is Y. The irrelevant flanking stimuli (such as two Ys in the case of YXY) often have interference effects on performance. For example, Eriksen and Hoffman (1973) showed that reaction to a target letter was slowed by the presence of irrelevant letters associated with the wrong response. More important, this interference rapidly diminished as letters associated with the wrong response were moved farther away from the target. This distance effect has been interpreted in terms of a spotlight metaphor. Near distractors produce interference because they fall within the attentional spotlight that is focused on the target, and hence they are selected for further perceptual processing or for potential response. By contrast, distant distractors fall outside the spotlight, and are therefore ineffective.

Eriksen and St. James (1986) proposed a zoom lens model, in which the attentional focus was enlarged to include all precued locations, but the speed of response decreased as the precued area expanded. They also found that the disruptive effect of incompatible noise letters decreased progressively as the noise letter was located from 0.5 to 1.5 of
visual angle from the edge of the cued area. In addition, this gradient pattern of attentional processing at the border of the focal area was invariant regardless of the size of the precued area.

Pan and Eriksen (1993) suggested an ellipse as the appropriate metaphor for the attentional focus, rather than a spotlight or a zoom lens. In their study, they manipulated the size of the focal area by means of requiring subjects to compare two letters which were separated by 0.5°, 1.0°, or 2.0° visual angles vertically or horizontally. The two to-be-compared letters were flanked by a distractor that could be 0.25°, 0.5°, or 1.0° away from the major axis of the two targets. They found that for 0.5° separation between two targets, only the 0.25° distractor had a significant response-competition effect, and the 1.0° distractor did not cause any response interference. On the other hand, for 2.0° separation between two targets, the attentional field seemed to be expanded and any distractor within 0.5° had a significant interference effect.

They suggest that rather than being a circle, the shape of the attended area seems to be elliptical. The principal axis is defined by the spatial separation of the locations of the targets and the minor axis is proportional to the principal axis. Around the attended area is an inhibitory field. The spatial extent revealed from the response-competition effects resulted from the inner limits of an inhibitory field, rather than from the outer limits of the attended field. When targets are only 0.5° apart, the 0.5° distractor is excluded from attentional focus and thus inhibited; when targets are 2.0° far apart, the 0.5° distractor is included in attentional focus and thus not inhibited because the attentional window has been expanded.
LaBerge and Brown (1989) propose that attention activities spread across the visual field as gradients. They used a dual-target procedure to measure how attention was spread over the selected area. The first target was either a single letter within a string or a whole word, both of which would induce a distribution of processing resources across the field. After a very short duration, the second target, a letter flanked by two noise forms, was presented at different distances from the first target in order to probe how the distribution was formed across the attended field. The subjects were required to respond if the second target matched the predesignated form.

In the case of attending to a single letter within a string, the V-shaped RT curve with a peak at the first target location was generated due to the gradient operation of the filter mechanism. The target letter was in the center of the filter so that its location had the largest information flow and, thus, the fastest response. In the other case of attending to a whole word, the RT curve was flattened out, with no peak, because the attention activity was distributed evenly. LaBerge and Brown suggested that there were two processes involved in this V-shaped gradient operation: facilitation and inhibition. The facilitatory process operates at the center location of the target display, that is, the target letter within a string, so that the highest information flow comes from the center location relative to other locations. The inhibitory process is combined with the former process and operates to block the information flow from the distractors at the other locations.

In summary, converging evidence from the response-competition paradigm suggests that the distance effect is quite robust in spatial attention, and its underlying mechanism may be via inhibition of unattended locations. Nonetheless, an attention set should be
established endogenously prior to the target display in this paradigm, so evidence from
the response-competition paradigm does not necessarily support a distance effect in
spatial attention following the exogenous cue, which directs the distribution of attention
via the property of a stimulus itself. It is speculated that there may not be a distance effect
following the exogenous cue. This hypothesis is supported indirectly by studies of visual
search.

Visual search refers to the task in which observers search for a target item embedded in
some number of distractor items. When the distractors are all identical and the difference
between target and distractor is in a single feature, such as color or orientation, the search
time is independent of the display size. In other words, no matter how many distractors
surround the target, the distractors will not interfere with the target detection. For
example, Treisman and Gormican (1988) found that when targets contained a unique
distinguishing feature relative to the neighboring distractors, the number of distractors did
not affect the reaction times of the observers’ search for targets. In one experiment, they
tested the feature of line orientation. Subjects were required to detect a tilted line among
vertical lines which were scattered randomly in an area subtending 7.8° x 6.8°. The results
showed that detection time was equally fast when the number of vertical lines was zero,
five, or eleven.

On the one hand, this result can be accounted for by a parallel search process (bottom-
up process), in which the target feature is singled out of the distractor feature without
involving focal attention. On the other hand, this also implies that stimulus-driven
selection induces a restricted allocation of attention over the target location. Therefore,
the distractors do not have any power to distract attention and thus cause no interference. The deployment of attention in response to the exogenous cue is also in a stimulus-driven fashion, which suggests that attention may be allocated narrowly to the cued location when the exogenous cue is used. Thus, there may be no distance effect in spatial attention following the exogenous cue. This prediction makes ecological sense. The exogenous cue, such as a sudden movement or an abrupt flash, usually has a survival value, either signifying a potential danger (predator) or food (prey), so it would be worthwhile to focus attention fully on it.

2.2 Interaction of stimulus-driven and goal-directed selection

Empirically, the distinction between endogenous and exogenous cues lies in their time course of drawing attention—i.e., how fast they can draw attention. Muller and Rabbitt (1989) compared a peripheral flash randomly associated with the target location and a central cue with 80% predictive validity. They found that accuracy for the recognition of targets following the peripheral flash reached a maximum around 100 to 175 ms of cue-to-target SOA, then decreased. Relatively, the central cue produced asymptotic accuracy to the target at longer cue-to-target SOA—within 275-400 ms, then it sustained at the same performance level. Cheal and Lyon (1991) compared peripherally and centrally presented symbolic cues. Both cues had 100% predictive validity. The cue-to-target SOA varied from 0 to 200 ms. Subjects were required to make a four-alternative forced-choice discrimination of differently oriented Ts. The results showed that accuracy reached the maximum at 100 ms of SOA for the peripheral cue, then decreased to a lower level.

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Nonetheless, accuracy reached an optimal level at about 300 ms of SOA for the central cue. A general conclusion seems to be that peripheral cues tend to draw attention more rapidly than do central cues.

A possible reason for this difference is that the endogenous cue needs to be perceived and decoded to determine which location it indicates, whereas no such translation or decision process is required for the exogenous cue. It is suggested that peripheral cues trigger a fast-acting mechanism, which draws attention automatically and quickly; however, central cues initiate a slow-acting mechanism, which draws attention in a voluntary and slow fashion.

Theoretically, the distinction between exogenous and endogenous cues can lie in how the attention mechanism is initiated. An endogenous cue typically predicts the likely target location and thus induces an attentional set (Posner, 1978). The facilitation effect of the valid cue on the target detection must be ascribed to the perceptual goal generated endogenously because the target never appears at the center of visual display as the cue does. On the other hand, an exogenous cue does not contain any information about target locations. Because subjects do not expect the target at the cued location intentionally, any benefit for the processing of the target may be ascribed to the sudden stimulus onset that draws attention automatically (Rafal and Henik, 1994). Therefore, the initiation of attention orienting can be a function of the stimulus onset property or internal goals.

This distinction also indicates that the endogenous control of attention is goal-directed (or a top-down process), whereas the exogenous control of attention is stimulus-driven (or a bottom-up process). It is also implied that exogenous orienting is an automatic
process, whereas endogenous orienting is a voluntary process. For example, Jonides (1981) found that the exogenous cue was distinguished from the endogenous cue by three criteria of automaticity, one of which is that the exogenous cue was resistant to intentional suppression, whereas the endogenous cue suffered intentional ignorance.

Jonides (1981) required subjects to view a display of eight letters arranged along an imaginary circle and searched for the letter “L” or “R”. Before the search display, one of two types of cues was presented: an arrowhead in the periphery near the target location (peripheral cues) or an arrowhead at the fixation point (central cues). The predictive validity of the cue was only 12.5%. In other words, the cue did not predict the likely location of the target. A cue-to-target SOA of 50 ms was used. Subjects in the “attend” group were instructed to attend deliberately to the cued location on each trial. Subjects in the “ignore” group were instructed to ignore the cue because the cue provided no predictive information about the likely target location. The results showed that reaction times in valid trials were still faster than in invalid trials when subjects actively ignored the peripheral cue. However, such a cueing effect disappeared when subjects actively ignored the central cue. It is implied that attempted suppression of the peripheral cue does not affect its ability to summon attention. It seems that the deployment of attention by peripheral cues is more automatic than it is by central cues.

Another reason for this result is that because subjects are in attention-diffuse mode—no specific location to be attended to, the peripheral cue can attract attention regardless of whether the cue is ignored or attended. More specifically, the peripheral cue with an abrupt-onset property can capture attention automatically. A corroborating result was
reported by Yantis and Jonides (1984). They used a visual search task in which subjects had to decide whether a designated letter was in the display. The display included several figure-eight placeholders grouped by seven line segments and one blank location. There were two kinds of target letters: no-onset and onset. No-onset stimuli mean those which appear at the locations of placeholders through the removal of two line segments. Onset stimuli mean those which appear in a blank location very swiftly. The onset stimulus randomly happened to be the target letter. The results showed that the search time was independent of the display size if the target was an onset stimulus. However, if the target was a no-onset stimulus, the search time increased linearly with the display size. Those results suggested that attention was always captured by the onset stimulus first during the search process.

Therefore, it can be assumed that the peripheral cues may interfere with the central cues if they both are put together against each other, especially when the central cue is not highly predictive. To test this hypothesis, Muller and Rabbitt (1989) used a display of four boxes in the periphery (4.4° distant from fixation). Subjects were asked to identify the orientation of a letter “T” occurring in one of four boxes. Before the appearance of the target, two cueing events occurred successively: an arrowhead presented at fixation, followed by an abrupt brightening of outline of a box 500 ms later. Subjects were instructed to attend to the location precued by the arrowhead, even though the predictive validity of the cue was only 50%, and to ignore the irrelevant peripheral flash that was randomly associated with the target location. They found that a subsequent peripheral flash could interrupt the endogenous cue. The target recognition in valid-cued location
lost the benefit on accuracy when the other location was flashed. However, the target recognition even in invalid-cued location obtained the benefits on accuracy if that location was flashed. Muller and Rabbitt (1989) concluded that the intentional direction of attention in advance could not prevent a shift of attention to the abrupt flashed location.

On the other hand, Yantis and Jonides (1990) found that the abrupt onset did not necessarily capture attention when attention was directed to a specific location by an endogenous cue prior to the abrupt onset. In their experiment, a central cue appeared, pointing to the left or the right of fixation, with 80% predictive validity. After 200 ms, a target, either an onset or no-onset letter, appeared in either the cued (valid) or the uncued (invalid) position. When the target occurred, a distractor also appeared in the opposite position of the target. A distractor can be either an onset letter if a target is a no-onset letter or a no-onset letter if a target is an onset letter. The letters—both target and distractor—appeared 5.8° to the left and to the right of fixation. The results showed that reaction times of the onset target in invalid trials were still slower than in valid trials. Therefore, when attention is highly focused at some location in advance, it will not be distracted by the following abrupt-onset cue. The results suggest that the abrupt onsets do not capture attention automatically.

Similarly, Theeuwes (1991) also found that voluntary allocation of attention could prevent attention distracted from the peripheral onsets. In one experiment, a central arrowhead appeared earlier (300 or 600 ms) or later (200 ms) than the target display that was an array of four no-onset letters, with 100% predictive validity. At various peripheral
marker-to-target SOAs (-160, -80, 0, 80 ms, or none), a marker near one of the letters was abruptly switched on. This peripheral onset was randomly associated with the target location. When attention was in focused mode (a central cue appeared prior to the target), abrupt-onset at nontarget locations did not affect performance relative to the baseline condition. Nonetheless, when attention was in diffuse mode (a central cue appeared posterior to the target), abrupt-onset at target location facilitated performance, whereas abrupt-onset at nontarget locations slowed down performance, relative to the baseline condition. These findings suggest that the peripheral abrupt-onset can capture attention only when attention is in diffuse mode.

However, in Remington, Johnson, and Yantis' (1992) experiment, subjects were instructed to actively ignore the peripheral cue because that cued location was certain not to contain the target. The results showed that the reaction time to the target was elevated under this circumstance. In other words, subjects’ attention was distracted to the cued location first even though they knew that the cue was 100% invalid. It suggests that the abrupt-onset cue captures attention automatically despite subjects’ intention to ignore it. But unlike Yantis and Jonides’ (1990) experiment, the cue did not specify unambiguously which location would hold the target (i.e., three remaining possibilities). The possible reason for the abrupt-onset cue to be able to capture attention is that subjects can not focus on one specific location with absolute certainty following the negation of the cue.

Similarly, Folk and Remington (1996) found that a central cue that indicates the location of an abrupt-onset flash would not prevent subjects’ attention being distracted by the abrupt onset. In their experiment, a central cue was presented several hundred
milliseconds (from 250 to 550) prior to the target display that included four possible
target locations. The cue indicated the location of the following abrupt onset, which in
turn indicated that the target would not occur at the same location. In other words, the
target could occur in one of the other three locations. Therefore, the central cue did not
induce an attention-focused mode. The results showed that the presence of an abrupt-onset
distractor produced a cost in response times regardless of whether the central cue
was present or not. The results suggested that attention was captured by the abrupt-onset
distractor first because the advanced information provided by the central cue did not
induce highly focused attention.

also used a peripheral arrowhead that contained negative information. The difference is
that the peripheral cue indicated that the target would otherwise occur at the opposite
position 80% of the time. In the early sessions, identification of the targets in peripherally
cued locations was faster than in the locations opposite to the cued locations. This
suggests that subjects' attention was captured by the peripheral cue despite the fact that
the upcoming target would more likely appear opposite to the cued location. However,
after several sessions of practice, subjects began to show RT benefits to the targets in the
location opposite the cue. It seems that the attention-capture property of an abrupt onset
cue can be disabled by practice. The conclusion is that exogenous orienting is partially
automatic.

In summary, whether an abrupt-onset cue can override the goal-directed selection and
capture attention seems to be inconclusive. If subjects can be precued to attend to a
specific location unambiguously (in fully focused mode), the abrupt-onset cue will be less likely to interrupt the orienting following the previous central cue. On the other hand, if subjects have to attend to more than one location (in diffuse mode), then subjects’ attention will be captured by the abrupt-onset cues despite their intentions or beliefs.

To resolve this inconsistency, Folk, Remington, and Johnston (1992) proposed that whether or not an abrupt onset would capture attention was contingent on an attentional control setting, a high-level behavioral goal generated endogenously according to the properties of locating and processing the target stimulus. To test this idea, they required subjects to identify a target that was defined by a color discontinuity (e.g., a unique color) or by an abrupt onset in a stimulus array. The attentional control setting was set to perceive this target’s defining feature. Before the target appeared, an irrelevant cue (always an invalid cue) was presented at a different location from the target. The cue was either a color discontinuity or an abrupt onset. They found that the cue disrupted performance only when it shared the target’s defining feature—the attentional control setting. In other words, performance on identifying a target with a unique color feature was not disrupted by an irrelevant abrupt-onset cue that was presented before the target. Compare this result with those found by Jonides (1981) and Yantis and Jonides (1990). Interestingly, Folk et al. (1992) found that the abrupt-onset cues did not capture spatial attention automatically even under conditions of spatial uncertainty—when attention was not focused in advance.

It seems that the exogenous and endogenous attention control may not be independent of each other. The interaction of exogenous and endogenous attention control has become
an interesting topic of investigation. According to Folk et al.’s (1992) findings, the exogenous control may be mediated by the endogenous attentional control setting. However, Theeuwes (1992) found that attention was distracted by an irrelevant color diamond (e.g., red) first when searching for a target located in a green circle that was embedded in the other green diamonds. This suggested that stimulus-driven selectivity was not withheld by the attentional set.

On the other hand, Bacon and Egeth (1994) argued that the reason for Theeuwes’s (1992) results was that subjects adopted a singleton detection strategy which would guide attention by a feature discontinuity because the target instance was a unique circle embedded in the other diamonds. Therefore, sometimes attention was attracted to the uniquely colored object without the target inside. Bacon and Egeth (1994) included two or three target instances (e.g., more green circles) in the display, so that the target was not in a unique shape in the entire display any more. This change made the singleton detection strategy ineffective. The results suggested that an irrelevant color singleton did not delay the search time any longer.

In summary, empirical evidence reviewed above suggests that the deployment of attention can be driven by either the stimulus property (e.g., abrupt onset or feature singleton) or observers’ intentions, knowledge, or goals. Further, both stimulus-driven and goal-directed selectivity interact with each other. On the one hand, stimulus-driven selection may dominate regardless of where else observers’ intentions aim at. More specifically, the irrelevant abrupt-onset cue may overrule the voluntary allocation of attention following a central cue. In the visual search task, the irrelevant feature singleton
may capture attention first even though it has nothing to do with the target. On the other hand, stimulus-driven selection can be withheld by observers' strong goal settings. Specifically, the irrelevant abrupt onset cue may not have the power to distract attention if attention has been highly focused. In the visual search task, the to-be-ignored feature singleton will be suppressed if it does not match the target property or the searching mode.

Taken together, the notion of attentional control settings (Folk et al., 1992) has captured one aspect of interaction between stimulus-driven and goal-directed selection. However, unlike the endogenous cue, attentional control settings do not direct attention to a specific location of the forthcoming target in advance of the target display. This line of research does not provide direct evidence of how the exogenous cue competes with the endogenous cue. According to the literature reviewed so far, we can only conclude that the attentional status—focused or diffuse mode—may have captured one aspect of interaction between exogenous and endogenous cues. In addition, as described in the previous section, there is a distance effect in the spatial distribution of attention following the endogenous cue. We speculate that the extent to which the irrelevant abrupt-onset cue can distract attention may well depend on the spatial separation between the abrupt-onset distractor and the central cue. We wish to demonstrate that spatial separation between exogenous and endogenous cues may be another specification of the nature of that interaction in the later experiments.
2.3 A connectionist model approach to visual attention

Although some metaphors reviewed in section 2.1, such as a spotlight, zoom lens, and even ellipse, have described what distribution of spatial attention may be, they do not answer why such distribution is formed. We believe that the computational approach may be able to answer the question.

A connectionist model is a massively interconnected network in which the basic element is a neuron-like processing unit. The activity of each unit is accumulated by the weighted summation of its inputs. Quantitatively, the net input to unit $j$ is defined as follows:

$$\text{net}_j = \sum_i W_{ij}x_i, \quad (2.1)$$

where $x_i$ denotes the activity of unit $i$ which connects to unit $j$ and $W_{ij}$ is the weighting factor from unit $i$ to unit $j$. The output of unit $j$ is then a function of the net input, i.e., $f(\text{net}_j)$. Each unit computes in parallel. Information is represented as a pattern of activation over the units. The architecture of the network usually includes more than two layers: input, hidden, and output layers. The activity of units typically flows from input up to output units in one direction or sometimes from the higher to lower layers recurrently. The nature of parallel distributing processing in the connectionist model corresponds to the neural computation in the brain processing. Therefore, the connectionist model approach has been used to construct models at a level that can characterize the essential properties of visual attention both computationally and
biologically. The following reviews some representative works in visual selective attention by both cognitive psychologists and computer vision researchers.

Phaf, Van der Heijden, and Hudson (1990) proposed a connectionist model of visual selective attention, which is termed SLAM. The main purpose of SLAM is to simulate the filtering task in which two objects compete for selection by their color, shape, or position. For instance, in a stimulus with a blue circle at the left and a red square at the right, this model performs the task of identifying the color of the left one or identifying the location of the red one, and so forth.

Basically, the architecture is composed of 7 modules including a total of 25 units. The modules are separated into three layers. First, a mapping layer with three modules contains nodes for all combinations of the features in two dimensions, such as left-square or right-circle. Second, an attribute layer with three modules contains six nodes representing every single feature (e.g., color, shape, or position) that has two values. Third, a response layer contains nodes representing the six possible answers (e.g., red, blue, circle, square, left, and right).

Any nodes representing the same feature in different layer are connected each other. The different modules in the same level inhibit each other. In simulation, the required selective behaviors would be obtained when the extra activation was given to the object at the lowest layer and the feature module at the intermediate layer. In other words, selection resulted from extra activation of some units in the mapping layer or attribute layer, namely in a stimulus-driven fashion.
Along with the neurophysiological findings of two parallel processing pathways for object location and object identification in the visual system, Van der Heijden and Bem (1997) revised SLAM because in their view, the feature of spatial position had a special status in selective attention.

In the revised model, visual information enters the input map (i.e., the mapping layer) which outputs feature information, including position, shape, and color. Then position information flows to the location map and shape and color information flow to the identity map simultaneously. The most important characteristic of this model is that the location map connects to the input map recurrently as a feedback. Selection of attention is based on location and thus the system of feedback connections represents the neural circuit for selective attention. Specifically, the activation of the location map is transmitted back to the input map via those feedback connections, therefore some subset of units in the input map will be preferentially processed.

Both bottom-up and top-down activation can determine which region in the location map will be enhanced selectively. For example, the visual salience in the input map creates one or more regions of enhanced activation in the location map (bottom-up processes). On the other hand, the activation originates in the higher centers may transport to the relevant position in the location map and selects the region that is enhanced (top-down processes). In sum, attention results from the pattern of activation in the location map. Nonetheless, it seems doubtful whether there is a feedback connection from location module to input module in the human visual system.
Mozer (1991) proposed a connectionist model in which the attention mechanism is independent of the visual information processing system. The attention mechanism (AM) network is a set of units arranged in a retinotopic map in one-to-one correspondence with the units of the feature map of visual inputs. The activity of the units in the AM indicates that units in the corresponding location on the retina are attended. The purpose of the AM is to select one object for processing among multiple objects. The activity of the AM units \((a_{xy})\) serves to gate the flow of activity from the lowest feature map to the higher levels. The transmission probability for the units in the feature map is \(\xi + (1 - \xi) a_{xy}\), where \(0 < \xi < 1\).

The activity of the AM units \((a_{xy})\) is updated according to the rule of steepest ascent. Specifically, \(a_{xy}\) is updated in proportion to the derivative \(\partial H/\partial a_{xy}\), where \(H\) represents the goodness of a particular AM state. If \(\partial H/\partial a_{xy}\) is positive and, thus, \(H\) and \(a_{xy}\) go in one direction, then \(a_{xy}\) should be increased. If \(\partial H/\partial a_{xy}\) is negative and, thus, \(H\) and \(a_{xy}\) go in the opposite direction, then \(a_{xy}\) should be decreased. \(\partial H/\partial a_{xy}\) is affected mainly by three factors: external inputs, the local neighborhood activity around \(a_{xy}\) and the average activity of the whole network.

To be more specific, the external input is the activity of units in primitive feature maps and/or the knowledge from the higher centers to tell the AM network where to focus. Bottom-up processes can be implemented by having every unit in primitive feature maps project to its corresponding AM unit, so that a particular area of the AM units will be enhanced. On the other hand, top-down processes can be implemented by having higher
level of cognition modulate the effect of each feature unit in the AM unit. Generally, attentional selection operates by the AM network that constructs a variable-diameter spotlight on the retinotopic representation. Sensory information is preferentially processed within that spotlight.

Humphreys and Muller (1993) proposed a connectionist model, termed “Search via Recursive Rejection” (SERR), to simulate human performance on visual search among similar objects. SERR comprises six levels of representations from bottom to top: retinal arrays, single-feature maps, combined-feature maps, map of locations, matching maps, and template units. Stimulus displays are represented as patterns of on and off states of the units in the retinal arrays. Stimuli are vertical or horizontal lines of a certain width and length. Units at the single-feature level are detectors for such lines at particular locations. The output from units at the single-feature level goes to units at the combined-feature level, which produces feature conjunctions. The location units gate transfer of activation from combined-feature units to units in the match map.

For each type of target and distractor in the stimulus display, there is a match map and a template unit. Each unit in the match map samples a particular location on the combined-feature maps for evidence for or against its particular type of target or distractor. Grouping (top-down process) is implemented in the match maps by within-map excitatory connections and between-map inhibitory connections. Thus, coding of a particular type of target or distractor at a given location facilitates coding of the same type of item at other locations and inhibits coding of any other type of items. As a result,
similar items tend to group. In search for a target, the groups are selected and rejected one by one until the target is found.

The simulation seems to agree with human performance. In search for an inverted T among identical T's of one other type produces reaction times that are nearly independent of the display size. In search for an inverted T among three different types of T's generates reaction times that increase linearly with the display size.

Tsotsos (1993) proposed a general-purposed model. Selective attention is implemented as an inhibitory beam which enables the visual system to select the relevant features for further processing and eliminate the irrelevant features. He believes that attention is just the result of selection throughout the visual information processing system (Tsotsos, 1997).

Generally, the network architecture is a multiple-layered pyramid in which each node computes the weighted sum of its inputs as its output in a feedforward manner. The network assembly consists of interpretive units ($I_i$) and gating units ($G_i$). The former receives visual inputs from layers below and performs processing related directly to the interpretation of inputs (e.g., color, edge). The latter computes the winner-take-all (WTA) result for a particular interpretive unit and gates inputs through to next higher interpretive units. WTA is an iterative and neurally-plausible mechanism to find a unique maximum, which is based on mutual inhibition among nodes that are all connected to one another (Koch and Ullman, 1985).

Each interpretive unit in each layer except the bottom layer is accompanied with a WTA network (an assembly of gating units), a gating control unit ($C_i$) and a bias unit ($B_i$).
The bias unit receiving the task guidance from outside of the network (e.g., working memory) is for the top-down process. Gating control units are responsible for sending signals to either activate or shut down WTA processes.

Once the WTA processes are activated, the value of gating unit \( G_j \) in the WTA network is updated by the rule:

\[
G_j^t = R \left\{ G_j^{t-1} - \frac{\sum_i W_{ij} R(\Delta_{ij})}{\sum_i W_{ij}} \right\} \text{ at time } t, \tag{2.2}
\]

where \( \Delta_{ij} = G_j^{t-1} - G_i^{t-1}, i \neq j \), and \( R \) is a rectifying function: \( R(x) = x \) if \( x > 0 \), otherwise \( R(x) = 0 \). Since the inhibitory signal is based on the response differences, \( G_j^{t-1} - G_i^{t-1} \), the largest unit will not be inhibited at all, but will take part in inhibiting all other units. On the other hand, the smallest unit will not inhibit any other units but will be inhibited by all. Through the iterations of mutual inhibition, in the long run, the gating units in the competition are partitioned into two classes: those with value zero and those with value above the threshold. The latter will be selected as winners.

The inhibitory beam is implemented as follows. First of all, the top layer will receive stimuli from the input layer. Then its output representation will be computed. A WTA process will compute the global winner on the top layer. This global winner is at the top of the visual processing hierarchy and represented by a very large receptive field. The global winner will activate the WTA that operates only over its direct inputs. As a result, within its receptive field, only inputs connecting to winners will be selected and the others will be pruned. This pruning process is then applied recursively to successively lower layers. The final result is that the visual inputs at lower layers tune selectively in to
the strongest response unit at the top layer. Generally, selective attention is realized by inhibition of irrelevant connections throughout the visual system.

In addition, Tsotsos' model is especially consistent with the findings from neurophysiology and cognitive psychology. First of all, a pyramidal architecture is consistent with neurophysiological evidence that the visual system is organized as a hierarchical structure with 10 levels in the primate visual cortex (Fellman and Essen, 1991). Second, the computational complexity of visual search can be solved partially by the input abstraction through a pyramidal hierarchy that can reduce the amount of computation logarithmically (Tsotsos, 1990). Third, unlike Mozer's AM network, the WTA algorithm includes two components: facilitation and inhibition. This is consistent with the experimental findings in spatial attention as reviewed in section 2.2. Fourth, the single-cell recordings of the striate visual cortex and the temporal cortex in awake and behaving primates (e.g., Moran and Desimone, 1985) showed that the cells behaved as if their receptive fields changed properties as a result of attentive selection. This evidence makes the WTA algorithm more biologically plausible because the WTA process selects relevant connections and prunes irrelevant connections within the receptive field of an interpretive unit.

In summary, attention is expressed in different ways, but top-down and bottom-up processes are implemented in common among those models. In Van der Heijden and Bem's (1997) model, selective attention is realized by activation flowing from the location map back to the visual input map. Top-down bias goes from the higher center down to the location map. Bottom-up information comes from the input map up to the
location map. In Mozer's (1991) model, selective attention operates via the attention mechanism network independent of the visual information processing system. The attention mechanism operates like a spotlight to gate activation in the feature map. Top-down bias goes from the higher center down to the connections between the feature map and the attention mechanism to gate the flow of activation. Bottom-up information comes from the feature map to activate the specific area in the attention mechanism network. However, in Tsotsos' (1993) model, selective attention is an emergent property in the visual information processing system. Through the winner-take-all algorithm relevant connections are selected and irrelevant connections are inhibited in the system. Top-down bias comes from outside of the network to the bias units, which in turn send information to the WTA network. Bottom-up information is generated from the input units and flows upward through the entire network.

As reviewed in section 2.2, selectivity results from interaction of stimulus-driven and goal-directed processes. Much empirical evidence has demonstrated that an abrupt-onset distractor may overrule an advanced central cue (Muller and Rabbitt, 1989; Remington, et al., 1992). However, none of those models reviewed above has detailed implementation of interaction between top-down and bottom-up processes. Therefore, I wish to build a connectionist model which not only simulates the differential effect of exogenous and endogenous cues on the spatial distribution of attention, but also predicts the nature of interaction between exogenous and endogenous cues.

Among the models above, the bottom-up and top-down processes are better implemented in Tsotsos' model than in the other models. In this sense, Tsotsos' model is
superior to the other model for simulation of the competition between exogenous and endogenous orienting. In addition, Tsotsos’ model is motivated from the findings of neurophysiology. Therefore, I build a computational model based on Tsotsos’ model, which will be described in more detail in the next chapter.
EXPERIMENT 1: THE SPATIAL DISTRIBUTION OF VISUAL ATTENTION

3.1 Working hypotheses

In the past studies of spatial attention, the general conclusion is that attentional effects on response performance decrease with increasing spatial separation between attended and unattended locations. The distance effect in the allocation of attention seems to be a parallel between exogenous and endogenous orienting, despite the fact that exogenous and endogenous orienting can be differentiated by automatic vs. voluntary processes. However, there are three reasons to speculate that there may be a differential effect of endogenous and exogenous cues on the spatial distribution of attention.

The first reason is that attention orienting in response to an exogenous cue is automatic, whereas attention orienting in response to an endogenous cue is voluntary. The directionality of an endogenous cue needs to be interpreted and decoded into working memory before attention is directed, whereas no such translation process is required for an exogenous cue. The notion of limited capacity assumes that the total of attentional resources is fixed. If the decoding process takes less resources, there should be more left
for allocating to the possible target locations. Based on this reasoning, following an exogenous cue, the uncued locations may still be attended slightly. Following an endogenous cue, the unexpected locations nonetheless may be ignored and have no allocation of attention at all because the location-coding process will consume some resources. Therefore, it is reasonable to think that the RT costs for the uncued locations may be larger in endogenous orienting than in exogenous orienting.

The second reason for positing a differential effect is that the deployment of attention via an exogenous cue is stimulus-driven, whereas the deployment of attention via an endogenous cue is goal-directed. Indirect evidence from the visual search paradigm showed that in the feature search task, the time to detect a target with a distinctive feature was not affected by the number of the distractors surrounding the target (Treisman and Gelade, 1980). This suggests that no matter how distant the distractors are from the target, they will be ignored and thus will not interfere with the target detection. Because stimulus-driven selection is involved in the feature search task, this also implies no distance effect in stimulus-driven selection. In contrast, evidence from the response-competition paradigm showed that responses to a pre-designated target letter were interfered with by surrounding irrelevant letters associated with the wrong response and more importantly, this interference effect decreased as the noise letters were moved farther away from the target. This implies a distance effect in goal-directed selection.

The third reason is that exogenous orienting is a bottom-up process, whereas endogenous orienting is a top-down process. According to the CODE theory by Logan
(1996), the representation of a location is distributed across the space in a Laplace distribution. The probability density function for the one-dimensional distribution is defined as:

\[ f(x) = \frac{1}{2} \lambda \exp \left[ -\frac{1}{\lambda} |x - \theta| \right] \quad (3.1) \]

where \( \theta \) represents the center of the distribution in the \( x \) dimension and \( \lambda \) determines the spread of the distribution over the \( x \) dimension. The distribution also represents the probability of sampling features in one item within the location. The CODE surface refers to the summation of all distributions representing different items located in the space. Perceptual grouping is formed by applying a threshold to the CODE surface. The items (or locations) located in the same above-threshold region of the CODE surface will belong to the same perceptual group. Therefore, when one item (or location) is selected, its proximate items (or locations) may also be selected in part if that part is within the above-threshold region of the surface.

The CODE theory further assumes that attention samples the features that are available within the above-threshold region. The probability of sampling features is called feature catch. Either top-down or bottom-up processes can influence the size of feature catch for each location. Bottom-up processes will reduce the variability of the feature distribution, so that the feature catch of the proximate items (or locations) will decrease within the above-threshold region. It is implied that the attentional focus will be narrower following an exogenous cue. On the other hand, top-down processes, instead of changing the shape of the surface, will lower the threshold level, so that the feature catch of the proximate
items (or locations) will increase within the above-threshold region. It is implied that the attentional focus will be broader following the endogenous cue. This implication is consistent with the previous reason.  

Taken together, there are two empirical predictions derived from the above reasons. First, as opposed to an exogenous cue, the RT costs of uncued locations following an endogenous cue should be significantly larger. Second, the distance effect will be found in endogenous orienting, whereas the RT costs for the uncued locations may show a uniform pattern in exogenous orienting, i.e., no distance effects.

3.2 Method

The purpose of Experiment 1 was to test those predictions by directly comparing exogenous and endogenous cues under the same experimental settings. The stimulus display (see Figure 1), adapted from Handy et al. (1997), included six boxes arranged along a semicircle in peripheral vision, 5.7° distant from the fixation center, so that each box had the same visual acuity. A line presented at the fixated point served as an endogenous cue, predicting the upcoming target with a likelihood of 70%. The outline of one of the six boxes was brightened abruptly to serve as an exogenous cue. In this experiment, only two locations could be precued, which were the rightmost and the leftmost boxes. The reason is that only a few observations (24% of the trials) can be made for all uncued locations in endogenous cueing and thus collecting a sufficient number of data points at any single uncued location requires an extremely long experiment.
Therefore, we only directed subjects’ attention to two of six possible locations and
allowed enough observations to be made at each uncued location within one hour and a
half.

To ensure that covert attention shift, not overt movements of eyes, was responsible for
performance, eye movements were monitored using EOGs electrodes. EOGs were
recorded from three sites, i.e., a horizontal EOG recorded from the left outer canthus and
a vertical EOG recorded from the sites inferior and superior to the left eye. All electrodes
were referenced to the right outer canthus.

Subjects. Fifty-two Ohio State University undergraduates participated in a single 1 1/2-
hour session, in partial fulfillment of an introductory psychology class requirement. All
had normal or corrected-to-normal visual acuity. Twenty-six participants were randomly
assigned to endogenous and exogenous cueing sessions, respectively. Two participants in
the exogenous cueing session were discarded from the analysis, because of frequent eye
movements.

Apparatus. Stimulus displays were presented on a ViewSonic 4E 14” color monitor
driven by a 486 PC equipped with a Cirrus Logic SVGA graphic card. Subjects sat in a
comfortable chair in a sound-attenuating and dimly lit booth. The monitor was placed at
eye level on a table. The viewing distance measured from the surface of the monitor to
the subjects’ eyes was fixed at approximately 65 cm. Subjects responded by pressing keys
on a terminal keyboard.
EOGs were collected via an analog-to-digital converter, amplified (via Grass/Model 12) with a gain of 5000 and digitized at a sampling rate of 200Hz. A voltage criterion of 20 μV shift within 30-50 ms was set for defining eye movements. Any trials with eye movements or blinking detected were discarded and rerun later in the experiment.

**Stimuli.** The stimulus display included six boxes outlined in black color against a gray screen background (13 foot Lamberts; fL), arranged along a semicircle in the upper visual field. A small white square (0.31° tall x 0.22° wide) placed at the center of the display served as the fixation point. Each box was 1.32° tall x 1.14° wide, 5.7° from fixation, and equally spaced, 2.64° center to center, from its neighbor. Two most lateral boxes were positioned 1.76° above the horizontal meridian. The stimulus display was symmetric about the vertical meridian, with three boxes in each visual hemifield. A white straight line (1.32° long x 0.04° wide) was presented at fixation, serving as a central cue. The outline of any one box was brightened (33 fL) for 100 ms, serving as a peripheral cue. The target was either the letter “P” or “B” (0.79° long x 0.35° wide) placed in the center of a box. The possible farthest target location was 9.3° away from the cued location.

**Procedure.** In the endogenous cueing session, a fixation square, along with six boxes, was first presented. Subjects were instructed to fixate the square throughout the trial. After 900 ms a cue appeared at fixation for 150 ms. On 80% of the trials, the cue was a white line pointing either to the leftmost or the rightmost box. The cue predicted the upcoming target with 70% validity. On 20% of the trials, a neutral cue with six lines
pointed to every box. The interval between the offset of the cue and the onset of the target (inter-stimulus interval; ISI) varied from 300 to 500 ms. A target, either the letter "P" or "B", was presented for 90 ms in either the cued box 70% of the time or in any one of the uncued boxes 6% of the time. Finally, a pattern mask followed. Subjects determined whether the target was "P" or "B" and responded by pressing the period key (.) with their right index finger if the letter "B" appeared and the semicolon key (;) with their middle finger if the letter "P" appeared. The next trial automatically started two seconds later.

Eye movements were monitored from the fixation display to the target offset. If subjects moved their eyes during that period, a warning message would appear on the screen. Then the next trial would not proceed until the space bar was hit. Subjects were instructed to use this period to rest their eyes.

The procedure for the exogenous cueing session was identical to that for the endogenous cueing session, except for the following. The cue was an abrupt brightening of the outline of one of six boxes, on 80% of the trials. The ISI between cue and target varied from 50 to 150 ms, instead of 300 to 500 ms. The reason for this change is to avoid "inhibition of return", a finding that a previously cued location is inhibited if a target appears more than 300 ms after a peripheral cue (Posner and Cohen, 1984). However, this phenomenon does not exist in endogenous orienting. A target appeared in any one of six boxes with equal probability (i.e., 1/6 = 16.7%). On 20% of the trials, all six boxes were brightened simultaneously for 100 ms to serve as a neutral cue. Different from the endogenous cueing session, two additional locations could be precued to avoid the
possibility that participants might actively suppress the abrupt flash because the flash tended to elicit blinking responses naturally. If only two most lateral locations could be flashed, participants were very likely to suppress their responses to the flash intentionally.

**Design.** A 2 x 2 x 6 design was used. Two within-subjects variables were cueing locations (leftmost/rightmost)\(^1\) and target locations (0°, 2.6°, 4.9°, 6.5°, 8.1°, and 9.3° distant from the cued location). One between-subjects variable was cueing type (endogenous vs. exogenous). The number of trials for each combination of the cueing location and the target location is shown in Table 1.

The central cue pointed to either side equally often. A total of 496 trials was divided into 4 blocks of 124 trials each. The task was forced-choice letter discrimination of “B” and “P” that were randomly chosen. Subjects were encouraged to follow the central cue and to prepare for the upcoming target while maintaining fixation at the center of the display. The peripheral cue also appeared in two most lateral locations equally often. A total of 360 trials was divided into 3 blocks of 120 trials each. Subjects were told that the peripheral brightening has nothing to do with the upcoming target location.

**Data analysis.** To eliminate the trials in which subjects did not respond to the target until after an unusually long delay or prematurely respond to the target, reaction times slower than 1500 ms or faster than 200 ms were considered errors and discarded from the analysis.

\(^1\) Having said that four locations could be precued in exogenous cueing session, only the data collected from two most lateral locations were analyzed for the reason of comparing with endogenous cueing session. Without this note, Table 1 may be also somewhat confusing.
analysis (Handy, et al., 1997). There were three types of trials in this experiment. A valid trial is one in which cue and target locations are matched. An invalid trial is one in which cue and target locations are not matched. Neutral trials are those with a neutral cue. The RT benefit (a negative) was computed by subtracting the mean RT of neutral trials from the mean RT of valid trials. The RT cost (a positive) was computed by subtracting the mean RT of neutral trials from the mean RT of invalid trials. Analysis of variance (ANOVA) was based on the RT benefit/cost calculated for each participant.

3.3 Results

The results are graphed in Figure 2. First of all, data from exogenous and endogenous cueing were analyzed separately. The RT costs and benefits were analyzed in an ANOVA with a within-subjects factor, which was cueing laterality. There was no significant effect of laterality in either endogenous cueing or exogenous cueing, $F(1, 25) = 2.13, p = .157$ and $F(1, 24) < 1$, respectively. There was no significant interaction of laterality x target locations, in either endogenous cueing or exogenous cueing, $F(5, 125) = 1.47, p = .2$ and $F(5, 120) < 1$, respectively. In other words, no matter which visual field the cue occurred in, the RT patterns across all target locations were similar to each other. Therefore, we combined the data from two symmetrical cued locations for the further analysis.

Data from endogenous cueing. A repeated measures ANOVA on RT costs and benefits was then conducted, with target locations as the only factor. There was a significant effect of target locations, $F(5, 125) = 5.28, p < .01$, indicating that there was a
significant RT benefit when the probe happened at the cued location (valid trials) relative to the uncued locations. In order to examine whether the attentional effect was only isolated to the valid location, a contrast analysis among means was performed. The results showed that there was a significant difference between 2.6° and 4.9° distant invalid locations, F(1, 25) = 4.46, p < .05. It appeared that spatial attention was spread as a gradient within 4.9° distant from the expected location. On the other hand, there were uniform RT costs when the target happened in the locations 6.5°, 8.1°, and 9.3° distant from the cued location. This pattern of uniform RT costs suggested an inhibitory component in endogenous orienting.

Data from exogenous cueing. Results from exogenous cueing (see Figure 2) were similar to but somewhat different from those described above. An ANOVA on RT costs and benefits showed that there was a significant effect of spatial separation, F(5, 115) = 2.52, p < .05, indicating that there was a significant RT benefit when the probe happened at a cued location, relative to uncued locations. However, if the valid location was excluded, the other uncued locations had uniform RT costs, which seemed to be smaller than those found in endogenous cueing. This result suggested that spatial attention was narrowly focused within 2.6° distant from the cued location.

A mixed analysis. A split-plot ANOVA was performed with cueing type (endogenous vs. exogenous) as a between-subjects factor and spatial separation as a within-subjects factor. We found that the interaction of cueing type and spatial separation was not significant, F(5, 240) < 1. However, the main effect of cueing type was close to the
significant level, $F(1, 48) = 3.69, p = 0.06$, and the main effect of spatial separation was significant, $F(5, 240) = 6.96, p < .01$. This suggests that both endogenous and exogenous cues induce a very similar pattern of RT costs and benefits. That is, attention orienting, following the cue, generated RT benefits to recognition of the target in the cued location, and generated uniform RT costs to recognition of the target in most uncued locations. In addition, the endogenous cue tended to induce larger RT costs to recognition of the target in the uncued locations. A similar split-plot ANOVA, except for excluding the valid and $2.6^\circ$ invalid locations, found that only the main effect of cueing type was significant, $F(1, 48) = 5.1, p < .05$. This suggests that generally in endogenous cueing the costs of the uncued locations distant beyond $2.6^\circ$ were larger than those found in exogenous cueing.

The mean percentages of errors in the valid, invalid, and neutral trials are shown in Table 2. In endogenous cueing, the overall error rate was $10.1\%$. Accuracy was analyzed in a repeated measures ANOVA with cued locations and target locations as factors. Only the main effect of target locations was significant, $F(5, 125) = 3.32, p < .01$, indicating that accuracy was higher when the target occurred in the rightmost location than in any other locations, no matter which visual field was cued. There was no significant difference in accuracy between the two visual fields because neither the effect of cued locations nor interaction of cued locations and target locations was significant. In addition, there was a positive correlation ($0.57$) between error rate and mean response times across all combinations of cued and target location, indicating no strong speed/accuracy trade-off.
In exogenous cueing, the overall error rate was 23% and the correlation between error rates and reaction times was .24, also indicating no problem of speed/accuracy trade-off. Accuracy was analyzed in a repeated measures ANOVA with cued locations and target locations as factors. None was significant, indicating that accuracy patterns in the left and right visual fields were similar to each other.

3.4 Discussion

There are two differences between endogenous and exogenous cueing. First, a gradient of attention is found in endogenous cueing, although the spatial extent of the gradient is not larger than 4.9° visual field surrounding the cued location. In exogenous cueing, attention is, however, focused narrowly at the cued location and the RT costs for the uncued locations are not mediated by distance. Second, for those uncued locations beyond 4.9° distant from the cued location, the RT costs in endogenous cueing are larger than in exogenous cueing. In sum, these results have corroborated our predictions. There is a distance effect in endogenous cueing, while no such effect is manifested in exogenous cueing under the stimulus display of this experiment.

Umilta, Riggio, Dascola, and Rizzolatti (1991) conducted one experiment to compare central and peripheral cues. They also found that reaction times to detect targets in the unexpected locations increased with increasing spatial separation between expected and unexpected locations when an central cue was used; however, there seemed to be no such distance effect in the peripheral cues.
In addition, Umilta et al. proposed a premotor theory to account for the distance effect. The theory postulates that covert attention is related to the programming of ocular movements, even though the saccade is not actually executed. Once a directional cue is presented, a motor program for a saccade is prepared, which specifies two features of the saccade—direction and amplitude. When the stimulus appears in an unexpected position, the modification of the motor program, such as amplitude, is necessary and thus causes a delay of manual responses. As the unexpected location appears farther from the prepared location, the larger adjustment of the amplitude is needed and, therefore, it takes more time. Umilta et al. (1991) suggested that this was the origin of the distance effect. However, the premotor theory does not seem to account for the results of our experiment because beyond 4.9° distant from the prepared location, the farther unexpected location does not induce larger RT costs than the nearer locations. Another difficulty for the premotor theory is that no distance effect is found in exogenous cueing; the theory is unable to explain the fact that there is no difference in adjustment of motor program between far and near uncued location.

Spatial selection seems to involve two aspects of attention: facilitation and inhibition. Undoubtedly, processing in the cued location is enhanced, so that performance on that location is the fastest in both types of cueing conditions. On the other hand, processing in uncued locations is more strongly inhibited in endogenous cueing than in exogenous cueing. Obviously, the spotlight metaphor (Posner, 1980) cannot explain the distance effect because information can either be enhanced in the area of spotlight or be ignored.
out of the spotlight. There are no various degrees of processing within the spotlight. The zoom lens metaphor (St. James and Eriksen, 1986) may be able to explain the differential degrees of processing within the spotlight by adding the parameter of variable resolution in the different area of the spotlight. However, the zoom lens model may not explain the inhibitory area outside of the attentional focus. Other metaphors, such as an attentional window or gating (Pan and Eriksen, 1993), may explain the inhibitory operations in the uncued locations, but they lack an ‘adjustable’ window to explain the distance effect in the area of window. Finally, the variable and permeable filters metaphor (Cheal, 1997) may explain the results well by using as many filters of mixed excitation and inhibition as necessary. Two different groups of filters will be needed to explain the different spatial distribution of attention in response to exogenous and endogenous cues. However, this metaphor seems to create another problem—how one attention system in the brain reconciles with two different systems of filters.

Based on the clear pattern of RT costs and benefits across the visual field, it is believed that spatial selection is realized by enhancing processing of the relevant locations, as well as by inhibition of the irrelevant locations. As Tsotsos (1993) suggested, the attentional “beam” includes both facilitatory and inhibitory zones which operate in the brain map, not simply like a spotlight shining on the two-dimensional visual space. The facilitatory zone defines a group of excitatory connections between neurons. The inhibitory zone defines a group of inhibitory connections between neurons. The gradient pattern of RT costs and benefits is caused by the intersection between two zones. Because attentional
facilitation is cancelled out by inhibition within the intersection zone, performance in this area will be in the intermediate level of the scale of costs and benefits. As a result, the curve of RT benefits and costs will reflect a gradient pattern surrounding the cued location.

It is worth noting that exogenous cueing has revealed a different pattern with no distance effect and a less strong inhibitory component. We hypothesize that this may result from the difference between bottom-up and top-down processes in deciding which connections should be selected or inhibited. To confirm these hypotheses, we adopted Tsotsos' (1993) model, including the winner-take-all (WTA) algorithm and a pyramidal network structure because the pyramidal processing has been proven to be able to reduce the computational complexity of vision (Tsotsos, 1990). Most importantly, we implement a process of integrating bottom-up and top-down influences to reflect the differences between exogenous and endogenous cueing.

The network architecture consists of four layers (see Figure 3), including one input layer, one output layer, and two hidden layers in between. This architecture approximately corresponds to the visual information flow from the retina through the lateral geniculate nucleus to visual area 1 and then to visual area 4 in the primary visual cortex (Mishkin, Ungerleider, and Macko, 1983).

The top (output) layer has six interpretive units that represent response outputs for the visual stimuli in six boxes or locations. The interpretive unit \( I_i \) receives visual inputs from layers below and performs processing related directly to the interpretation of inputs.
(e.g., orientation, edge). The bottom (input) layer has twenty-four interpretive units representing stimulus inputs, of which each adjacent four-unit group corresponds to visual features appearing in each box. Each interpretive unit has a receptive field of seven inputs units in the layer below.

In addition, each interpretive unit in each layer except the bottom layer is accompanied with a WTA network (containing seven gating units) and a bias unit \( (B_k) \) as shown in Figure 4. The bias unit receiving the task guidance from outside of the network (e.g., working memory) provides the top-down influence. The gating units \( (G_i) \) compute the WTA result for a particular interpretive unit and gate inputs through to the next higher interpretive units. Most important, gating units are interactively activated by two sources—top-down and bottom-up information. Formally,

\[
G_{j,k} = B_k \times I_{j,k-1}
\]

where \( G_{j,k} \) represents the \( j \)th WTA gating unit in layer \( k \), \( B_k \) is the bias for \( G_{j,k} \), and \( I_{j,k-1} \) is \( j \)th interpretive unit in layer \( k-1 \) that is linked to \( I_{j,k} \) in layer \( k \) through \( G_{j,k} \).

The value of gating unit \( (G_j) \) in the WTA network is updated by equation 2.2. The WTA process stops once the gating units in the competition are partitioned into two classes: those with value zero and those with value greater than \( \theta \). Those interpretive units that connect to zero-valued gating units will be pruned and those that connect to nonzero-valued gating units will be selected.

Basically, the simulation process can be divided into two phases corresponding to two information processing stages in endogenous orienting. In the first phase, information of
visual inputs traverses upward and the top-down bias is sent to the proper gating units and to a particular output unit corresponding to the cued location. At the end of this phase, a particular output unit is selected as the global winner and the location coding is completed. In the second phase, information traverses downward and the WTA operations begin to select the relevant connections and inhibit the irrelevant connections in the receptive field of that particular output unit. The endogenous cue represents a top-down bias to influence the WTA computation. The exogenous cue represents bottom-up information to influence the WTA computation. At the end of this phase, a facilitatory zone in the receptive field is formed around the cued location, i.e., preparatory attention (LaBerge, 1995) is formed prior to the time that a target is expected to occur. A typical connectivity resulting from endogenous and exogenous cueing is graphed in Figure 5 and Figure 6, respectively.

Finally, a target occurs in either expected or unexpected locations. The response of each output unit is represented as a sigmoid function of the unit’s total input, bounded between 0 and 1. The simulation process in detail is presented in Appendix A. The results showed that the activation pattern of output units for endogenous orienting (see Table 6) qualitatively resembled a distance effect in RT data, whereas the activation pattern of output units for exogenous orienting did not (see Table 8).

For further analysis, it is assumed that the unit’s activation represents the stimulus sampling rate (Johnson and Yantis, 1995). The larger the activation, the shorter the response time. The activation benefits and costs for each output unit are computed as if
they were reaction times. A mathematical function that can transfer the activation of each output unit to the corresponding response time is:

\[ RT(x) = \lambda [a(x)] + \varepsilon, \tag{3.3} \]

where \( RT(x) \) denotes the RT costs or benefits for the target at location \( x \), \( a(x) \) denotes the activation costs or benefits for the output unit at location \( x \), \( \lambda \) denotes a constant that translates the activation into reaction times, and \( \varepsilon \) is a residual time.

For endogenous cueing, a fit of activation cost/benefit onto RT cost/benefit, \( F(1, 4) = 54.6, p < .002, R^2 = .932 \), took the following form:

\[ RT(x) = -53.15[a(x)] + 14.17 \tag{3.4} \]

For exogenous cueing, a fit of activation cost/benefit onto RT cost/benefit, \( F(1, 4) = 69.3, p < .001, R^2 = .945 \), took the following form:

\[ RT(x) = -44.78[a(x)] + .58 \tag{3.5} \]

The simulated RT benefit/cost is graphed in Figure 7. The difference of slope between those two curves may reflect the difference between top-down and bottom-up processes in the model. The agreement between simulated and empirical data suggests that the WTA algorithm may have captured one aspect of neural computations in visual attention. In addition, the information flow in the model can be cut off unambiguously at a point where the upward flow corresponds to the stage of location coding of a central cue and the downward flow corresponds to the stage of attention allocating. In this sense, any subsequent interruption in the information flow can happen in either one of two stages. In the later experiments, we will explore this possibility.
As Myung and Pitt (1998) argued, a good fit of a model onto the data does not imply that the model has captured the underlying processes that generate the data because the model’s complexity, such as the model’s number of parameters and its functional form, may contribute to goodness of fit. In other words, goodness of fit is a necessary but not sufficient condition to evaluate a good model. Especially for the connectionist model, the model’s complexity is a serious problem to be dealt with because the model usually involves the arbitrary assumptions, such as the transfer function relating the unit’s activation to reaction times, and a huge number of parameters, such as the connection weights between any two units, which is far larger than the number of empirical data. This is also the specific problem that our model has confronted.

Myung and Pitt (1998) have demonstrated that a three-layer back-propagation network with six inputs, two hidden units, and one output, can fit a variety of data patterns respectively whether the pattern is concave, convex, or sigmoidal. However, this model may not fit new data once its parameters are fixed because of its absorption of random error during calibration of the parameter values. To test our model, a means of cross-validation is very usable to deal with the complexity problem of our model. Specifically, the identified parameter values of the model that has provided the best fit to the data of Experiment 1 (calibration sample) will be fixed and then the model’s ability to fit future experimental data (validation sample) from the same underlying process will be tested using a goodness-of-fit measure. If the model can fit to new data, it will be more convincing to say that the model captures the underlying processes that generate the data.
CHAPTER 4

EXPERIMENT 2: LUMINANCE VALUES IN THE ABRUPT-ONSET FEATURE

4.1 Introduction

The exogenous cue used in Experiment 1 has two properties. One is the abrupt onset of the flash; the other is brightness of the flash. These two properties may together determine the salience of the flash. The degrees of stimulus salience may, however, only be determined by the brightness level of the flash; the brighter (contrasted with the background), the more salient.

The abrupt-onset feature activates a transient subsystem in the visual processing system, which in turn orients observers' attention to the onset locations in the space (Todd and Van Gelder, 1979). This dynamic change of the stimuli, as opposed to the static stimulation, has been claimed to be the main determinant of attentional capture (Yantis and Jonides, 1984). In addition, in visual search, stimulus salience is said to trigger a preattentive system, making the stimulus with a distinctive feature be detected quickly without any interference of the surrounding distractors (Treisman and Gelade, 1980).
The results of Experiment 1 showed that an exogenous cue induced weaker inhibition of the uncued locations than did an endogenous cue. The question of interest is whether the size of this inhibition can be modified. If the inhibitory mechanism is initiated by detection of the abrupt-onset feature, then the manipulation of stimulus luminance will not modify the size of inhibition. If inhibition is initiated by another system that is related to detection of stimulus energy, we speculate that the less energetic stimulus may induce more inhibition of the uncued locations because attentional resources need to be more focused on that stimulus location and thus will be withdrawn from the other uncued locations.

In addition, evidence from the simulation of the connectionist model suggests that luminance of various degrees in a peripheral flash may have no effect on the allocation of spatial attention. In the simulation, the input units corresponding to a brighter cue was assigned a strength value of 100 as used in the simulation of Experiment 1. Relatively, the input units were assigned a strength value of 60, serving as a dimmer cue. The ratio of 100 over 60 resembled the ratio of 33.7 fL over 18.9 fL used in the experiment. The simulation process was identical to that for exogenous orienting in Experiment 1. Both cues of different strength produced a very similar result in terms of the distribution of activation of the output units (see Figure 8).

In this experiment, we manipulated the degrees of salience in an abrupt-onset stimulus, namely, the luminance level of the flash. A dim peripheral flash was made of luminance of 18.9 fL. A bright peripheral flash was made of luminance of 33.7 fL. Both types of peripheral cues were against a display background of 9.2 fL. The experimental method was identical to Experiment 1, except for those differences described below.

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4.2 Method

Subjects. Twenty-nine Ohio State University undergraduates participated in a single 1 1/2-hour session, in partial fulfillment of an introductory psychology class requirement. All had normal or corrected-to-normal visual acuity. Four participants were discarded from the analysis because of frequent eye movements or very low accuracy (below 50%).

Stimuli. The stimulus display included six boxes outlined in black color against a gray screen background (9.2 fl). Each box was 1.1° tall x 1.14° wide. The outline of one box (either location 1 or location 4) was brightened for 100 ms, serving as a peripheral cue. The luminance of the flash could be either 33.7 fl or 18.9 fl. The target was either the letter “P” or “B” in black (0.62° long x 0.35° wide), placed in the center of a box. The possible farthest target location was 9.3° away from the cued location.

Design. A 2 x 2 x 6 design was used. Three within-subjects variables were brightness of the cue (dim/bright), cueing locations (location 1 and location 4), and target locations (0°, 2.6°, 4.9°, 6.5°, 8.1°, and 9.3° distant from the cued location). The trials with different brightness of the cue were blocked.

A total of 480 trials was divided into 4 blocks of 120 trials each. Two blocks were bright-cue trials. Another two blocks were dim-cue trials. Each block was randomly assigned to the observers. On 80% of the trials, the peripheral cue appeared with 16.7% predictive validity. On 20% of the trials, all boxes were brightened simultaneously, serving as a neutral cue. The peripheral cue appeared in two possible locations equally often. Subjects were told that the peripheral brightening had nothing to do with the upcoming target location.
Data analysis. Reaction times slower than 1500 ms or faster than 300 ms were considered errors and discarded from the analysis. The low cutoff value of 300 ms was on average more than 2.5 standard deviations below the mean RT for each subject. 4.1% of the trials were truncated overall for this reason. There were three types of trials in this experiment. A valid trial is one in which the flashed and target locations are matched. An invalid trial is one in which the flashed and target locations are not matched. Neutral trials are those in which every location is flashed. Although the peripheral cue does not have any predictive validity, we still use the terms—valid and invalid—to describe the spatial relationship between the cue and the target.

Because there were only eight trials for each target location in the neutral condition, we decided not to calculate the RT costs and benefits based on a reference to the mean RT in neutral trials. Instead, we simply calculated the RT cost for each uncued location with a reference to the mean RT in the valid cue trials (Egly and Homa, 1991). For the purpose of comparing this experiment to Experiment 1, we only present the data from the trials in which the peripheral cue occurs in the rightmost location.

4.3 Results

The results are graphed in Figure 9. Reaction times were analyzed in a repeated measures ANOVA with cue brightness and target locations as two factors. The main effect of target locations was significant, \( F(5, 120) = 7.25, p < .01 \), indicating that responses to identification targets in the valid location were quicker than in the invalid location. The effect of cue brightness was not significant, \( F(1, 24) = 1.2, p = .28 \). The interaction of cue brightness and target locations was not significant either, \( F(5, 120) < 1.69 \).
The overall error rates were 15.3% and 14.3% for the bright-cue and dim-cue condition, respectively. Accuracy was analyzed in a repeated measures ANOVA with cue brightness and target locations as two factors. The main effect of target locations was significant, $F(5, 120) = 3.4, p < .01$, indicating that a target in the cued or 2.6° distant location was responded to more accurately than targets in other locations. The main effect of cue brightness was not significant, $F(1, 24) < 1$. The interaction of cue brightness and target location was not significant either, $F(5, 120) = 1.1, p = .35$. The results suggest that there is no difference between bright-cue and dim-cue conditions in terms of error rates.

The RT costs in terms of invalid RTs minus valid RTs were analyzed in a repeated measures ANOVA with cue brightness and target locations as two factors. None was significant. The effect of target locations was close to a significant level, $F(4, 96) = 2.17, p = .08$. The reason was that the RT cost of 2.6° distant location was slightly lower than other target locations. The results suggest that the RT costs are not significantly different between bright and dim cues. However, it is worth noting that reaction times for the dim cue were slightly longer than for the bright cue. For instance, the mean RT of valid trials for the dim cue was slightly longer than for the bright cue (559 vs. 547 ms).

4.4 Discussion

The peripheral flash not only directs observers' attention to a particular location in the space, but also alerts observers. The bright cue was more salient than the dim cue and hence induced more alerting effects. As a result, reaction times in the bright-cue trials were slightly quicker than in the dim-cue trials.
However, the dim cue did not induce a larger cost for the target identification in invalid trials than did the bright cue. The possible reason is that the attention system for orienting is in response to the abrupt-onset feature of the stimuli, but not to the luminance values of the stimuli. In other words, what matters to the orienting system is the dynamic change of the stimulus, but not its static contrast.

It has been argued that the visual system is composed of two subsystems: a transient system that only responds to dynamic changes in visual stimulation, such as onset, offset, or movement, and a sustained system that responds to static visual stimulation, such as visual patterns (Todd and Van Gelder, 1979; Livingston and Hubel, 1988). It is very likely that in one route, the abrupt-onset feature of the peripheral cue is detected by the transient system automatically, which in turn triggers the orienting system (possibly in the parietal lobe). In the other route, the luminance value is analyzed by the sustained system, which in turn activates the alerting system. On the one hand, those two routes seem to be independent of each other because the experimental results show that the luminance values (i.e., the degrees of salience) do not have any impact on attentional orienting. On the other hand, it is also very likely that those two systems will interact in a certain way because obviously the most salient stimulus has a higher likelihood of capturing attention. For instance, the brightest dot in a display of gray dots will pop out and be detected at first.

In sum, the peripheral flash provides two types of visual information: the dynamic change of stimulation and the static luminance contrast. The orienting of attention is mainly determined by information of dynamic changes. This finding reflects a minor problem in the method of Experiment 1, in which the target appears in previously blank
location, i.e., an onset stimulus. In the endogenous cueing session, the effect of the target onset may be averaged out using the mean RT of neutral trials as a baseline in the computation of RT costs and benefits. However, in the exogenous cueing session, the target onset may compete with the peripheral cue in the invalid trials and make ongoing processes complicated (Muller and Rabbitt, 1989).

The solution is to use no-onset targets. The no-onset presentation procedure has been well described in Todd and Van Gelder (1979). At the beginning of each trial, observers see a display of figure-eight placeholders grouped by seven line segments. Following a brief interval, some of the line segments in a figure eight are removed to reveal a letter, such as E, H, F, or L. Those so-called no-onset letters are already present before they are revealed. Thus, no abrupt onset accompanies their appearance. This technique will be adopted in the later experiments in which a peripheral flash is administered.
CHAPTER 5

EXPERIMENTS 3 & 4: COMPETITION BETWEEN IRRELEVANT ABRUPT-ONSET DISTRACTOR AND CENTRAL CUE

5.1 Introduction

As reviewed in Chapter 2, it has been well established that the abrupt peripheral onset can capture attention and thus interrupt the voluntary allocation of attention that follows a central cue, especially when the central cue does not provide absolute spatial certainty (Muller and Rabbitt, 1989; Theewues, 1991; Yantis and Jonides, 1984). According to the results of Experiment 1, the extent to which the distractor may be attended depends on its distance from the cued location. Thus, we can infer that not only is interruption of the distractor mediated by the attentional state, but interruption may also be mediated by the spatial distance between the cued location and the distractor.

From the information-processing perspective, the competition between exogenous and endogenous cues can possibly occur at two stages. The first stage occurs in location coding because directionality of the endogenous cue must be decoded before the shift of attention can take place. When the subsequent exogenous cue arrives at this stage, its interruption on the previous endogenous cue may simply cause the failure of the location
coding of the endogenous cue. As a result of this interruption, attention must be in diffuse mode at that moment and then shift to the location of the exogenous cue. After realizing that the target occurs somewhere else, observers shift their attention back to the target location. An empirical function relating the reaction times to the distance of the attention shift has been reported to be approximately linear (Shulman, Remington, and McLean, 1979; Tsai, 1983). According to this line of reasoning, performance on target identification will be faster when the target is near the distractor than when it is far from the distractor.

The second stage can occur in attention focusing, in which attention is in the process of allocation to the cued location. The results of Experiment 1 have suggested that within 4.9° of visual angle, there is a gradient allocation of attention directed by a central cue at a given moment in time. In other words, the closer to the cued location the distractor is located, the more allocation of attention the distractor is given. It is reasonable to think that the distractor may increase power to interrupt the central cue when it is closer to the cue, a prediction which is just the reverse of the previous one.

Theeuwes (1991) made an interesting observation that supported this hypothesis. He found that when subjects focused on the likely target location (a central cue appeared 300 or 600 ms before the target display), performance on the target identification was not affected by the presentation of a peripheral abrupt-onset near a nontarget location (i.e., far away from the target) during the processing of the target. This observation is similar to Yantis and Jonides' (1990) findings. However, when the peripheral onset occurred near the target location, response times to the target were slowed down. This result suggests
that the extent to which abrupt onsets interrupt the endogenous cues depends on the spatial separation between the peripheral onset and the cued (or target) locations.

Consequently, in addition to the distance effect involved in the distribution of spatial attention, we speculate that there may well be a distance effect in the interaction of exogenous and endogenous cues. In other words, the interruption of an irrelevant exogenous cue on an endogenous cue depends on the distance between the two locations that those two types of cues indicate respectively.

This prediction also makes ecological sense. From an ecological perspective, an exogenous cue (e.g., a sudden movement or a flash) usually signifies a potential danger to the animals. It is reasonable to think that the way this exogenous cue can interrupt the endogenously attentive ongoing behavior (e.g., catching a bug) may depend on how far the potential danger is and how deeply the endogenously attentive behavior has been engaged in. The latter is related to the time course of attentive behavior.

5.2 Research hypotheses

There are two main hypotheses. First, the interruption of processing of a central cue by an irrelevant abrupt-onset distractor depends on spatial separations between the cued location and the peripheral distractor. Second, this distance effect varies with whether attention is in diffuse or focused mode.

A strong empirical prediction of this hypothesis is that the effect of the abrupt-onset distractor on the central cue should be a monotonic function of spatial separation between the distractor and the cued location. More specifically, two predictions can be formulated as follows: (A) If the abrupt-onset distractor occurs 200 ms after the central cue
(attention is in focused mode), the distractor nearest the cued location will induce the largest interruption, which then decreases with increasing distance from the cued location. (B) If the abrupt-onset distractor occurs almost simultaneously with the central cue (attention is in diffuse mode), the distractor farthest from the cued location will induce the largest interruption, which then decreases as close to the cued location.

5.3 Experiment 3

The purpose of Experiment 3 was to test prediction A. The stimulus display is graphed in Figure 10. Rather than using blank boxes as in Experiment 1, we used the black letter H to mark six possible target locations, arranged on an imaginary semicircle in the upper visual field. The center was the fixation point. Thus, each location had equal visual acuity. Subjects had to recognize whether one of six Hs was changed to E or F. Because only one or two line segments need to be onsets to make F or E from H, this design can reduce the attention-capture power of the target onsets to some extent.

On each trial, a line cue appeared at the fixation point for 150 ms, pointing to either the leftmost or the rightmost location. The cue indicated the location of an upcoming target (E or F) accurately on 75% of the trials. The cue-to-target SOA varied from 300 to 350 ms, under which Muller and Rabbitt (1989) had reported an optimal performance. At 100 ms prior to the onset of the target (i.e., 200-250 ms after the onset of a central cue), any position of H other than the leftmost and the rightmost locations was brightened for 50 ms, serving as the abrupt-onset distractor that was randomly associated with target locations. In another subset of trials, the central cue appeared alone, serving as the baseline condition. If an abrupt-onset distractor interrupts the orienting following a
central cue, it is predicted that responses to the target in valid trials with a distractor will take longer than without a distractor. This difference of reaction times is the index of interruption. It is also predicted that the extent to which the abrupt-onset distractor will interrupt the central cue is negatively correlated with spatial distance between those two cueing events.

5.3.1 Method

Subjects. Eighteen Ohio State University undergraduates participated in a one-hour session, in partial fulfillment of an introductory psychology class requirement. All had normal or corrected-to-normal visual acuity. Two of them were not included in the data analysis because of frequent eye movements or too much blinking.

Apparatus. Stimulus displays were presented on a ViewSonic 4E 14" color monitor driven by a 486 PC equipped with a Cirrus Logic SVGA graphic card. Subjects sat in a comfortable chair in a sound-attenuating and dimly lighted booth. The monitor was placed at eye level on a table. The viewing distance measured from the surface of the monitor to the subjects’ eyes was fixed at approximately 70 cm. Subjects responded by pressing keys on a WYSE terminal keyboard.

The monitoring of eye movements was identical to that in Experiment 1. EOGs were collected via an analog-to-digital converter, amplified with a gain of 5000 and digitized at a sampling rate of 200Hz. A voltage criterion of 20μV shift within a sampling time of 30-50 ms was established for defining eye movements. Any trials with eye movements or blinking detected were discarded and rerun later in the experiment.

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**Stimuli.** The stimulus display included six black letters of H against a gray screen background, arranged along a semicircle. A small white square (0.24° tall x 0.16° wide) placed at the center of the display served as fixation. Each H was 0.73° tall x 0.32° wide, 5.71° from fixation and equally spaced, 2.45° center to center, from its neighbor. Two most lateral Hs were positioned 2.13° above the horizontal meridian. The stimulus display was symmetric about the vertical meridian, with three Hs in each visual hemifield. A white straight line (1.22° long x 0.08° wide) was presented at fixation, serving as a central cue. The abrupt-onset distractor was a 50-ms brightening of any H except for two most lateral Hs. The possible farthest abrupt onset was 8.93° from the cued location. The possible nearest abrupt onset was 2.45° from the cued location.

**Procedure.** The stimulus events, including fixation display, cue display, distractor display, and target display, are graphed in Figure 11. A fixation square, along with six black Hs, was first presented in the fixation display. Subjects were instructed to fixate the square throughout a trial. After 900 ms a white line appeared at fixation for 150 ms, pointing either to the leftmost or the rightmost H. The cue predicted the upcoming target with 75% validity. Following a brief interval varying from 50 to 100 ms, one position of H was brightened for 50 ms. The cue-to-distractor SOA was variable from 200 to 250 ms. Finally, a target, E or F, appeared 75% likely at the cued position to replace H. The cue-to-target SOA was variable from 300 to 350 ms. Subjects determined whether an E or an F was present and responded by pressing the period key (.) with their right index finger if the E appeared and the semicolon key (;) with their middle finger if the F appeared. The E or F would not disappear until subjects responded in order to increase response accuracy. The next trial automatically started two seconds later. If subjects moved their
eyes during the trial, a warning message would appear on the screen. The next trial would not proceed until the space bar was hit. Subjects were instructed to use this period to rest their eyes.

**Design.** A 2 x 5 design was used, the factors of which were location of the endogenous cue (leftmost/rightmost) and location of the abrupt-onset distractor (none, 2.45°, 5.30°, 7.32°, 8.93° from the cued location). Both were within-subjects factors. The central cue pointed to either side with equal frequency. A total of 240 trials were divided into 3 blocks of 80 trials each. Thus, there were 24 trials in each of the ten combinations of centrally cued and flashed locations. On 75% of the trials, the target appeared in the location that the central cue indicated, while on 20% of the trials, the target would follow the abrupt-onset distractor at the same location. On the remaining 5% of the trials, the central cue was presented alone and a target appeared in the uncued location. Thus, as far as the trials with a distractor were concerned, the abrupt-onset distractor would predict the target location with a validity of 25%. The task was two-alternative forced-choice letter discrimination. The target letter, E or F, was randomly chosen. Subjects were encouraged to follow the central cue and to prepare for the target while maintaining fixation.

**Data analysis.** Trials with reaction times slower than 1500 ms were discarded because eye movements were no longer monitored 1500 ms after onset of the target. Reaction times faster than 300 ms were considered a premature response and also discarded. 1.3% of the trials were truncated overall for these reasons. The data of interest were reaction times in the cue-valid trials. Only reaction times of correct trials were included in the analysis of variance. The index of interruption was computed by 79
subtracting the mean RT in valid-cued trials without any distractor from the mean RT in valid-cued trials with a distractor.

5.3.2 Results

The results of Experiment 3 are graphed in Figure 12. It appears that the abrupt-onset distractor did interrupt the voluntary allocation of attention. Data from different centrally cued locations were analyzed separately. The mean correct reaction times from the trials of precuing the rightmost location were analyzed in an ANOVA with abrupt-onset locations as the single within-subjects factor. The main effect of abrupt-onset location was significant, $F(4, 60) = 3.49, p < .05$. The contrast analysis showed that the nearest and second nearest distractors produced slower responses to identification target in the cued location relative to the baseline condition without any distractor, $F(1, 15) = 9.12, p < .01$ and $F(1, 15) = 6.05, p < .05$, respectively.

The mean correct reaction times from the trials of precuing the leftmost location were analyzed in an ANOVA with abrupt-onset locations as the single within-subjects factor. The main effect of abrupt-onset location was significant, $F(4, 60) = 3.96, p < .01$. The contrast analysis revealed that only the nearest distractor produced slower responses relative to no-distractor trials, $F(1, 15) = 11.55, p < .01$.

Furthermore, the interruption was stronger when the abrupt-onset distractor was near the cued location than far from the cued location. This evidence was revealed from the results of a repeated measures analysis of variance on the interruption index, with the endogenous cue location and the abrupt-onset location as within-subjects factors. The main effect of the endogenous cue location was not significant, $F(1, 15) < 1$, nor was the
effect of the abrupt-onset location, $F(3, 45) = 1.58$. Most important, there was a significant interaction between the endogenous cue location and the abrupt-onset location, $F(3, 45) = 3.32, p < .05$. Another repeated measures ANOVA used endogenous cue location and spatial separation between the distractor and the cued location as two within-subjects factors. The results showed that neither the main effect of the endogenous cue location nor the interaction between the two factors was significant, $F(1, 15) < 1$ and $F(3, 45) < 1$, respectively, but the main effect of spatial separation was significant, $F(3, 45) = 5.32, p < .01$. The contrast analysis among means of each spatial separation showed that the $2.45^\circ$ distractor produced larger interruption than the others. For $2.45^\circ$ distractor vs. $5.3^\circ$ distractor, $F(1, 15) = 13.27, p < .01$. For $2.45^\circ$ distractor vs. $7.32^\circ$ distractor, $F(1, 15) = 6.43, p < .05$. For $2.45^\circ$ distractor vs. $8.93^\circ$ distractor, $F(1, 15) = 6.52, p < .05$. This suggests that the abrupt-onset distractor right next to the endogenously cued location induced the strongest interruption, which then decreased as the distractor moved farther away from the cued location.

The error rate was 9.5% when the rightmost location was precued and 8% when the leftmost location was precued. There was no significant difference between those two conditions, $F(1, 15) = .74$. The overall error rate in this experiment was 8.8%. Table 3 summarized the error rates and reaction times in each combination of abrupt-onset and cued locations. There was a positive correlation (.53) between error rates and mean response times, indicating no strong speed/accuracy trade-off.
5.3.3 Discussion

Presumably, given 300 ms of cue-to-target SOA, subjects were able to shift attention to the cued location appropriately. However, even though attention has been focused on the likely target location in advance, the abrupt-onset distractor was able to slow down the responses to the target in the centrally cued location, whether the distractor was near or far from the cued location. This result is different from what has been found by Yantis and Jonides (1990). The reason for this difference may be because the distractor predicts the likely target location with a validity of 25%, slightly higher than the random probability (i.e., $1/5 = 20\%$), which may give the subjects a reason for expecting a target in the distractor location if they can implicitly learn about this predictive probability (Lambert, Naikar, McLachlan, and Aitken, 1999). In addition, the central cue predicts the likely target with a validity of 75%, which is slightly lower than what was used in Yantis and Jonides’ (1990) experiments. In any event, it seems that subjects’ attention is always distracted by the abrupt onset under the settings in this experiment. Of most interest, the size of interruption depends on the distance between the cued location and the distractor. As expected, the nearest distractor produced the strongest distraction from the voluntary allocation of attention.

We believe that the competition between the cue and the distractor occurs in the stage of focusing attention in this experiment. As the results of Experiment 1 show, the distribution of spatial attention at a given moment in time forms a gradient surrounding

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2 Though there were six possible target locations, a target could only occur in one of five boxes following a central cue. If the leftmost box is cued, a target will not appear in the rightmost box, and vise versa.
the cued location within some spatial extent, i.e., the farther to the cued location, the less amount of allocation of attention. In addition, beyond 4.9° distance from the cued location, there is equal amount of inhibition across the visual field. According to these results concerning the spatial distribution, we can explain the distance effect in the competition between cue and distractor. When the distractor is near the cued location, it will obtain more attention than when it is far. Therefore, the distractor nearest the cued location will have the most power to distract attention that is being allocated in the cued location in advance.

From the perspective of Desimone and Duncan (1995), the receptive fields viewed as critical visual processing resources are the locus where competition between two objects occurs. For example, Moran and Desimone (1985) demonstrated the competition involved in the receptive fields of cells in area 4 of the visual cortex and the inferior temporal cortex. In their study, monkeys were trained to perform a discrimination task on the target stimuli at one location in the visual field and to ignore simultaneously presented distractors at a second location. When the target and the distractor both were within the receptive field of the recorded cell, responses to the distractor were greatly attenuated. The cells responded as if their receptive fields had shrunk around the target, which was a result of competition between the target and the distractor. According to the reasoning above, it seems that the distractor nearest the cued location will most likely be included in the receptive field of processing the cued location and hence becomes the most competitive for the resources. Since the central capacity is limited, the distractor nearest the cued location will deprive a larger portion of resources from all than one that is farther from the cued location.
In any event, the results of this experiment can be accounted for by both competition between the receptive fields and the gradient model of spatial attention. From the perspective of the connectionist model, competition between exogenous and endogenous cues is just an emergent property in the WTA operations because the gating units in the WTA network is activated from the interaction of top-down and bottom-up influences (i.e., B x l). The competition occurs in the stage when information flows down from the top to the bottom in the connectionist model. At this stage, the WTA processes operate to select the relevant inputs and prune irrelevant inputs in the receptive field of the output unit corresponding to the cued location.

Each gating unit in the WTA network receives bottom-up visual information from the different locations corresponding to a retinotopic map. Similarly, top-down information flows down to different gating units according to the directionality of central cueing. Competition between distractor and cue becomes rivalry between the receptive fields of the distractor and the cued location. Whichever finishes the WTA computation first will win the race and gain the control of limited capacity.

When the abrupt-onset distractor is far apart from the centrally cued location, some gating units in the receptive field of the distractor are mainly activated by top-down influences, while some others are mainly activated by bottom-up influences. As a result, it may take a long time for the WTA computation to finish, because each gating unit almost has equal activation and thus has equal potential to inhibit one another. However, when the distractor is close to the cued location, the top-down influence, together with the bottom-up influence, most likely will contribute to the same gating units in the receptive field of the distractor. That is, some gating units are strongly activated while
others are weakly activated. As a result, the WTA computation may finish sooner and have higher probabilities to win the race with the receptive field of the cued location. According to this reasoning, the nearer distractor may interrupt the central cue more than does the farther one.

A connectionist model described in the discussion of Chapter 3 was used to simulate the competitive processes described above. A simplified criterion is adopted to determine which receptive field wins the race. For the WTA computation, the receptive field of the cued location takes a lead, four iterations ahead of the receptive field of the distractor. After two more iterations, whichever has the fewest non-zero gating units will win. A facilitation zone is then formed within that winning receptive field. The simulation process in detail is presented in Appendix B.

As a result of simulation, the activation of the output unit for the target was a sigmoid-like function of spatial separation between cued and distractor locations. The empirical RT data from the left and right visual fields were combined according to spatial separation between cued and distractor locations. In contrast, the empirical RT was a monotonically decreasing function of spatial separation between cued and distractor locations. A linear fit of activation (A) onto RT, $F(1, 3) = 6.23, p =.088, R^2 = .675$, took the form:

$$RT = 53.9(1 - A) + 610 \quad (5.1)$$

The estimated RTs are graphed in Figure 13. The poor fit is caused mainly by the disagreement between simulated and empirical data on the trials in which the distractor is two positions away from the cued location. The mean activation from these trials should have been much stronger than that from the trials in which the distractor is one position
away from the cued location. When the distractor is one position away from the cued location, the receptive field of the cued location loses to the receptive field of the distractor 44 out of 100 times of simulation. In contrast, when the distractor is two positions away, the receptive field of the cued location only loses 32 out of 100 times of simulation. Ideally, the activation of the output unit for a target should be either one if the cue wins or close to zero if the distractor wins. Therefore, the mean activation of the output unit for a target should be approximately equal to .56 vs. .68 when the distractor is one vs. two positions away. This is only the expected result. The simulation outcome (.37 vs. .33) does not come along with the ideal result. One reason for this discrepancy is that the distractor also does some damage to the receptive field of the cued location by turning the facilitation area towards the distractor location at the early level of the model even though the receptive field of the cued location wins (see Figure 14). Consequently, the output unit for the cued location was not fully activated (i.e., the activation value was somewhere between 0.5 and 0.7). Because the competition occurring in the second stage must be preceded by the first stage, this side effect of the distractor may be related to the competition between cue and distractor occurring in the earlier stage—location coding, which is exactly what will be explored in the next experiments.

It is worth noting that competition between cue and distractor can take place in the earlier stage than in attention focusing. Obviously, directionality of a central cue should be decoded before attention can be focused in the cued location. Because location coding in this stage is a controlled process, the abrupt-onset distractor will have a chance to interrupt the coding process. The next experiment concerns competition occurring in the stage of location coding.
5.4 Experiment 4

The purpose of Experiment 4 was to test prediction B as described earlier, which was that the farthest abrupt-onset distractor has the largest interruption on the allocation of attention following a central cue when cue and distractor are presented almost simultaneously. The method is the same as used in Experiment 3, unless described otherwise. The only change is cue-to-distractor SOA, which is decreased to 100 ms, instead of 200-250 ms in Experiment 3. By doing so, we believe that location coding of a central cue must be interrupted by an abrupt-onset distractor. We further predict that when attention is in diffuse mode, the farthest abrupt-onset distractor will demonstrate the strongest interruption on relocation of the target.

5.4.1 Method

Subjects. Twenty-two Ohio State University undergraduates participated in a one-hour session, in partial fulfillment of an introductory psychology class requirement. All had normal or corrected-to-normal visual acuity. Two of them were not included in the data analysis, because of too much blinking or mistakenly pressing the wrong response keys.

Procedure. The procedure was almost the same as in Experiment 3, except for the changes described as follows. A central cue appeared at the fixation point for 100 ms, which was followed by an abrupt brightening of an H for 80 ms. After 30-60 ms, a target appeared. The cue-to-target SOA was variable from 210 to 240 ms, instead of the 300-
350 ms in Experiment 3, because the exogenous distractor-to-target SOA was kept at a level shown in previous research to maximize exogenous cueing effects.

**Data analysis.** Trials with reaction times slower than 1500 ms or faster than 300 ms were considered errors and discarded. 3.27% of the trials were truncated overall for this reason. The data of interest are reaction times in the cue-valid trials. Only reaction times of correct trials were included in the analysis of variance. The index of interruption was computed by subtracting RT in valid-cued trials without any distractor from RT in valid-cued trials with a distractor.

### 5.4.2 Results

Similar to Experiment 3, the results of Experiment 4 also revealed that the abrupt-onset distractors did slow down the response to the targets following a central cue, no matter where the cue indicated in the display. As Figure 15 shows, when the central cue appeared at the rightmost location, the nearest abrupt-onset distractor produced the strongest interruption, which then decreased with increasing spatial separations, but finally bounced back to a strong interruption for the farthest distractor. A separate one-way ANOVA on reaction times showed that the effect of abrupt-onset location was significant, F(4, 76) = 4.47, p < .01. A mean contrast analysis among different abrupt-onset locations showed that when abrupt-onset distractors occurred at 2.45°, 5.30°, and 8.93° separation from the cued location, reaction times were significantly slower than in the no-distractor condition: F(1, 19) = 10.78, p < .01; F(1, 19) = 24.3, p < .01; F(1, 19) = 6.79, p < .05, respectively.
However, when the central cue appeared at the leftmost location, the farthest distractor produced the strongest interruption and then decreased with decreasing spatial separations, as predicted. Nonetheless, what deviated from the prediction was that the nearest distractor also produced a pronounced interruption, instead of the smallest interruption. A separate one-way ANOVA on reaction times showed that the effect of abrupt-onset location was significant, $F(4, 76) = 3.37, p < .05$. A mean contrast analysis among different abrupt-onset locations showed that when abrupt-onset distractors occurred at 2.45° and 8.93° distance from the cued location, reaction times to the target in the cued location were significantly slower than in the condition without a distractor: $F(1, 19) = 7.32, p < .05$; $F(1, 19) = 6.34, p < .05$, respectively.

This different interruption patterns across two lateral cued locations were revealed from a repeated measures ANOVA on the index of interruption, with the endogenous cue location and spatial separations between cue and distractor as two within-subjects factors. The main effect of endogenous cue location was not significant, $F(1, 19) < 1$, nor was the effect of spatial separations, $F(3, 57) < 1$. Most important, there was a significant interaction between the endogenous cue location and spatial separation, $F(3, 57) = 3.23, p < .05$. This suggests that whether the nearest or farthest abrupt-onset distractor produced the strongest interruption depended on the laterality of the endogenous cue.

The error rate was 9.88% when the rightmost location was cued and 9.86% when the leftmost location was cued. There was no significant difference between those two conditions, $F(1, 19) < 1$. The overall error rate in this experiment was 9.87%. Table 4 summarizes the error rates and reaction times in each combination of abrupt-onset and
cued locations. There was a positive correlation (.56) between error rates and mean response times, indicating no strong speed/accuracy trade-off.

5.4.3 Discussion

It seems that 100 ms cue-to-distractor SOA is near the boundary between focused and diffuse attention modes. Observers may be in either one of two modes at some stochastically dependent moment in time. When attention is in focused mode, the nearest distractor has the strongest interruption; when attention is in diffuse mode, the farthest distractor has the strongest interruption. Basically, the results in this experiment reflect a mixture of these two modes. Furthermore, attention seems to be oriented to the right visual field more easily than to the left visual field. Therefore, when the cue indicates the right visual field, it is more probable to have entered the stage of orienting in 100 ms of cue-to-distractor SOA. This is inferred from the result that the nearest distractor has the strongest interruption, which then decreased with increasing spatial separations but bounced back to a pronounced level of interruption at the farthest separation. Nonetheless, it is more probable to not have entered the stage of orienting in 100 ms when the cue indicates the left visual field. This is inferred from the result that the farthest distractor has the strongest interruption, which then decreased with increasing spatial separations but finally bounced back to a second strongest level of interruption.

There are two components operating underlying the voluntary allocation of attention. The first is that directionality of the cue should be encoded. The second is that this internal code of location signals the visual attention system to allocate attentional resources to process information at that location. If the first operation fails, the farthest
distractor will have the strongest interruption effect on the identification of the target. On the other hand, if the first operation succeeds and attentional resources are being allocated, the nearest distractor will have the strongest interruption effect on the target identification.

One interesting finding is that there is a difference in the laterality of cue processing. Because observers fixate the central point, the left-directed visual cue presented at the left side will be processed in the right cerebral hemisphere, whereas the right-directed visual cue presented at the right side will be processed in the left cerebral hemisphere. According to the results, the left-directed cue tended to be interrupted at the stage of location coding and could not signal the voluntary allocation of attention most of the time. In other words, it was faster to orient to the right visual field relative to the left visual field. This evidence suggests that the left cerebral hemisphere has the advantage in translating the symbol to the internal code of directionality over the right hemisphere. One possible reason could be that this translation process may be related to language processing (Logan, 1995), so the left hemisphere has the advantage. Another possible reason for this hemispheric asymmetry in response to the central cue could be that all observers in this experiment are right-handed. Thus, the left hemisphere has more efficacy in processing the central cue, relative to the right hemisphere.

The finding regarding the laterality in processing the central cue may shed some light on accounting for a well documented abnormality in spatial attention—visual neglect, a attentional disorder following impairment to the right hemisphere of the brain, particularly the right parietal lobe. Patients with visual neglect usually suffer a failure to
orient to or be aware of the stimuli in the left side of space even though their vision is still normal (Rafal, 1998).

Kinsbourne (1993) proposed a hemispheric rivalry account for visual neglect. There are two components in his account. First, each hemisphere is responsible for an orienting response in the contralateral direction. That is, the left and right hemispheres compete with each other to direct attention to its contralateral visual field. Second, a unilateral lesion causes a breakdown in the balance of competition so that the normal side of the brain dominates the control and allocates attention to the ipsilesional field without rivalry. According to our finding, it seems that there is a hemispheric asymmetry for an orienting response to the central cue in the normal brain; that is, there is an attentional bias towards the right visual field. Therefore, visual neglect may result from the magnification of this hemispheric asymmetry due to the lesion of the right parietal lobe.

Even though the results of Experiment 4 did not completely confirm our predictions, there was a sign of competition between cue and distractor in the location-coding stage especially when the cue pointed to the left visual field. Comparing the results of Experiments 3 and 4, the distractor that produces the strongest interruption effects has been shifted from the nearest to the farthest from the cue when attention is directed to the left visual field.

It appears that observers are still able to encode the directionality of cue successfully even when the cue occurs only 100 ms before the distractor. Therefore, to ensure that the distractor will interrupt the location coding of a central cue before it finishes, we present the cue and the distractor more closely in the next experiment. We predict that the reverse results from Experiment 3 will be obtained.
CHAPTER 6

EXPERIMENT 5: DYNAMICS OF LOCATION CODING OF A CENTRAL CUE

6.1 Introduction

In Experiment 3, when the cue-to-distractor SOA was 200 ms, the location coding of a central cue was already completed. Therefore, interruption of the distractor occurred in the later stage of allocating attention. In Experiment 4, when the cue-to-distractor SOA was decreased to 100 ms, the location coding of a central cue was at the borderline of completion and incompletion. Interruption of the distractor could occur either in the stage of location coding or attention allocating stochastically. This inference was based on the results that the farthest and the nearest distractors both generated pronounced interruption of identification of the target in the cued location in either the left or the right visual field.

In this experiment, several changes regarding the experimental design are made to ensure that the interference in the central cue will occur in the stage of location coding. First, the cue-to-distractor SOA is decreased to 84 ms. Second, the duration of the central cue is decreased to 56 ms, making the cue harder to perceive. However, a central cue presenting 50 ms alone has been reported to be able to enhance performance on cued locations (Muller and Rabbitt, 1989). If the abrupt-onset distractor does interfere with
location encoding of the central cue under these settings, we predict that the farthest
distractor will induce the strongest interruption, which then decreases with decreasing
spatial separations between the cued location and the distractor.

6.2 Method

Subjects. Twenty Ohio State University undergraduates participated in a single one-
hour session, in partial fulfillment of an introductory psychology class requirement. All
had normal or corrected-to-normal visual acuity. Two of them were not included in the
data analysis, because of not following the instructions or illusion of seeing two targets
simultaneously.

Stimuli and procedure. The procedure and stimuli are almost the same as in
Experiment 4, except for the following changes. First, a black figure eight replaced the
letter “H” to mark the possible target locations. The target could be the letter “F” or “L”,
instead of the letter “E” or “F”, in black color. They were presented through removal of
some line segments of a figure eight. In doing so, the targets became totally no-onset
stimuli (Todd and Van Gelder, 1979) and were easier to be discriminated from each other
than the pair of “E” and “F”. Second, the central cue was presented across the midline,
instead of on each side of the midline. Third, a central cue appeared at the fixation point
for 56 ms. After 28 ms, the cue was followed by an abrupt brightening of a figure eight
for 84 ms. After variable time intervals of 56 to 84 ms, the target appeared 75% likely at
the cued position. The cue-to-target SOA was variable from 224 to 252 ms, instead of
300-350 ms in Experiment 3, because the exogenous distractor-to-target SOA was kept at
a level shown in previous research to maximize exogenous cueing effects.
Data analysis. Reaction times slower than 1400 ms or faster than 250 ms were considered errors and excluded in the analysis. 2.6% of the trials were truncated overall for this reason. The new criteria, 1400 and 250, seem to work better for this data set than the previous settings—1500 and 300, in terms of efficiency of trimming extreme values. The data of interest were reaction times in the cue-valid trials. Only reaction times of correct trials were included in the analysis of variance. The index of interruption was computed by subtracting correct RT in valid-cued trials without any distractor from correct RT in valid-cued trials with a distractor.

6.3 Results

The results of Experiment 5 are graphed in Figure 16. First of all, data from different precued locations are analyzed separately. The mean correct reaction times from the trials of precuing the rightmost location were analyzed in an ANOVA with abrupt-onset locations as a single within-subjects factor. The main effect of abrupt-onset location was significant, F(4, 68) = 3.23, p < .05. The contrast analysis showed that the farthest distractor produced slower responses to identification of the target in the cued location relative to the baseline condition without any distractor, F(1, 17) = 23, p < .01.

The mean correct reaction times from the trials of precuing the leftmost location were analyzed in an ANOVA with abrupt-onset locations as a single within-subjects factor. The main effect of abrupt-onset location was significant, F(4, 68) = 6.28, p < .01. The contrast analysis showed that the farthest and the second farthest distractors produced slower responses to identification of the target in the cued location relative to the baseline condition.
condition without any distractor, $F(1, 17) = 15.6, p < .01$ and $F(1, 17) = 10.7, p < .01$, respectively.

Furthermore, in each visual field, interruption was stronger when the abrupt-onset distractor was farthest from the cued location than when it was near the cued location. This evidence was revealed from the results of a repeated measures analysis of variance on the interruption index, with the endogenous cue location and the abrupt-onset location as within-subjects factors. The main effect of the endogenous cue location was not significant, $F(1, 17) < 1$, nor was the effect of the abrupt-onset location, $F(3, 51) < 1$. Most important, there was a significant interaction between the endogenous cue location and the abrupt-onset location, $F(3, 51) = 5.86, p < .01$.

Another repeated measures ANOVA used endogenous cue location and spatial separation between the distractor and the cued location as two within-subjects factors. The results showed that neither the main effect of the endogenous cue location nor the interaction between the two factors was significant, $F(1, 17) < 1$ and $F(3, 51) < 1$, respectively, but the main effect of spatial separation was significant, $F(3, 51) = 5.19, p < .01$. The contrast analysis among means of each spatial separation showed that the $8.93^\circ$ distractor produced larger interruption than the others. For $2.45^\circ$ distractor vs. $8.93^\circ$ distractor, $F(1, 17) = 21.45, p < .01$. For $5.3^\circ$ distractor vs. $8.93^\circ$ distractor, $F(1, 17) = 8.72, p < .01$. For $7.32^\circ$ distractor vs. $8.93^\circ$ distractor, $F(1, 17) = 5.75, p < .05$. This suggests that the abrupt-onset distractor farthest from the endogenously cued location induced the strongest interruption, which then decreased as the distractor moved closer to the cued location.
The error rate was 2.8% when the rightmost location was cued and 3.4% when the leftmost location was cued. There was no significant difference between those two conditions, $F(1, 17) < 1$. The overall error rate in this experiment was 3.1%. Table 5 summarized the error rates and reaction times in each combination of abrupt-onset and cued locations. There was a positive correlation (.42) between error rates and mean response times, indicating no strong speed/accuracy trade-off.

6.4 Discussion

Together with the results of Experiments 3 and 4, it is clear that the time for location coding takes somewhere between 84 and 100 ms. After 100 ms, the location coding of a central cue is completed so that subsequent distractors have their interruption effects in the attention-allocating stage. In between 84 and 100 ms, the location coding is in the borderline between completion and incompletion. Prior to 84 ms, the location coding is not completed yet so that the subsequent distractor has an interruption effect in the location-coding stage.

As expected, when the competition between cue and distractor occurs in this stage of location coding, the farthest distractor has the largest interruption, which in turn decreases with the decreasing spatial distance from the cued location. This is because attention is captured by the abrupt-onset distractor when in diffuse mode, then attention is required to shift back to the target location when observers realize that their attention is supposed to be paid to the previously cued location.

Interestingly, this result may in turn shed some light on the argument in the literature about how attention is shifted from one location to another, i.e., whether reaction times of...
the attentional shift are a linear function of spatial distance or are constant with spatial distance. Some researchers have argued that the time required for a shift of attention does not depend on the distance over which attention must be shifted (Remington and Pierce, 1984). Other researchers have argued that the movement of attention is, nonetheless, an analogy of a moving spotlight in a constant velocity, so that the shift of attention for a longer distance should take much more time than for a shorter distance (Shulman et al., 1979; Tsai, 1983). Our findings support the latter argument. As far as shifting attention from the abrupt-onset distractor location to the target location is concerned, it takes a longer time for a long distance than for a short distance. Therefore, the farthest distractors seem to cause the largest interruption of identification target in the centrally cued location.

In the connectionist model, competition in the stage of location coding occurs when visual input flows upward to the output units corresponding to different cueing locations but before the WTA process starts. As described earlier, the activation of the gating units is decided by both bottom-up and top-down information. In the receptive field of a particular output unit, the farthest abrupt onsets (bottom-up influences) tend to activate different gating units from those receiving the top-down bias. In other words, top-down and bottom-up influences tend to “support” different groups of gating units, respectively. Once the WTA process starts, two opponent groups of gating units compete with each other for the winners. If the group supported by the distractor wins, the selected (facilitatory) zone will be contracted around the distractor as if the receptive field had shrunk to the distractor location. Thus, the distractor location will be processed more
preferentially than the centrally cued location. As a result, when the target occurs in the cued location, the reaction times to the target identification are slowed down.

Relatively, the abrupt onset near the centrally cued location causes less interference of processing the target, because both top-down and bottom-up influences tend to activate the same group of gating units. As a result of the WTA operations, the selected zone is contracted around the cued location. In fact, as we see in some subjects' data, the nearest distractor might, on the contrary, facilitate the processing of the target in the cued location because of the additional alerting effect of the abrupt flash.

We have tried to use a connectionist model described in the discussion of Chapter 3 to simulate the competitive processes described above. When the central cue pointed to the leftmost location and the distractor appeared in the farthest location, the facilitatory zone in the model shifted far away from the cued location, compared to Figure 5. Figure 17 shows this connectivity pattern of the facilitatory zone in the receptive field of the cued location. When the central cue pointed to the leftmost location and the distractor appeared in the nearest location, the facilitatory zone appeared still around the cued location. Figure 18 shows this connectivity pattern. The simulation process in detail is presented in Appendix B.

As a result of simulation, the mean activation of the output unit for the target was a monotonically decreasing function of spatial separation between cued and distractor locations. The empirical RT data from the left and right visual fields were combined according to spatial separation between cued and distractor locations. In contrast, the empirical RT was a monotonically increasing function of spatial separation between cued
and distractor locations. A linear fit of activation (A) onto RT, $F(1, 3) = 26.4, p < .02, R^2 = .898$, took the form:

$$RT = 46.6(1 - A) + 645$$  \hspace{1cm} (6.1)

The estimated RTs are graphed in Figure 19. The agreement between simulated and empirical data suggests that the nature of competition between a central cue and an abrupt-onset distractor may be an emergent property of interactive activation of the bottom-up visual input and the top-down bias throughout the visual information processing system.
CHAPTER 7

GENERAL DISCUSSION AND CONCLUSION

7.1 A summary of experimental findings

The pattern of RT costs and benefits in Experiment 1 showed that the cued location was enhanced and the uncued locations were inhibited in general. This result is consistent with other spatial cueing experiments by Downing and Pinker (1985), Egly and Homa (1991), and Handy, et al. (1997). More specifically, in endogenous orienting, facilitation decreased with increasing distance from the cued location within the spatial extent of 4.9 degrees. Comparing the patterns between exogenous and endogenous cueing conditions, it is found that there is a differential effect of exogenous and endogenous cues on the spatial distribution of visual attention. The first difference is that there is a distance effect in the spatial distribution of attention following an endogenous cue, whereas the distance effect is not manifested in exogenous orienting. This finding is consistent with Umilta, et al. (1991). The second difference is that the inhibitory component seems to be less strong in exogenous orienting than in endogenous orienting.

Experiment 2 further manipulated the luminance values in the abrupt-onset feature. The bright peripheral flash was two times brighter than the dim one against a gray
background. The index of costs was computed by subtracting the RTs of valid trials from the RTs of invalid trials. The results showed that the RT costs of the uncued locations in the bright-cue condition were about the same as in the dim-cue condition. However, the overall reaction times for identification of the targets in the bright-cue condition seemed to be quicker than in the dim-cue condition.

Experiments 3, 4, and 5 explored the issue regarding the nature of interaction between a central cue and an irrelevant peripheral onset. We manipulated the cue-to-distractor SOA, assuming that competition between distractor and cue could occur in two information-processing stages. The first stage occurs in location coding of the central cue. The second stage occurs in attention allocation. In addition, the cue-to-target SOA was also varied across Experiments 3, 4, and 5 in order to keep the exogenous distractor-to-target SOA at a level where exogenous cueing effects have been shown to be optimal.

At the beginning of each trial, a line cue pointed to either the rightmost or the leftmost location. Following a brief interval (i.e., SOA), an abrupt flash occurred in any location other than the centrally cued location. The reaction times to identification of the targets were measured (the letter “E” and “F” in Experiments 3 and 4 or the letter “F” and “L” in Experiment 5). If the peripheral distractor overrides the central cue, the reaction times to the target in the cued location will be slowed down. The index of interruption was computed from reaction times differences between two subsets of cue-valid trials: one without distractors and the other with distractors in different locations.

Experiment 3 found that when the cue-to-distractor SOA was over 200 ms, the nearest distractor produced the largest interruption. Experiment 4 found that when the cue-to-distractor was 100 ms, the farthest distractor produced the largest interruption as the left
visual field was centrally precued, but the nearest distractor still produced the largest interruption when the right visual field was centrally precued. Experiment 5 found that when the cue-to-distractor SOA was only 84 ms, the farthest distractor produced the largest interruption in each visual field. In addition, a new data set combining the data of Experiments 3 and 5 was analyzed by a split-plot ANOVA. The cue-to-distractor SOA was a between-subjects factor. Two within-subjects factors were the cued location and spatial separation between the cued location and the distractor. The results showed that the only significant effect was interaction of the cue-to-distractor SOA and spatial separation between the cued location and the distractor, $F(3, 96) = 8.58, p < .001$, indicating that whether the farthest or the nearest distractor produced the largest interruption depended on the cue-to-distractor SOA.

A connectionist model was built up from two components in Tsotsos' (1993) model: a pyramidal architecture of the network and the winner-take-all algorithm. There are two important aspects of information processing implemented in the model. First, the exogenous cue provides bottom-up information and the endogenous cue provides the top-down bias. Second, those two types of information activate interactively the gating units in the WTA network. In the model, the differential effect of exogenous and endogenous cues in the spatial distribution of attention is ascribed to the bottom-up versus top-down processes. The competition between a central cue and a peripheral onset is ascribed to interactive activation of bottom-up visual inputs and the top-down bias throughout the visual system.

The model was fit to the empirical data of Experiment 1 with connection weights in the WTA network and biases as free parameters. The fit was quite good, with $R^2 = .93$. For
subsequent experiments the parameter values estimated for experiment 1 were used. The model also fit the data of Experiment 5 well. $R^2$ is 90%, which is also the index of cross-validation. This suggests that the WTA algorithm and interactive activation of bottom-up and top-down information may be involved in the neural computation associated with the competition between cue and distractor. However, the model poorly fit the data of Experiment 3. $R^2$ is 67%. Something is still missing in the model. In addition to the cue-to-distractor SOA, a temporal aspect in the experiment, the exogenous distractor-to-target SOA, seems to be crucial as well. However, this aspect is not addressed in the model.

7.2 Selective mechanisms

Logically, visual selection can be accomplished by one of three possible algorithms. The first algorithm is to enhance the relevant locations and inhibit the irrelevant locations at the same time. The second algorithm is to enhance the irrelevant locations while leaving the irrelevant locations unchanged. The third algorithm is to inhibit the irrelevant locations while leaving the relevant locations unchanged. Some metaphors of selective attention, such as a spotlight and a zoom lens, posit the second algorithm. Some metaphors, such as a gate or a filter, seem to utilize the third algorithm. According to the results of Experiment 1, the selective mechanisms in visual attention include two components: facilitation and inhibition. The algorithm of selection is to enhance the cued locations and to inhibit the uncued locations in the location-cueing tasks. The difference between stimulus-driven and goal-driven selection may lie in the value of a parameter in the inhibitory component.
In addition, different stimulus displays may induce different attentional strategies. For example, Hughes and Zimba (1985) found that attention selected an entire hemifield of the cue and strongly inhibited the other hemifield of no cue in a blank visual field. Because there is no potential interference of distractors present in a blank field, the facilitation area may become as broad as possible to include the target. However, the stimulus display that we used marks the “nontarget” locations (i.e., boxes) surrounding the cued location. These “nontarget” locations may exert a potential to distract attention from the most likely target location. If so, a facilitation area should be contracted to some extent to exclude these “nontarget” locations. As a result, we found that a facilitation gradient was limited within 4.9° visual field surrounding the cued location. Beyond 4.9° visual field is an inhibition area.

On the other hand, Cepeda, Cave, Bichot, and Kim (1998) tested the spatial distribution of attention when distractors are physically present together with the target and impose interference on the target. The task that they used is pretty similar to a visual search task. The stimulus display contained a single digit of the target color and three digits of the distractor color. The subjects were required to report the target. Following a brief interval, the search display disappeared and a probe stimulus appeared at different locations in the display. The results showed that response times were faster for probes at the location of the target digit than at the locations of distractor locations. Most important, probes at blank locations between digits produced even faster responses than at the location of the target digit, indicating that selection was accomplished by inhibiting distractor locations but not other areas. These results suggest that the algorithm of
stimulus-driven selection is mainly to inhibit the distractor locations without the necessity of facilitation.

However, in the exogenous orienting task, we found that stimulus-driven selection is mainly in the form of facilitation of the cued location, together with a small amount of inhibition. The finding is quite on the contrary to Cepeda, et al.'s (1998). One possible reason is that the present interference of distractor features in their task induces a strong inhibitory mechanism, whereas a target occurs in each location equally often in the exogenous cueing task and thus the uncued locations may not be inhibited strongly.

In sum, the algorithm of the selective mechanism is quite flexible and adaptable. The utilization of each algorithm depends on the different experimental settings. In the situation of detecting a target with concomitant distractor features, the attention system may choose to use the algorithm suggested by Cepeda, et al. (1998). On the other hand, in the situation of detecting a target without concomitant distractors, the attention system may choose to use another algorithm suggested by our findings.

7.3 Competitive mechanisms of selection

The competitive mechanisms of stimulus-driven and goal-directed selection can function in two information-processing stages of a central cue. Stimulus-driven selection is an automatic process, so it may interfere with the controlled process of location coding or with the process of attention allocating, depending on the dynamics between two types of selective processes. When the irrelevant abrupt onset occurs 200 ms after the onset of a central cue, the nearest abrupt-onset distractor produces the largest interruption in identification of the targets at the cued location. On the other hand, when the irrelevant
abrupt onset occurs 84 ms after the onset of a central cue, the farthest abrupt-onset
distractor produces the largest interruption in identification of the targets at the cued
location.

From the information-processing perspective, when the cue-to-distractor SOA is short,
the process of location coding suffers. At that moment, attention is in diffuse mode
because the orienting system does not know where to focus. Attention is then shifted to
the distractor location. The shift of attention from the distractor to the target location
delays processing of the target. From the neural computation perspective, the competitive
mechanisms occur in the computation for dividing the resources of the receptive field. In
the connectionist model, when the farthest distractor competes with the central cue, the
facilitatory zone tends to be contracted around the distractor, instead of the cued location.
As a result, processing of the target is slowed down due to lacking the processing
resources.

When the cue-to-distractor SOA is long, the distractor is likely to disrupt the process of
allocating attention. Because a gradient of facilitation is formed around the cued location,
the distractor nearest the cued location has the most power to distract attention from the
cued location. The deviation of attention causes the delay of processing the target. From
the neural computation perspective, the competitive mechanisms occur in the competition
for the receptive fields between the distractor and the cued locations. The receptive field
of the nearest distractor overlaps with that of the cued location in a larger part, so the
nearest distractor is most likely to deprive the cued location of the resources of its
receptive field.
In general, the results of our experiments showed that the irrelevant abrupt onset can override central cues that have 75% predictive validity. This finding is consistent with Muller and Rabbitt (1989), and Yantis and Jonides (1990). Previous research concluded that whether the abrupt-onset distractor can override the central cue depends on the spatial certainty of the central cue. In addition, our findings suggest that the temporal dynamics may define a new nature of interaction between goal-directed and stimulus-driven selection.

7.4 The time course of visual attention

The location coding of an endogenous cue takes about 84-100 ms. Based on this finding, we can infer that attentional orienting in response to an endogenous cue must take 84-100 ms longer to occur than in response to an exogenous cue. If the same, and not separate, mechanisms are involved in endogenous and exogenous orienting, there should be a difference of about 84-100 ms in the time course of attentional deployment between two types of cues. However, it has generally been found that an optimal performance following an endogenous cue occurs about 175-200 ms later than following an exogenous cue (e.g., Muller and Rabbitt, 1989; Cheal and Lyon, 1991). This evidence indirectly indicates that an exogenous cue and an endogenous cue induce separate attentional mechanisms, respectively. One mechanism responds automatically to an exogenous cue and draws attention rapidly; the other responds voluntarily to an endogenous cue and requires a longer time to recruit the attentional resources.
7.5 Neural networks of visual attention

The connectionist model suggests that the nature of interaction between a central cue and a peripheral onset may be an emergent property of interactive activation of bottom-up visual inputs and the top-down bias throughout the visual information processing system.

In the visual system, visual information is processed by two parallel pathways: the dorsal system specialized for the processing of spatial location and movement detection; and the ventral system specialized for the processing of primitive features related to color and pattern (Mishkin et al., 1983). On the cortical level, the dorsal system runs from visual area 2 (striate cortex) to inferior parietal cortex, whereas the ventral system runs from visual area 2 to inferior temporal cortex. Finally, both pathways have further connections to the frontal lobe.

Interestingly, the parietal lobe is said to be responsible for attention orienting because visual neglect, an abnormality of spatial orienting, is in particular associated with a lesion of the right parietal lobe. In the location-cueing task, directionality of a central cue must be encoded and stored in working memory that is associated with the prefrontal lobe (Goldman-Rakic, 1987). Working memory is also responsible for sending the top-down bias to the orienting system.

Taken together, we speculate that the neural network of spatial attention may be in the dorsal system, including the parietal lobe and the frontal lobe. There is indirect evidence to support this hypothesis regarding the neural bases of spatial attention. First of all, the results of Experiment 2 showed that the abrupt-onset feature, and not luminance of the
flash, was used to trigger the orienting system. The dorsal system is selective for movement detection and highly sensitive to the contrast. The ventral system is selective for form and color. Therefore, the abrupt-onset information can be perceived best by the dorsal system, instead of the ventral system. In addition, even the low contrast flash can be perceived very well because the dorsal system has high contrast sensitivity. This may be the reason why the bright and dim cues do not cause any difference in terms of the costs to the uncued locations. Secondly, the lesions of brain structures, including parietal cortex, frontal cortex, and cingulate cortex, can produce varying degrees of neglect syndrome. Therefore, Mesulam (1981) proposed a network model of attention, which contains these three cortical regions. Thirdly, Alivisatos and Milner (1989) compared patients with unilateral frontal lesion and normal subjects or control subjects with temporal lesions in a location-precuing experiment. Subjects were required to follow a centrally presented cue and to perform a choice reaction time task. They found that patients with frontal lesions showed significantly less benefit from the location precues than did either normal subjects or subjects with temporal lesions.

In sum, the neural network of spatial attention may involve the entire visual pathways, especially in the dorsal system. More specifically, parietal cortex and frontal cortex both may be the neural substrata for attentional orienting. Frontal cortex may in particular be involved in endogenous orienting because frontal cortex can exert a top-down influence. Parietal cortex may in particular be involved in exogenous orienting because the cells in parietal cortex are selective for movement detection.
7.6 Conclusions

The data from the present research, in conjunction with those from previous studies, converge on the following conclusions regarding covert visual orienting: (a) The algorithm of visual selection is adaptive to the different tasks. Observers perform the location-precuing task using an algorithm that is to enhance the cued location and inhibit the uncued locations. (b) The distribution of spatial attention following an endogenous cue is mediated by the spatial distance from the cued location, whereas attention is more narrowly focused on the cued location when directed by an exogenous cue. (c) The exogenous orienting in response to a peripheral flash is mainly triggered by the abrupt-onset feature of the flash, rather than by its luminance. (d) An irrelevant peripheral flash can override a central cue with 75% predictive validity. Furthermore, the extent to which an abrupt-onset distractor will override a central cue depends on interaction of the cue-to-distractor SOA and spatial distance between the cued location and the distractor.

7.7 Implications

The nature of interaction between stimulus-driven and goal-directed selection manifested in this research has some implications for the theories of visual search. It is generally agreed that visual search involves two stages: a preattentive stage for the parallel processing of basic features and an attentive stage for further processing of the selected item in an item-by-item fashion. Wolf (1994) claims that preattentive parallel search is guided by specific foreknowledge of a target stimulus. Folk, Remington, and Wright (1994) also suggest that visual search does not occur in a purely stimulus-driven
fashion, but is contingent on attentional control settings (top-down control). However, Theeuwes (1992) claims that visual selection is completely stimulus driven. Our findings further suggest that interaction of stimulus-driven and goal-directed selection is constrained by temporal dynamics and the spatial distance between the two sources of selection. The specification of these constraints in visual selection may help better understand the visual search tasks that we face in everyday life.

In addition, the finding that the location coding is a key element for endogenous orienting may have some implications in the clinical field. Because the location coding of a central cue is vulnerable to interruption by a distractor, a syndrome of attention deficit—distractibility—may be associated with difficulties in spatial information processing. Any damage involving in the dorsal system, particularly on the cortical level, may cause attention deficit. Interestingly, in addition to the visual system, location information can also be processed through the auditory system. The location coding via the auditory system may be able to compensate for the disability of the visual system in endogenous orienting. Thus, it will be also interesting to explore the interaction of auditory and visual attention systems.

7.8 Directions for future research

A significant problem remains to be solved is to find a decision criterion for choosing a winner in the race between two receptive fields. How to simulate the parallel computation involved in competition between two receptive fields seems to be another significant problem to be investigated next. The solution may improve the model's performance. In addition, incorporating the current neurophysiological findings of what is the competitive
mechanism of two receptive fields will help to identify the missing processes in the connectionist model.

Another direction of research goes to the issue regarding the cross-modal control of attention. Recent evidence reveals that there is a link between auditory and visual attention systems. For example, Spence and Driver (1996) show that endogenous covert orienting through the auditory system can facilitate the processing of visual targets. A question of interest is: can the abrupt flash disrupt the facilitation of a visual target through auditory orienting? The answer to this question may give a more complete picture of human attention system.
APPENDIX A

SIMULATION OF ENDOGENOUS AND EXOGENOUS ORIENTING

Endogenous orienting includes two information-processing stages. In the stage of location coding, information traverses upward. An endogenous cue provides a top-down signal to the bias units \( (B_i) \). Synchronously, visual input \( (I) \) flows upward from the bottom to the top layer. Simply, \( I_{\text{output}} = \sum I_{\text{input}}W_{io} + \text{bias} \). The WTA does not function at this stage so that visual input can pass directly to the next higher layer successively. The activation of the gating unit \( (G_i) \) at layer \( i \) is \( I_{i-1}B_i \).

Location information of a cue is encoded in working memory, which in turn sends the signal to the bias units. Because \( I_{i-1} \) is constant, the bias units \( (B_i) \) can have influences on which specific input will be selected within the receptive field of the output unit. This reflects the top-down process.

An exogenous cue does not provide the top-down bias, so the biases are constant. However, some specific input units \( (I) \) at the cued location will be activated much more than others. The gating units \( (B*I) \) will have a memory trace of the strength of the interpretive units. This reflects the bottom-up processing.

In the stage of attention allocating, information traverses downward. The WTA network starts to operate. The output unit at the top layer with the maximum activation
will be selected as the global winner (for example, if the leftmost box is precued, the corresponding output unit for the leftmost location will have the maximum activation because that unit receives the largest top-down bias). In turn, the global winner will activate the WTA process that operates only over its direct inputs. As a result, any branches of the network that do not contribute to the global winner will be pruned from the receptive field (i.e., attenuation of connection weights). This pruning process is then applied successively to the lower layers. The formation of a connectivity pattern at the end of this stage is a preparatory state (LaBerge, 1995) for the occurrence of the target.

Assumptions

1. The interpretive units are arranged in one-to-one correspondence to the gating units. In other words, the gating units preserve a spatial relationship with the interpretive units in the layer below.

2. The directionality of an endogenous cue is encoded in a coarse fashion described as follows. When the endogenous cue points to the rightmost location (location 1), the three gating units in the WTA network (see Figure 4), G_1, G_2, and G_3, will be given a larger bias than the rest. When the cue points to location 2, G_2, G_3, and G_4 will get a larger bias than the rest, and so forth. When the cue points to the leftmost location, G_5, G_6, and G_7 will get a larger bias than the rest.

3. When the cue points to the X-th location, the X-th output unit at the top layer will receive a larger bias than the rest.

4. The activation function of the units in the top layer and the layer below is:

\[ f(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \]  

(A.1)
where $x$ represents a net input in the range of $0 \rightarrow +\infty$. The output of this function is between 0 and 1. In addition, the units in the layer above the bottom layer have a linear activation function, i.e., $f(x) = x$. 

5. The preparatory state of the network will decay at the end of each trial and will not be transferred to the next trial.

**Simulation processes**

The simulation processes are implemented by C++ programming in a 586 PC running LINUX. More specifically, the entire simulation can be summarized as follows.

**Step 1.** Visual input ($I_i$) is generated at random from a uniform distribution ranging from 0.1 to 0.9, and then is fed into the entire network. However, visual input corresponding to a peripheral cue is given a value of 100. The connection weights, $W$, are selected at random from a uniform distribution ranging from 0.1 to 0.4. The signals traverse upward to the output units. The activation of each output unit at each layer is simply $\sum I_i W_{ij} + \text{bias}$. 

**Step 2.** The top-down bias ($B_i$) is generated and input to each gating unit according to the location of endogenous cueing. The augmented bias is given a value from a normal distribution (mean = 5, SD = 1) and others are selected at random from a uniform distribution ranging from 0.1 to 0.9. The strength of gating units ($G_i$) is computed by $B_i * I_{i+1}$. For the neutral condition, all bias values are selected at random from a uniform distribution ranging from 0.1 to 5.

**Step 3.** As soon as this upward traversal is finished (from input to output), the WTA process in each layer starts to operate from top to bottom. The connection weights in the WTA network is initialized at random from a uniform distribution ranging from 0.1 to
0.2. Six iterations are executed in each WTA process. As a result, the gating units are partitioned into two classes: those with a zero value and those with a non-zero value (winners). Only the interpretive units connecting to the winners will be selected. In the receptive field of a selected unit, the weights of winning connections are augmented by a factor of 10 and the weights of losing connections are discounted by a factor of 0.1. The weights of other connections outside the receptive field of winning units are left unchanged (ignored area). An example of resultant connectivity pattern at the end of this step is graphed in Figure 20.

The following is a trace of gating units when the leftmost location is precued endogenously. The number of each interpretive unit is referenced to the number shown in Figure 20.

**for the selected unit at layer 4:**

<table>
<thead>
<tr>
<th></th>
<th>G7</th>
<th>G6</th>
<th>G5</th>
<th>G4</th>
<th>G3</th>
<th>G2</th>
<th>G1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st iteration</td>
<td>20.66</td>
<td>16.45</td>
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<td>1.10</td>
<td>2.32</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3rd iteration</td>
<td>20.66</td>
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<td>8.15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4th iteration</td>
<td>20.66</td>
<td>13.42</td>
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<tr>
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<tr>
<td>6th iteration</td>
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<td>11.17</td>
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**for the selected units at layer 3:**

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<th>G5</th>
<th>G4</th>
<th>G3</th>
<th>G2</th>
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<tr>
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<td>8.58</td>
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<td>0</td>
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<tr>
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<td>6.08</td>
<td>10.38</td>
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**Unit 3**

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<tr>
<td>3rd iteration</td>
<td>8.76</td>
<td>7.12</td>
<td>8.78</td>
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</table>
4th iteration 8.76 6.08 8.78 0 0 0 0
5th iteration 8.76 5.34 8.78 0 0 0 0
6th iteration 8.75 4.40 8.78 0 0 0 0

for the selected units at layer 2:

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<th>G5</th>
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<th>G1</th>
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</thead>
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<td>0.68</td>
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<td>0.71</td>
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<td>0</td>
</tr>
<tr>
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<td>5.67</td>
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<td>0.77</td>
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<td>0.27</td>
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<td>2.41</td>
<td>6.14</td>
<td>5.70</td>
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</tr>
<tr>
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<td>5.63</td>
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<td>0</td>
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</tr>
<tr>
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<td>0</td>
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<td>5.55</td>
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<td>0</td>
</tr>
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<td>5.35</td>
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</tr>
<tr>
<td>6th iteration</td>
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<td>6.14</td>
<td>5.23</td>
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</tbody>
</table>

<table>
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<tr>
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<th>G7</th>
<th>G6</th>
<th>G5</th>
<th>G4</th>
<th>G3</th>
<th>G2</th>
<th>G1</th>
</tr>
</thead>
<tbody>
<tr>
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<td>4.99</td>
<td>0.55</td>
<td>0.31</td>
<td>0.32</td>
<td>0.51</td>
</tr>
<tr>
<td>1st iteration</td>
<td>4.39</td>
<td>2.14</td>
<td>4.99</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2nd iteration</td>
<td>4.30</td>
<td>1.20</td>
<td>4.99</td>
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<td>0</td>
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<td>0</td>
</tr>
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<td>3rd iteration</td>
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<td>4.99</td>
<td>0</td>
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<td>0</td>
<td>0</td>
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<tr>
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<td>0</td>
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<td>5th iteration</td>
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<td>4.99</td>
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<td>0</td>
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<tr>
<td>6th iteration</td>
<td>3.82</td>
<td>0</td>
<td>4.99</td>
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<table>
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<th>G6</th>
<th>G5</th>
<th>G4</th>
<th>G3</th>
<th>G2</th>
<th>G1</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.72</td>
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<td>4.81</td>
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</tr>
<tr>
<td>2nd iteration</td>
<td>2.16</td>
<td>7.03</td>
<td>4.44</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3rd iteration</td>
<td>1.21</td>
<td>7.03</td>
<td>4.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4th iteration</td>
<td>0.08</td>
<td>7.03</td>
<td>3.49</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5th iteration</td>
<td>0</td>
<td>7.03</td>
<td>2.89</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6th iteration</td>
<td>0</td>
<td>7.03</td>
<td>2.19</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Step 4. When the target appears, the corresponding input units are activated with strength of one and the rest of input units only have their rest activation with strength of 0.1. For example, assuming the target appears in the most lateral location, the input vector would be: 1, 1, 1, 1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1,
0.1, 0.1. This input vector is fed into the entire network. The activation of each output unit represents the response to the target at the different locations. Note that we assume that the letter 'P' and 'B' both have the same input pattern (1,1,1,1) because the different pattern ('1,1,0,1' for 'P' and '1,1,1,0' for 'B') seems to produce a similar result.

In the simulation of exogenous orienting, the corresponding visual input units will be activated with strength of 100. We assume that position information of the exogenous cue will be stored in working memory, which in turn sends a bias to the corresponding output unit. The simulation then follows step 3 and step 4, except that there is no top-down bias signal provided to the gating units and the weights of losing connections are not attenuated.

In the simulation of neutral conditions, because the cue does not contain any information of a target location, all biases are given a random value. We assume that each output unit has equal probability to be selected as a winner. The WTA processes are similar to those in the valid condition.

**Results**

The results are summarized in Table 6 through 9. Each data point is the mean of 50 trials. The value in each cell represents the activation of the output unit. The calculation of cost/benefit is the same as of reaction times. The cost/benefit of activation fits linearly to the empirical RT data. $R^2 = .93$ for endogenous orienting; $R^2 = .94$ for exogenous orienting.

**Network behaviors**

Since the WTA process is an important principle in the model, one may ask why the WTA process is implemented in every layer except for the input layer. To answer this
question, we have explored the network behaviors by having the WTA process implemented in just one layer or two layers, instead of every layer. The results regarding the simulation of endogenous orienting are summarized as follows (see Figure 21). (1) If the WTA is implemented only in layer 3, the model is unable to resolve the cued location because the model tends to produce the largest response at the uncued location. (2) If the WTA is implemented in the output layer (layer 4), the model has difficulties in producing the gradient pattern of activation. (3) If the WTA is implemented only in layer 3 and layer 4, the model also has difficulties in producing the gradient pattern of activation.

The results suggest that implementing the WTA process at each layer is necessary for the neural network model to produce an activation pattern that qualitatively matches the RT results.

**Limitation of the model**

The model is not built for simulating the accuracy data because the model is not trained to perform the letter discrimination task. In addition, the features of each target letter are not well represented in the model because only four units are designed for representing the visual input of a letter. In the simulation, the input pattern, “1,1,1,1”, represents the presence of a target. The input pattern, “1,1,1,0”, is not different from another input pattern, “1,1,1,1”, in terms of the simulation results.
APPENDIX B

SIMULATION OF COMPETITION BETWEEN CUE AND DISTRACTOR

B.1. Simulation of Experiment 3

The parameter values, such as connection weights in the WTA network, bias values, and visual input of an exogenous cue, are the same as those used for the simulation of endogenous orienting in Appendix A. The connection weights between any two interpretive units are kept in the same range as previously used.

The simulation process is almost the same as the previous one in Appendix A, except that visual input corresponding to the distractor enters when information in the receptive field of the cued location begins to flow downward. A new algorithm is implemented to determine whether the receptive field of the cued location or that of the distractor will finish the WTA computation at first.

First of all, information traverses upward and the top-down influences enter. When information starts to flow downward, visual input for the distractor enters and flows upward. The gating units are activated by adding up information from two competitive sources at different time: top-down bias and bottom-up information. Because those two sources are from different locations, they will contribute to the gating units in different
position respectively. As information traverses downward, the WTA computation for the cued location leads four iterations ahead of the WTA computation for the distractor. After two more iterations, if the number of non-zero gating units in the WTA network of the cued location is still larger than that in the WTA network of the distractor, then the receptive field of the cued location loses the race. In other words, the WTA computation for the distractor is resolved more quickly. Consequently, the receptive field of the distractor gains the control. A facilitation zone is then formed in the receptive field of the distractor. As a result, the activation of the output unit for the target will be very weak because the target occurs in the cued location, instead of the distractor location. Figure 22 is an example of the simulation results for this case.

In the other case, if the number of non-zero gating units in the WTA network of the cued location is not larger than that in the WTA network of the distractor, then the receptive field of the cued location wins the race. In other words, the WTA computation for the cue is resolved more quickly. Consequently, the receptive field of the cue gains the control. A facilitation zone is formed in the receptive field of the cued location. As a result, the activation of the output unit for the target will be very strong because the target occurs in the cued location. Figure 23 is an example of the simulation results for this case.

100 times of simulation are run for each spatial separation between cued and distractor locations. The mean activation of the output unit for the target location is linearly fit to the empirical RT data collapsed from the left and right visual fields. $R^2$ equals to .675. The simulation results are presented in Table 10 and Table 11. One possible reason for this poor fit is that the distractor also does some damage to the receptive field of the cued
location even though the receptive field of the distractor loses to the receptive field of the cued location (See Figure 14). This side effect of the distractor is related to the competition between cue and distractor at the earlier stage.

**B.2. Simulation of Experiment 5**

The parameter values are the same as those used in the previous one. The simulation process is almost the same as the previous one in Appendix A, except that visual input corresponding to the distractor enters the network along with the top-down bias simultaneously. When information traverses upward, the gating units are activated from two competitive sources at the same time: top-down bias and bottom-up information. Because those two sources are from different locations, they will contribute to the gating units in different position respectively. As information traverses downward, the gating units supported mostly by the bottom-up influences will compete with those supported mostly by the top-down bias to be selected as winners through the WTA processes. The simulation results are presented in Table 12 and Table 13. The value in each cell represents the activation of the output unit for the target location, which is the mean of 50 trials. The activation data are linearly fit to the empirical RT data. $R^2$ equals to .898.

**A possibility to simulate error rates**

Though the model was originally not intended to model discrimination of one target letter from the other, the activation pattern of each output unit from this simulation (see Figure 22) may shed some light on a positive correlation between error rates and reaction times. As Figure 22 shows, the maximum activation sometimes occurs at the output unit for the distractor location, instead of the output unit for the cued location, when the target
occurs in the cued location. Assuming that the response is determined by the output unit with a maximum activation, errors will be very likely to be made because that unit does not contain any information about the target. Under such circumstances, response times may become longer, rather than shorter, because of competition for action between those two output units corresponding to the cued and distractor location respectively.
### Table 1. Number of trials per block for each combination of cued and target locations in Experiment 1. In the exogenous cueing session, trials in which the cue occurs in location 3 and location 4 are not analyzed.

<table>
<thead>
<tr>
<th>Target location</th>
<th>Cue location</th>
<th>Exogenous cueing session</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>35&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> the validity of an endogenous cue is 70%.

<sup>b</sup> the validity of an exogenous cue is 16.7%.

Note. Cue and target location numbers (1 - 6) correspond to the six display locations used in the experiment, as can be seen in Figure 1.
<table>
<thead>
<tr>
<th>Cued location</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Rightmost)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Endogenous cueing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rightmost</td>
<td>5.9</td>
<td>7.1</td>
<td>9.8</td>
<td>13.0</td>
<td>14.5</td>
<td>12.6</td>
</tr>
<tr>
<td>Leftmost</td>
<td>6.3</td>
<td>7.2</td>
<td>12.3</td>
<td>11.7</td>
<td>9.5</td>
<td>10.4</td>
</tr>
<tr>
<td>Neutral</td>
<td>5.7</td>
<td>12.5</td>
<td>9.4</td>
<td>12.2</td>
<td>9.9</td>
<td>12.2</td>
</tr>
<tr>
<td>Exogenous cueing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rightmost</td>
<td>18.2</td>
<td>20.0</td>
<td>27.6</td>
<td>23.4</td>
<td>22.8</td>
<td>23.2</td>
</tr>
<tr>
<td>Leftmost</td>
<td>18.1</td>
<td>21.0</td>
<td>19.3</td>
<td>21.5</td>
<td>23.7</td>
<td>26.3</td>
</tr>
<tr>
<td>Neutral</td>
<td>20.2</td>
<td>25.5</td>
<td>28.2</td>
<td>26.1</td>
<td>26.1</td>
<td>22.8</td>
</tr>
</tbody>
</table>

Table 2. The mean percentages of errors for Experiment 1 as a function of cueing locations, target locations and cueing type. Target locations are labeled 1 through 6 from the rightmost to the leftmost.
### Table 3

<table>
<thead>
<tr>
<th>Distractor location</th>
<th>Rightmost (1)</th>
<th>Leftmost (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>594 9.5</td>
<td>618 8.5</td>
</tr>
<tr>
<td>2</td>
<td>640 9.7 46</td>
<td>640 6.1 22</td>
</tr>
<tr>
<td>3</td>
<td>615 9.9 21</td>
<td>641 9.3 23</td>
</tr>
<tr>
<td>4</td>
<td>615 9.4 21</td>
<td>648 9.0 30</td>
</tr>
<tr>
<td>5</td>
<td>619 9.2 25</td>
<td>674 7.2 56</td>
</tr>
</tbody>
</table>

Note. Cue and distractor location numbers (1 – 6) correspond to the six display locations used in Experiment 3, as can be seen in Figure 10.

Table 3. Mean Reaction Times (RTs; in Milliseconds), Percent Errors (PE) and Interruption Index (II; in Milliseconds) for each combination of the endogenous cueing location and the abrupt-onset distractor location in Experiment 3.
<table>
<thead>
<tr>
<th>Distraction location</th>
<th>Rightmost (1)</th>
<th></th>
<th></th>
<th></th>
<th>Leftmost (6)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT</td>
<td>PE</td>
<td>II</td>
<td>RT</td>
<td>PE</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>588</td>
<td>9.5</td>
<td></td>
<td></td>
<td>614</td>
<td>8.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>638</td>
<td>12.0</td>
<td>50</td>
<td>668</td>
<td>9.0</td>
<td>54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>629</td>
<td>12.8</td>
<td>41</td>
<td>635</td>
<td>10.7</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>607</td>
<td>8.9</td>
<td>19</td>
<td>632</td>
<td>8.4</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>622</td>
<td>9.6</td>
<td>34</td>
<td>653</td>
<td>9.4</td>
<td>39</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Mean Reaction Times (RTs; in Milliseconds), Percent Errors (PE) and Interruption Index (II; in Milliseconds) for each combination of the endogenous cueing location and the abrupt-onset distractor location in Experiment 4.
<table>
<thead>
<tr>
<th>Distractor location</th>
<th>Rightmost (1)</th>
<th></th>
<th></th>
<th>Leftmost (6)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT</td>
<td>PE</td>
<td>II</td>
<td>RT</td>
<td>PE</td>
<td>II</td>
</tr>
<tr>
<td>None</td>
<td>651</td>
<td>1.6</td>
<td></td>
<td>639</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>666</td>
<td>3.6</td>
<td>15</td>
<td>694</td>
<td>4.3</td>
<td>55</td>
</tr>
<tr>
<td>3</td>
<td>677</td>
<td>2.9</td>
<td>26</td>
<td>683</td>
<td>3.9</td>
<td>44</td>
</tr>
<tr>
<td>4</td>
<td>674</td>
<td>3.9</td>
<td>23</td>
<td>660</td>
<td>3.9</td>
<td>21</td>
</tr>
<tr>
<td>5</td>
<td>697</td>
<td>2.0</td>
<td>46</td>
<td>661</td>
<td>3.0</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 5. Mean Reaction Times (RTs; in Milliseconds), Percent Errors (PE) and Interruption Index (II; in Milliseconds) for each combination of the endogenous cueing location and the abrupt-onset distractor location in Experiment 5.
<table>
<thead>
<tr>
<th>Cue location</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.99&lt;sup&gt;a&lt;/sup&gt;</td>
<td>.45</td>
<td>.17</td>
<td>.13</td>
<td>.08</td>
<td>.04</td>
</tr>
<tr>
<td>6</td>
<td>.04</td>
<td>.08</td>
<td>.12</td>
<td>.16</td>
<td>.42</td>
<td>.99&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Neutral</td>
<td>.24</td>
<td>.29</td>
<td>.32</td>
<td>.35</td>
<td>.32</td>
<td>.25</td>
</tr>
</tbody>
</table>

<sup>a</sup> cue-valid trial

Table 6. The activation of the output unit for the simulation of endogenous orienting.

<table>
<thead>
<tr>
<th>Measure</th>
<th>zero&lt;sup&gt;a&lt;/sup&gt;</th>
<th>one&lt;sup&gt;b&lt;/sup&gt;</th>
<th>two</th>
<th>three</th>
<th>four</th>
<th>five</th>
</tr>
</thead>
<tbody>
<tr>
<td>cost/benefit</td>
<td>.75&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.13</td>
<td>-0.17</td>
<td>-0.21</td>
<td>-0.22</td>
<td>-0.21</td>
</tr>
<tr>
<td>estimated RT (ms)</td>
<td>-25.43</td>
<td>7.26</td>
<td>23.20</td>
<td>25.33</td>
<td>26.13</td>
<td>25.20</td>
</tr>
<tr>
<td>empirical RT (ms)</td>
<td>-23</td>
<td>-0.58</td>
<td>31.37</td>
<td>27.53</td>
<td>24.54</td>
<td>21.82</td>
</tr>
</tbody>
</table>

<sup>a</sup> cue-valid trial.
<sup>b</sup> "one" means one position away, and so forth.
<sup>c</sup> data collapsed from cue location 1 and 6.

Table 7. Continued from Table 6. The mean activation cost/benefit, the estimated RT, and the empirical RT in different spatial distance between cued and target locations.
### Table 8.
The activation of the output unit for the simulation of exogenous orienting.

<table>
<thead>
<tr>
<th>Cue location</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.99&lt;sup&gt;a&lt;/sup&gt;</td>
<td>.24</td>
<td>.24</td>
<td>.23</td>
<td>.17</td>
<td>.08</td>
</tr>
<tr>
<td>6</td>
<td>.08</td>
<td>.16</td>
<td>.24</td>
<td>.24</td>
<td>.26</td>
<td>.98&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Neutral</td>
<td>.32</td>
<td>.34</td>
<td>.35</td>
<td>.34</td>
<td>.34</td>
<td>.32</td>
</tr>
</tbody>
</table>

<sup>a</sup> cue-valid trial

### Table 9.
Continued from Table 8. The mean activation cost/benefit, the estimated RT, and the empirical RT in different spatial distance between cued and target locations.

<table>
<thead>
<tr>
<th>Measure</th>
<th>zero&lt;sup&gt;a&lt;/sup&gt;</th>
<th>one&lt;sup&gt;b&lt;/sup&gt;</th>
<th>two</th>
<th>three</th>
<th>four</th>
<th>five</th>
</tr>
</thead>
<tbody>
<tr>
<td>cost/benefit</td>
<td>.67&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-0.09</td>
<td>-0.10</td>
<td>-0.11</td>
<td>-0.18</td>
<td>-0.24</td>
</tr>
<tr>
<td>estimated RT (ms)</td>
<td>-29.28</td>
<td>4.6</td>
<td>5.27</td>
<td>5.44</td>
<td>8.52</td>
<td>11.36</td>
</tr>
<tr>
<td>empirical RT (ms)</td>
<td>-29.89</td>
<td>4.8</td>
<td>3.1</td>
<td>12.5</td>
<td>6.7</td>
<td>8.7</td>
</tr>
</tbody>
</table>

<sup>a</sup> cue-valid trial.

<sup>b</sup> "one" means one position away, and so forth.

<sup>c</sup> data collapsed from cue location 1 and 6.
Table 10. The activation of the output unit for the simulation of Experiment 3.

<table>
<thead>
<tr>
<th>Cue location</th>
<th>none^a</th>
<th>location 2</th>
<th>location 3</th>
<th>location 4</th>
<th>location 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>location 1</td>
<td>.99</td>
<td>.34</td>
<td>.32</td>
<td>.73</td>
<td>.70</td>
</tr>
<tr>
<td>location 6</td>
<td>.99</td>
<td>.73</td>
<td>.72</td>
<td>.34</td>
<td>.40</td>
</tr>
</tbody>
</table>

^a no distractor

Table 11. Continued from Table 10. The mean activation, the estimated RT, and the empirical RT in different spatial distance between cued and distractor locations.

<table>
<thead>
<tr>
<th>Measure</th>
<th>none^a</th>
<th>one</th>
<th>two</th>
<th>three</th>
<th>four</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean activation</td>
<td>.99^b</td>
<td>.37</td>
<td>.33</td>
<td>.73</td>
<td>.72</td>
</tr>
<tr>
<td>estimated RT (ms)</td>
<td>610.78</td>
<td>644.35</td>
<td>646.29</td>
<td>625.02</td>
<td>625.56</td>
</tr>
<tr>
<td>empirical RT (ms)</td>
<td>606</td>
<td>657</td>
<td>631.5</td>
<td>628</td>
<td>629.5</td>
</tr>
</tbody>
</table>

^a no distractor
^b data collapsed from cue location 1 and 6.
### Table 12. The activation of the output units for the simulation of Experiment 5.

<table>
<thead>
<tr>
<th>Cue location</th>
<th>none&lt;sup&gt;a&lt;/sup&gt;</th>
<th>location 2</th>
<th>location 3</th>
<th>location 4</th>
<th>location 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>location 1</td>
<td>.99</td>
<td>.65</td>
<td>.45</td>
<td>.14</td>
<td>.09</td>
</tr>
<tr>
<td>location 6</td>
<td>.99</td>
<td>.09</td>
<td>.12</td>
<td>.43</td>
<td>.66</td>
</tr>
</tbody>
</table>

<sup>a</sup> no distractor

### Table 13. Continued from Table 12. The mean activation, the estimated RT, and the empirical RT in different spatial distance between cued and distractor locations.

<table>
<thead>
<tr>
<th>Measure</th>
<th>none&lt;sup&gt;b&lt;/sup&gt;</th>
<th>one</th>
<th>two</th>
<th>three</th>
<th>four</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean activation</td>
<td>.99&lt;sup&gt;b&lt;/sup&gt;</td>
<td>.66</td>
<td>.43</td>
<td>.12</td>
<td>.09</td>
</tr>
<tr>
<td>estimated RT (ms)</td>
<td>645.28</td>
<td>660.88</td>
<td>671.58</td>
<td>686.03</td>
<td>687.21</td>
</tr>
<tr>
<td>empirical RT (ms)</td>
<td>645</td>
<td>663.5</td>
<td>668.5</td>
<td>678.5</td>
<td>695.5</td>
</tr>
</tbody>
</table>

<sup>a</sup> no distractor

<sup>b</sup> data collapsed from cue location 1 and 6.

Note. The empirical RTs are the result of Experiment 5.
Figure 1. Spatial arrangement of stimulus display used in Experiments 1 and 2. Each possible target location was labeled by the number in the upper right-hand corner of each box. In the text, each display location was referenced to these numbers which were not included in the actual experimental display. The distance was measured as the shortest line between the center of any two locations. The longest distance between cued and target locations could be $9.3^\circ$. 
Figure 2. The results of Experiment 1 in which either the rightmost or the leftmost location is precued. Targets appear at a 0°, 2.6°, 4.9°, 6.5°, 8.1°, or 9.3° distance from the cued location. The reaction time (RT) cost/benefit to identification of the target is a function of the distance between cued and target locations. The validly cued location is represented by a visual angle of 0°.
Figure 3. A connectionist model described in the text. In the top layer, there are six output units that represent the response to the target in each location. Through the WTA processes, within the receptive field of the selected output unit (for location 5) in the top layer, the textured units and black solid connections are those selected; the dashed connections are those inhibited. The cue is said to produce preparatory attention, including the facilitatory zones (wide black solid lines) and inhibitory zones (dashed lines) around the target location in the brain map.
Figure 4. The WTA network includes seven gating units (in gray) that mutually inhibit one another. The gating units receive signals from both bias units and interpretive units that project to the gating units in a one-to-one mapping. For example, unit I1 projects to unit G1, unit I2 projects to unit G2, and so forth. The function of the gating units is to inhibit “non-winning” inputs at layer I and pass “winning” inputs on to the output unit at layer I+1.
Figure 5. The connectivity pattern in the receptive field of the selected output unit in the top layer. This pattern results from the WTA process when attention is directed to the leftmost location by an endogenous cue. The wide solid lines define a facilitatory zone and the broken lines define an inhibitory zone within the receptive field. The other area (narrow solid lines) is unchanged.
Figure 6. The connectivity pattern in the receptive field of the selected output unit in the top layer. This pattern results from the WTA process when attention is drawn to the leftmost location by an exogenous cue. The textured units represent those which are selected as winners. The wide solid lines define a facilitatory zone and the broken lines define an inhibitory zone within the receptive field. The other area (narrow solid lines) is unchanged.
Figure 7. Simulated data of Experiment 1.
Figure 8. Simulated data for Experiment 2 in which a peripheral flash appeared in the rightmost location (location 1), followed by a target in one of six locations. The activation of the output unit for a target is plotted as a function of target locations.
Figure 9. The results of Experiment 2 in which luminance of a peripheral flash was manipulated. A: The validly cued location is represented by a visual angle of 0°. Reaction times (RT) are plotted as a function of the distance between the flash and target locations. B: The dependent measure is RTs of invalid locations minus RTs of valid locations.
Figure 10. The stimulus display in Experiments 3 and 4. Six black H's were against a gray screen background, arranged along a semicircle with a radius of 5.7°. Each position of H was labeled by the number in the bottom of each H. In the text, each display location was referenced to these numbers which were not included in the actual experimental display.
Figure 11. The stimulus events in one trial with a distractor in Experiment 3. In the cue display, a line pointed to the most lateral location (location 1 for this case), serving as a central cue. In the distractor display, one H (location 5 for this case) was brightened for 50 ms, serving as a distractor.
Figure 12. The results of Experiment 3. A. Mean reaction times of valid trials are a function of distractor locations. B. The interruption of the distractor is a function of distractor locations. C. The interruption of the distractor is a function of spatial distance between the cued location and the distractor.
Figure 13. Simulated data of Experiment 3. Each data point was an average of data collapsed from the left and right visual fields in terms of the cued (or target) location.
Figure 14. The connectivity pattern in the receptive field of the cued location. The central cue pointed to the leftmost location (location 6), followed by a distractor at location 4. The wide black lines define a facilitatory zone in the receptive field.
Figure 15. The results of Experiment 4. A. Mean reaction times of validly cued trials are a function of distractor locations. B. The interruption of the distractor is a function of distractor locations. C. The interruption of the distractor is a function of spatial separation between the cued location and the distractor.
Figure 16. The results of Experiment 5. A. Mean reaction times of validly cued trials are a function of distractor locations. B. The interruption of the distractor is a function of distractor locations. C. The interruption of the distractor is a function of spatial separation between the cued location and the distractor.
Figure 17. The connectivity pattern in the receptive field of the cued location. A central cue pointed to the leftmost location (location 6), followed by a distractor at location 2. The wide black lines define a facilitatory zone in the receptive field, which is contracted around the distractor location.
Figure 18. The connectivity pattern in the receptive field of the cued location. The central cue pointed to the leftmost location (location 6), followed by a distractor at location 5. The wide black lines define a facilitatory zone in the receptive field.
Figure 19. Simulated data of Experiment 5. Each data point was an average of data collapsed from the left and right visual fields in terms of the cued (or target) location.
Figure 20. The connectivity pattern in the receptive field of the selected output unit (in gray) in the top layer. This pattern results from the WTA process when attention is directed to the leftmost location by an endogenous cue. The wide solid lines define a facilitatory zone and the broken lines define an inhibitory zone within the receptive field. The other area (narrow solid lines) is unchanged.
Figure 21. The model behavior in different implementation of the WTA network. The activation of the output unit is plotted as a function of spatial separation between cued and target locations. “1 location” means that the target is one position away from the cued location, and so forth.
Figure 22. An example of simulation results when the receptive field of the cued location loses to that of the distractor. Output unit 1 corresponds to the cued location or the target location. Output unit 3 corresponds to the distractor location and has the largest activation even though the target occurs at location 1.
Figure 23. An example of simulation results when the receptive field of the cued location wins. Output unit 1 corresponds to the cued location or the target location, and has the largest activation. Output unit 3 corresponds to the distractor location.
LIST OF REFERENCES


