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The Flexibility of Attentional Control in Selecting Features and Locations

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**THE FLEXIBILITY OF ATTENTIONAL CONTROL IN SELECTING
FEATURES AND LOCATIONS**

A Dissertation Presented

By

HSIAO-CHUEH EVANS

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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Psychology

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ABSTRACT

THE FLEXIBILITY OF ATTENTIONAL CONTROL IN SELECTING FEATURES AND LOCATIONS

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The visual processing of a stimulus is facilitated by attention when it is at an attended location compared to an unattended location. However, whether attentional selection operates on the basis of visual features (e.g., color) independently of spatial locations is less clear. Six experiments were designed to examine how color information as well as location information affected attentional selection. In Experiment 1, the color of the targets and the spatial distance between them were both manipulated. Stimuli were found to be grouped based on color similarity. Additionally, the evidence suggested direct selection on the basis of color groups, rather than selection that was mediated by location. By varying the probabilities of target location and color, Experiments 2, 3 and 4 demonstrated that the use of color in perceptual grouping and in biasing the priority of selection is not automatic, but is modulated by task demands. Experiments 5 and 6 further investigated the relationship between using color and using location as the selection basis under exogenous and endogenous orienting. The results suggest that the precise nature of the interaction between color and location varies according to the mode of attentional

control. Collectively, these experiments contribute to an understanding of how different types of information are used in selection and suggest a greater degree of flexibility of attentional control than previously expected. The flexibility is likely to be determined by a number of factors, including task demands and the nature of attentional control.

TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	iv
ABSTRACT.....	v
LIST OF TABLES	x
LIST OF FIGURES	xi
CHAPTER	
1. INTRODUCTION	1
Theoretical Accounts of Attentional Selection.....	2
Selection Based on Spatial Property	2
Selection Based on a Nonspatial Property	5
The Influence of Perceptual Grouping on Selection.....	7
The Interactive Account of Perceptual Grouping and Attention	11
Summary of Chapter 1	14
2. DIRECT SELECTION BY FEATURES.....	15
Is Selection Based on Nonspatial Properties Mediated by Location?	15
Space-Independent Hypothesis.....	19
Strategic Selection vs. Automatic Selection.....	23
Summary of Chapter 2.....	28
3. THE RELATIONSHIP BETWEEN SELECTING FEATURES AND LOCATIONS.....	30
The Independent Hypothesis.....	31
The Interactive Hypothesis	34
Endogenous and Exogenous Control of Attention.....	36
Summary of Chapter 3	39
4. THE CURRENT STUDY.....	40

5.	EXPERIMENT 1: THE INFLUENCE OF COLOR GROUPING ON ATTENTIONAL SELECTION.....	49
	Method	51
	Results.....	54
	Discussion.....	55
6.	EXPERIMENT 2: AUTOMATIC OR STRATEGIC USE OF COLOR IN SELECTION.....	59
	Method	60
	Results.....	61
	Discussion.....	62
7.	EXPERIMENT 3: THE FLEXIBILITY OF USING LOCATION AND COLOR IN ATTENTIONAL SELECTION.....	65
	Method	66
	Results.....	66
	Discussion.....	67
8.	EXPERIMENT 4: TOP-DOWN BIAS IN USING COLOR IN SELECTION.....	70
	Method	72
	Results.....	73
	Discussion.....	75
9.	EXPERIMENT 5: THE RELATIOSHIP BETWEEN USING LOCATION AND USING COLOR IN EXOGENOUS ORIENTING	77
	Method	80
	Results.....	81
	Discussion.....	83
10.	EXPERIMENT 6: THE RELATIOSHIP BETWEEN USING LOCATION AND USING COLOR IN ENDOGENOUS ORIENTING	86
	Method	88
	Results.....	89
	Discussion.....	90
11.	GENERAL DISCUSSION	93
	Direct Selection Based on Nonspatial Properties	93
	The Influence of Color Grouping	98

Top-down Perceptual Grouping.....	100
Different Principles of Perceptual Grouping	102
Selection Based on Location Information.....	106
Automatic vs. Top-Down Modulated Selection	110
The Flexibility of Attention	115
APPENDICES	
A. THE TABLES.....	118
B. FIGURE CAPTIONS.....	120
BIBLIOGRAPHY.....	130

LIST OF TABLES

Table	Page
1. Mean reaction times (in milliseconds) and accuracy (percentage) in three conditions for Experiments 1-3.....	118
2. Mean reaction times (in milliseconds) and accuracy (percentage) in four conditions in Experiment 4	118
3. Mean reaction times (in milliseconds) and accuracy (percentage) in four conditions for 376 SOA in Experiment 5	118
4. Mean reaction times (in milliseconds) and accuracy (percentage) in four conditions for 447 SOA in Experiment 5	119

LIST OF FIGURES

Figure	Page
1. Example stimuli in Experiments 1 to 3. The task was to compare if the two digits were in the same or different categories (See text for details). (a) An example of the <i>feature</i> condition in which the two digits shared the same color and were far apart. (b) An example of the <i>far</i> condition in which the two digits were in different colors and were far apart. (c) An example of the <i>near</i> condition in which the two target digits shared the same location and were in different colors. Displays are not to scale in this figure. See text for details.....	120
2. Sequence of events on a trial in Experiments 1 to 3. This example represented a <i>feature</i> trial.	120
3. The four conditions in Experiment 4. The central square served as both the fixation point and the color cue on each trial. (a) An example of the <i>near (invalid)</i> condition. (b) An example of the <i>valid-feature</i> condition. (c) An example of the <i>invalid-feature</i> condition. (d) An example of the <i>far (invalid)</i> condition. Displays are not to scale in this figure. See text for details.	120
4. Sequence of events on a trial in Experiment 4. This example illustrated a <i>valid-feature</i> trial.	120
5. Sequence of events on a trial in Experiment 5. The target appeared at the validly cue location with the validly cued color in this example. However, both location cue and color cue were uninformative.	120
6. Sequence of events on a trial in Experiment 6. The target appeared at the invalidly cued location with the validly cued color. Location cue was 60% informative while the color cue was 80% informative in this example.....	120
7. The results from Experiment 5. (a) Mean reaction times (in milliseconds) as a function of conditions and SOAs. (b) Mean accuracy (percentage) as a function of conditions and SOAs.....	120
8. The mean reaction times (in milliseconds) from Experiment 6 as a function of level of cue informativeness and type of cue. (a) Location cue 60% and color cue 60%. (b) Location cue 60% and color cue 80%. (c) Location cue 80% and color cue 60%. (d) Location cue 80% and color cue 80%.....	120
9. The mean accuracy (percent correct) from Experiment 6 as a function of level of cue informativeness and type of cue. (a) Location cue 60% and color cue 60%. (b) Location cue 60% and color cue 80%. (c) Location cue 80% and color cue 60%. (d) Location cue 80% and color cue 80%.....	120

CHAPTER 1

INTRODUCTION

Our environment is filled with various objects and events. A well-known problem in visual perception is that our visual system is limited in processing resources so that only a small amount of information can be fully processed and used in control of behaviors. Since there are numerous visual inputs competing for access to the resource-limited cognitive system at any given moment, a selection must be made. One of the important functions of attention is to select relevant information for further processing. It has been shown that the neural response of a stimulus is enhanced when the stimulus is attended compared to when it is not attended, suggesting that attention can modulate the visual processing of a stimulus (Desimone & Duncan, 1995; Also see Kastner & Ungerleider, 2000 for a discussion on various way of attentional modulation on neural responses, such as changing the baseline firing rates, or sharpening the tuning curves). Attentional modulation has been proposed to play an important role in competition bias so that the selected stimulus wins the competition.

An important topic in the research of selection of visual attentional concerns the basis on which attentional selection occurs. At least three theoretical accounts for attentional selection have been proposed: location-based, object-based and feature-based selection (Kanwisher & Wojciulik, 2000; Lamy & Tsal, 2001; Vecera, 2000). The current study will mainly focus on selecting on the basis of location and features. Selection on the basis of location and features holds a natural appeal for researchers because the visual cortex is functionally organized into retinotopic maps and modules for specific features,

such as motion and color. The roles of location and features have been incorporated into many theories of visual attention, including Feature Integration Theory and the Guided Search model (Treisman & Gelade, 1980; Wolfe, 1994; Wolfe, Cave & Franzel, 1989).

Theoretical Accounts of Attentional Selection

Selection Based on Spatial Property

Location-based selection proposes that the location of the stimulus is used by attention to select relevant information. When attention is directed to a location, the stimulus occupying the location will be selected regardless of its features. A common analogy of location-based selection is the spotlight model, which proposes that attention functions as a spotlight that moves through contiguous regions in the visual field. Stimuli falling inside the region of the spotlight are selected and the visual processing of the attended stimuli is facilitated compared to the stimuli outside the spotlight, which receive little processing (For a review, see Cave & Bichot, 1999). Other metaphors have been proposed to account for the spatial distribution of attention (e.g., zoom-lens model or gradient model), but these models have the same basic link between location and selection as the spotlight, and so the current study will use the spotlight metaphor for simplicity.

Evidence for the spotlight model has been obtained in a variety of tasks, including the dual-task paradigm, response competition paradigm, and spatial cueing paradigm. The first paradigm studies the use of location in controlling attentional selection without any specific top-down bias to location information. The other two paradigms study how location controls selection process when attention is directed to the target location in a top-down manner. In the dual-task paradigms, participants are usually asked to perform

two tasks concurrently, such as a visual search task and an orientation discrimination task. The performance of the secondary task is found to be better when it is in close proximity to the target location in the primary task (Hoffman & Nelson, 1981; Kim & Cave, 1995; Kramer & Hahn, 1995). This distance effect is interpreted as the result of attention being distributed over a region in space so that any stimulus falling inside this region receives facilitated processing. In the response competition paradigm, a target is flanked by distractors and the target location is usually known in advance (e.g., at the center of the display or at an underscored location). The typical findings are that response incompatible distractors have greater interference when they are close to the target location (within 1 degree of visual angle) compared to when they are distant from the target (Eriksen & Eriksen, 1974; Eriksen & Hoffman, 1973). This one degree radius has been interpreted as the minimal focus of the spotlight in space.

In the spatial cueing paradigm, the advance knowledge about the target location is presented, usually in the form of a visual or verbal cue. Attention can be directed to the cued location before the appearance of the stimulus display. The cue does not define what a target is. Allocating attention only to the cue is not enough to perform the task accurately. A cue can be either valid or invalid. A valid cue provides correct information about the target while an invalid cue provides incorrect information. The location cueing effect is defined as the improvement of the task performance when a target appears at a validly cued location relative to when it appears at an invalidly cued location. It indicates that the location of the stimulus is used as the selection basis so that a stimulus with the attended property is modulated by attention. Note that not only the location, but also the feature of a stimulus (e.g., color or motion direction), can be cued. The cueing effect

reflects how selection occurs: on the basis of the location or the feature of a stimulus.

Furthermore, the cueing effect can be found with both endogenous and exogenous cues. Endogenous cues (e.g., a central arrow pointing to the left) trigger a voluntary or top-down controlled process of attentional orienting that responds to the internal expectancies. Exogenous cues (e.g., an abrupt onset) trigger a reflexive or bottom-up process of attentional orienting that responds to the salience of the stimuli. The characteristics of endogenous and exogenous cues will be further discussed later in the introduction.

By using a spatial cueing paradigm, Posner, Snyder and Davidson (1980) showed that stimuli were selected based on locations. Participants were to detect an onset target at one of four possible locations. An endogenous cue, indicating the likely location of the target, was given in advance. Target detection was faster when the cue was presented in the validly cued location than when it was presented in an invalidly cued location. The location cueing effect suggested that advance knowledge of location was used to direct attention to a specific location so that the efficacy of the stimulus processing in the validly cued location was enhanced. Downing and Pinker (1985) used a cueing task and examined the effect of spatial distance between the cue and the target. By giving an endogenous location cue in a luminance-onset detection task, the authors found that the average response times (RT) to target detection increased as a function of the distance between the cued location and the target location, confirming that location of the stimulus was used as the selection basis.

In summary, location-based selection has tremendous influence on theories of visual attention. For example, Feature Integration Theory and the Guided Search model

both endorse that the selection of visual attention can only occur at the level of spatial locations (Treisman & Gelade, 1980; Wolfe, 1994; Wolfe et al., 1989). Location has been assigned a unique role in the literature (Kim & Cave, 1995; Lamy & Tsal, 2000, 2001; Shih & Sperling, 1996; Theeuwes & Van der Brug, 2007; Tsal & Lavie, 1993).

Selection Based on a Nonspatial Property

In addition to spatial properties, nonspatial properties, such as object structure or a feature of the stimulus, can be used to select relevant information. Object-based selection proposes that attention is directed to the entire object. All of the features of the object (e.g., color, shape or motion) are selected simultaneously and the visual processing of the features is facilitated compared to the features that belong to an unattended object (e.g., Duncan, 1984; Vecera & Farah, 1994). This is because all of the features on the same object are integrated together as a unit for selection. Feature-based selection, on the other hand, proposes that attention can select information based on a specific value on a feature dimension (e.g., selecting red items among items with other colors). When features are used to direct attention, all of the stimuli with the attended feature are selected simultaneously and visual processing is facilitated compared to stimuli with the unattended features.

To be distinct from location-based selection, selection on the basis of nonspatial properties, including object and features, presumes that attention directly uses a representation organized by object boundaries or by a particular feature dimension in selection without accessing a representation of the stimulus' location. This space-independence is an important hypothesis for selection based on nonspatial properties. However, as will be discussed in more details in Chapter 2, some studies have proposed

that nonspatial properties are used to direct attention to the location of the stimulus and that selection is ultimately location-based (Kim & Cave, 1995; Moore & Egeth, 1998; Shih & Sperling, 1996).

Contrary to the idea of location-based selection, which has been studied longer and more intensively, selecting on the basis of features is less well understood and accepted. A number of studies report the feature cueing effect and conclude that the task performance is facilitated by cueing the target feature in advance (Cooper & Juola, 1990; Laarni, 1999; Lambert & Corban, 1992). For example, in a line orientation discrimination task, Laarni presented two objects, one above and one below the fixation. A target, which was a short line segment, appeared in one of the two objects on each trial. The task was to discriminate the orientation of the line segment. A cue indicated either the location (e.g., a central arrow pointing upward) or the color of the object (e.g., a red dot) in which the target would appear. There were both color and location cueing effects, indicating that participants used color and location information to find the target. In an earlier study, Cooper and Juola presented eight letters that varied on the dimensions of location, color and size and asked participants to find a prespecified target letter. A combined endogenous cue, which consisted of two dimensions of the target information (e.g., location and color or location and size), was presented on each trial. The effectiveness of each cue dimension was varied independently. The authors found a significant location cueing effect and feature cueing effect, indicating that the advance knowledge about target location and target feature was used to select relevant stimuli so that task performance was improved when the target appeared in the cued location or with the cued feature. Although these studies show that feature information is used to direct

attention, it is hard to know whether selection is based directly on the cued feature, or whether the feature is used to find the location to be selected (Kim & Cave, 1995; Moore & Egeth, 1998; Shih & Sperling, 1996; See Chapter 2 for a detailed discussion).

The Influence of Perceptual Grouping on Selection

The aforementioned studies address how a certain feature (e.g., red) is used to control attention to select relevant stimuli by a verbal or visual cue. Attention is biased to use a specific feature value in a task-driven manner. The role of features in attentional selection has also been studied under the framework of image segmentation and perceptual grouping and is traditionally discussed in a bottom-up, stimulus-driven manner. Image segmentation is traditionally viewed as a fundamental problem that the visual system has to deal with in an early stage in order to make our experience of the world well-organized and coherent, rather than separate image fragments. Perceptual grouping refers to the process that visual inputs are structured appropriately into meaningful chunks that correspond to our experience of objects according to certain principles such as proximity, common motion, and feature similarity (See Driver, Davis, Russell, Turatto & Freeman, 2001 for a review). Perceptual grouping is often discussed in the context of object-based selection and object recognition. The traditional view of object-based theories proposes two distinctive stages of visual processing. The visual field is initially segregated into perceptual units as candidate objects based on Gestalt principles at the preattentive stage. At the attentive stage, attention is focused onto perceptual units or objects serially and the selected object can further enter higher-level processing (Duncan, 1984; Duncan & Humphreys, 1989; Treisman, 1982).

It has been shown that color, motion and connectedness of the stimuli can affect attention through target-distractor grouping even when perceptual grouping is completely task-irrelevant (Baylis & Driver, 1992; Driver & Baylis, 1989; Humphreys, 1981; Harms & Bundesen, 1983; Kramer & Jacobson, 1991). Humphreys asked participants to judge the orientation of a target curved line that was always presented in the same location. A distractor curved line was presented 0.5 ° away from the target and was either the same color as the target or a different color. Humphreys argued that if only location information was used in selection, color variance would not affect task performance because the target location was known and the optimal performance could be achieved by focusing attention to the target location. The results showed a significant interference from the distractor when the target and the distractor shared the same color and no interference when they were of different colors. With a similar paradigm, Harms and Bundesen showed that distractor interference was greater in a letter categorization task when a distractor shared the target color than when it was of a different color. Kramer and Jacobson found that the response-compatibility effect was eliminated when the target and the distractors were on different objects defined by color similarity and closure.

Duncan (1984) provided critical evidence for the selection of objects. He presented two objects overlapping in the same location (e.g., a box and a tilted line) and asked participants to report two properties of the objects. The two properties were either from the same object or from two different objects (e.g., the direction and texture of the tilted line or the direction of the line and the height of the box). He found that reporting two properties from the same object was more accurate than from different objects. The findings suggested that selection was based on the entire object and that there was a cost

in switching attention between objects. Duncan's findings have been replicated and extended by many researchers with various stimuli (Baylis, 1994; Baylis & Driver, 1992; Kramer, Weber, & Watson, 1997; Lavie & Driver, 1996; Law & Abrams, 2002; Vecera & Farah, 1994; Watson & Kramer, 1999). This pattern, in which judging two properties on the same object is more accurate or faster than two properties on different objects, is termed the same-object effect and it demonstrates an object-based limitation on attention.

Lavie and Driver (1996) modified Duncan's (1984) study and measured the effect of selection by location and selection by perceptual grouping in the same task. Two intersecting dashed lines were presented, with one horizontal and the other tilted 18° clockwise from the horizontal. The targets were either a long dash or a short dot in the lines. The task was to judge if the lengths of the two targets were the same or different. Three conditions with equal probability were tested: two targets either appeared on the same line with one on each side of fixation (*object* condition), on different lines but on the same side of fixation (*near* condition), or on different lines with one on each side of the fixation (*far* condition). If selection occurred on the basis of perceptual grouping (or objects in their context), the performance in the *object* condition should be better than the *far* condition because selection within the same group should be more efficient than selection between groups when the distance factor was controlled. If selection occurred on the basis of locations, the performance in the *near* condition should be better than that in the *far* condition because the two targets were closer in the *near* condition than the *far* condition, while the object factor was controlled across the two conditions. Selection based on location further predicted that the performance in the *object* condition should be the same as that in the *far* condition because the two targets were of equal distance in

these two conditions, regardless of whether the two targets were on the same or different objects. The authors found the same-object effect in which the performance in the *object* condition was better than that in the *far* condition, indicating objects or perceptual grouping influenced how stimuli were selected. The performance in the *near* condition, however, was the worst, suggesting that selection by locations was inefficient in this task. Lavie and Driver concluded that perceptual grouping or object structure constrained attentional selection so that stimuli in the same group were processed more efficiently even when the instruction and task requirements did not specify attention to objects in advance. Their study is especially relevant to the experiments presented below, and we will discuss it further in Chapter 4.

Evidence has shown that stimulus features are used in image segmentation and perceptual grouping even when attention is not biased to a specific feature value in advance, and attentional selection operates on the entire perceptual group (Baylis & Driver, 1992; Duncan, 1984; Harms & Bundesen, 1983; Humphreys, 1981; Kramer, Weber, & Watson, 1997; Lavie & Driver, 1996; Law & Abrams, 2002; Vecera & Farah, 1994; Watson & Kramer, 1999). The grouping effect observed in these studies implies that features are used to segment an image into perceptual chunks in a bottom-up manner and that the resulting perceptual grouping constrains the selection process. The grouping effect is generally treated as evidence against location-based selection because many Gestalt principles of grouping are based on nonspatial properties, such as color similarity and common motion (Baylis & Driver, 1992; Driver et al., 2001; Harms & Bundesen, 1983; Humphreys, 1981; Kramer & Jacobson, 1991). The stimuli are being grouped and selected together based on the features of the stimuli, rather than the locations. Thus,

selection is in some sense independent of the location of the perceptual group, although there is still some question as to whether this selection is truly space-invariant or whether these examples of group selection might ultimately be mediated by selection of the locations occupied by the groups. The idea of spatially invariant selection receives little investigation in the context of perceptual grouping and attention. We will continue the discussion in more details in Chapter 2.

Note that stimuli can be grouped based on spatial factors as well, such as proximity or connectedness. The current study is only interested in how nonspatial factors, especially color, affected attentional selection. Location-based grouping is not discussed within the current scope.

The Interactive Account of Perceptual Grouping and Attention

Perceptual grouping is widely considered to be early, automatic and preattentive in the framework of object-based theories (Duncan, 1984; Lamy, Segal & Ruderman, 2006; Moore & Egeth, 1997; Treisman, 1980). For example, the common interpretation of the same-object effect is that perceptual grouping must have been formed without attention so that attention can select from perceptual groups or objects (Duncan; Kramer & Jacobson, 1991; Lamy et al.). However, the traditional view of automatic perceptual grouping has been challenged (Ben-Av, Sagi & Braun, 1992; Freeman, Sagi & Driver, 2001; Han, Jiang, Mao, Humphreys & Gu, 2005; Linnell & Humphreys, 2007; Mack, Tang, Tuma, Kahn & Rock, 1992). Ben-Av et al. showed that discriminating the orientation of the perceptual groups (e.g., horizontal or vertical) was impaired when a demanding secondary task was performed simultaneously compared to when the grouping task was performed alone, indicating that perceptual grouping required

attention. Mack and colleagues argued that most of the evidence for preattentive processing was produced under divided attention and therefore previous results could not answer the question of whether perceptual grouping occurred without attention. To measure whether perceptual grouping occurred without attention, Mack and colleagues developed the inattention blindness paradigm in which attention was directed to a primary task so that the background grouping elements were task-irrelevant and unattended. The general findings in the inattention blindness paradigm were that task-irrelevant stimuli could not be perceived without attention, indicating visual features and perceptual grouping required attention to be registered and processed (See Kimchi & Peterson, 2008 and Moore & Egeth for a different conclusion). In an fMRI study, Han et al. showed that neural activities related to grouping by proximity were modulated by task demands and the size of the attentional window. Neural activities were increased when perceptual grouping was task-relevant compared to when it was task-irrelevant and when the grouped stimuli fell inside the attended area compared to when they were outside the attended area. Han et al. concluded that perceptual grouping was modulated by attention.

Since the preattentive/attentive dichotomy cannot account for the recent findings about perceptual grouping modulated by top-down factors, an interactive account has been put forward to explain the relationship between perceptual grouping or image segmentation and attention (Driver et al., 2001; Vecera, 2000; Vecera & Farah, 1997; Vecera & O'Reilly, 1998). On one hand, stimuli can be grouped in a bottom-up manner (e.g., based on image cues or Gestalt principles) so that the grouped stimuli constrain information selected by attention. On the other hand, how stimuli are grouped can be modulated by top-down factors (e.g., attention), especially when the bottom-up cues are

relatively subtle or provide ambiguous solutions. For example, Vecera and Farah showed that top-down knowledge (e.g., familiarity) could override lower level grouping heuristics, such as connectedness and common region, which were generally viewed as strong grouping principles. In their study, stimuli were selected by a top-down bias. Vecera further proposed that when visual inputs were competing to be segmented, partial activation was sent to activate a higher level of visual processing (e.g., object representation). Top-down activation in turn biased stimulus segmentation and competition so that one object would be selected by attention over the others. Kim and Cave (2001) pointed out that perceptual grouping might have occurred as soon as feature information was available or that perceptual grouping could instead have occurred after attentional selection was completed. The order between perceptual grouping and attentional selection is still far from clear. What is for certain now is that there is a close link between perceptual grouping and attentional selection and that perceptual grouping affects the allocation and selection of attention and vice-versa.

It is worth noting that although object-based theories propose that objects are the units for attentional selection, the concept of objects is often defined intuitively and lacks clear criteria on what structural properties constitute an object. Many studies have simply treated the products of Gestalt principles of grouping the same as discrete objects we perceive in the environment. As Driver and colleagues (2001) point out, most of the studies on object-based selection are concerned about the relationship between image segmentation or perceptual grouping and attention, and not about conceptual objects and attention. It is probably more appropriate to discuss these findings under the topic of how

image segmentation or perceptual grouping influences attention and vice-versa (grouping-based selection), instead of object-based selection.

Summary of Chapter 1

When there are multiple stimuli in the environment, they compete within lower levels of the visual system to be processed at the higher levels. A selection process of attention is necessary since the higher level cognitive resources are limited. Stimuli selected by attention are processed more efficiently and thus win the competition. It has been suggested that both location and features of the stimulus can affect attentional selection in a top-down or task-driven fashion, as shown in the cueing paradigm. When attention is focused to a specific location or feature value in advance, the efficacy of stimulus processing is enhanced for the attended stimulus compared to the unattended stimulus. Location and feature information can also be used in another way when no clear top-down bias to a location or a feature is available. Features affect attentional selection through image segmentation and perceptual grouping. Perceptual grouping provides the selection basis for attention, and attention is directed to an entire perceptual group. The more recent evidence suggests that the relationship between perceptual grouping and attentional selection is interactive: perceptual grouping constrains selection and vice-versa.

CHAPTER 2

DIRECT SELECTION BY FEATURES

Is Selection Based on Nonspatial Properties Mediated by Location?

Chapter 1 has discussed the evidence for the role of features in organizing the visual input and in controlling attention directly in selecting relevant stimuli (Baylis & Driver, 1992; Cooper & Juola, 1990; Driver & Baylis, 1989; Harms & Bundesen, 1983; Humphreys, 1981; Kramer & Jacobson, 1991; Laarni, 1999). Selection directly on the basis of nonspatial properties naturally presumes that such selection is done without accessing the stimulus' location. For example, when there are multiple items with different colors competing for further processing, attention can be biased to only the item with a certain color. An item with the attended color is selected from the others in the competition and receives facilitated processing. Since color is the basis for selection, all of the items with the attended color should be selected and processed simultaneously, regardless of their locations. Therefore, selection is spatially independent.

Other studies, on the contrary, have suggested that selection by features is ultimately mediated by location (Kim & Cave, 1995; Moore & Egeth, 1998; Shih & Sperling, 1996). Moore and Egeth had participants search for a digit in a multiple-letter display. Stimuli differed in color (e.g., green or blue) in Experiment 1 and in size (e.g., small or large) in Experiment 2. Participants were informed about the probability of the target feature (e.g., the target had a 1.0 probability of being green). The results showed that the reaction time decreased as the probability of the target having a certain feature increased, indicating that the advance knowledge of the target feature facilitated search.

However, when the search display was presented briefly and masked, advance knowledge of the target feature did not facilitate search performance. Moore and Egeth argued that feature knowledge could not facilitate search performance under data-limited conditions so that visual processing was not affected by attending to a feature. Instead, feature information was probably used to prioritize certain locations that contained the attended feature so that the locations were selected with higher priority. When the display was masked, attention was unable to shift to these locations and thus feature modulation disappeared. In their view, color information was used as the criterion by attention to identify the potential targets. After a potential target was identified, attention then shifted to the location of the target, and thus the basis for selection was ultimately the item's location.

Moore and Egeth's (1998) findings support the location-unique view, which proposes that features are used to direct attention to the location of the stimulus rather than to the feature itself. Feature-based selection is completely mediated by location. This view is further supported by Kim and Cave (1995), who had participants search for a target in a conjunction search task. In a small portion of the trials, a black dot, serving as a spatial probe, appeared after the search display disappeared. Participants were to detect the dot as soon as possible. RT to the dot reflected the allocation of attention in space since the dot did not share any of the features with the search stimuli but did share location. The findings showed that RT to the dot was faster when it appeared at the target location, but RT was also fairly fast for the locations of the distractors that had the target color. The authors suggested that the locations that contained the attended color were selected in conjunction search so that when the black dot appeared at these locations, it

was processed more efficiently. Kim and Cave proposed “feature-driven location selection” in which the function of the feature was to guide attention to the locations of the feature when the target location was unknown. The location-unique view is consistent with the Guided Search model, in which feature information is used to guide attention to the location of the stimulus and selection is made within the location map.

The same argument that location is unique also applies to the findings on perceptual grouping and attentional selection. As mentioned early, the grouping effect is generally interpreted as evidence against location-based selection because nonspatial properties of the stimuli can affect attention. When a group is selected based on its feature property, selection should be independent of the locations of the perceptual group (Baylis & Driver, 1992; Driver et al., 2001; Duncan, 1984; Harms & Bundesen, 1983; Humphreys, 1981; Vecera & Farah, 1994). The evidence for the *space-independent hypothesis* was first provided by Vecera and Farah. The authors adopted Duncan’s same-object design but further manipulated the spatial distance between the line and the box. The line and the box were either overlapped at fixation or each was presented on one side of fixation. The logic was that if the same-object effect truly resulted from selection from a spatially-invariant object representation, manipulating spatial distance between the two objects should not affect the effect. The results confirmed that object-based selection was spatially invariant because the same-object effect did not interact with the spatial distance between the two objects. The locations of the objects were not used in selection.

Nevertheless, Vecera and Farah’s (1994) distance manipulation has been criticized for not controlling for eccentricity when varying spatial distance as well as superimposition of the two objects (Kramer, Weber & Watson, 1997; Lavie & Driver,

1996). It was unclear if the same-object effect was attributed to selection from the space-invariant object representation or other factors, such as acuity differences in the eccentricity or masking due to superimposition. Kramer et al. modified Vecera and Farah's design with a postdisplay probe that appeared only in 25% of the total trials. They failed to replicate the findings of Vecera and Farah and found that the same-object effect was greater on the separated trials than on the superimposed trials. In addition, the mean probe reaction time was faster when it appeared at the location of the object that possessed both targets than when the probe appeared at the location of the object that possessed neither of the target properties on the separated trials. The authors concluded that the locations of the objects were activated in the task and that selection did not select from a spatially invariant object representation.

Several studies have argued that the effect of perceptual grouping is through the selection of the locations of the grouped stimuli (Kim & Cave, 1999, 2001; Kramer & Jacobson, 1991; Vecera, 1994, 1997). Kim and Cave had participants report the identity of a target letter flanked by distractors. The location of the target was known in advance and the distractors could either be the same or different color as the target. A spatial probe was presented after the stimulus display and it was either at the target location, same-color distractor location or different-color distractor location. The average reaction time to the probe was faster when it was at the same-color distractor location than at the different-color distractor location, suggesting the locations that contained a target feature received more attention than the locations that did not contain a target feature. The authors concluded that distractors and the target were grouped based on their color and the locations of the group were selected by attention. According to Kim and Cave, the

color effect reported in Harms and Bundesen (1983) as well as in Humphreys (1981) can also be interpreted as the locations of the grouped stimuli being selected by attention, rather than the color of the group being selected directly. Vecera further proposed the *grouped-array hypothesis* in which stimuli were organized preattentively into perceptual chunks or objects according to Gestalt principles, with attention ultimately selecting from the locations of the perceptual groups or objects.

Together, these studies suggest that direct selection by features is completely mediated by location (Kim & Cave, 1995, 1999, 2001; Kramer, Weber & Watson, 1997; Moore & Egeth, 1998; Shih & Sperling, 1996; Vecera, 1994, 1997). Attentional selection occurs within a representation that registers the locations of the features or grouped features. It is the location of the feature or the feature group that serves as the selection basis for attention. Therefore, feature information is not directly used to control attention in selecting relevant stimuli. Selection is ultimately location-based.

Space-Independent Hypothesis

The claim that selection by features is mediated by location does not necessarily eliminate the possibility of direct selection by features under some conditions. It is possible that both location and features were used simultaneously in Kim and Cave (1995), but the spatial probe was not designed to measure feature-based selection. Their results can not demonstrate if direct selection by features occurred. Lamy and Tsal (2001) also argued that the use of location was induced by asking participants to respond to spatial probes. Since the location information became task-relevant, it was not surprising that participants might strategically use the location of the objects to select relevant stimuli.

One reason why the debate has continued may come from the confounding that features are highly correlated with locations, since features usually occupy distinct locations in many search tasks. Feature modulation can be attributed to selection on the basis of location, features, or a combination of both. Location and features can be dissociated by presenting overlapping stimuli in the same location. This technique has become more and more popular to study if selection by features is independent of location (Busse, Katzner & Treue, 2006; Liu, Stevens & Carrasco, 2007; Muller et al., 2006; O'Craven, Downing & Kanwisher, 1999; Saenz, Buracas & Boynton, 2002; Stoppel et al., 2007; Vierck & Miller, 2005, 2006; Zhang & Luck, 2009). The rationale behind overlapping stimuli is that the spotlight model predicts that all of the stimuli falling inside the focus of the spotlight should be selected and processed regardless of their features. Location-based selection predicts no feature modulation when the stimuli are covered by the spotlight. If attending to a feature modulates performance inside the focus of attention, it should be attributed to selection on the basis of features because feature-based selection predicts feature modulation even when different features occupy the same location.

Several functional imaging studies with overlapping stimuli have shown that attention modulates neural responses in extrastriate visual areas that specialize in processing feature information. For example, attending to motion increases the activation in MT (Beauchamp et al., 1997; O'Craven et al., 1997), and attending to color increases the response in V4/V8 (Saenz et al., 2002). Similar results have been reported for homologous areas in the monkey brain (Treue & Martinez Trujillo, 1999; McAdams &

Maunsell, 2000). These findings suggest that features are directly used in attentional selection and thus selection can be spatially independent.

Another critical prediction for the *space-independent hypothesis* is that when attention is directed to a feature, all of the stimuli with the attended feature should be selected simultaneously across the entire visual field. This prediction is further supported by measuring the neural activation at an unattended location (Treue & Martinez-Trujillo, 1999; Saenz et al., 2002). Treue and Martinez-Trujillo showed that attending to a particular motion direction increased the firing rate of the neurons in the middle temporal visual areas (MT) tuned to that particular motion direction even though the receptive fields of the neurons were outside the attended location. (See a detailed discussion of this study in Chapter 3.) Saenz et al. measured brain activation in human visual cortex by presenting two overlapping fields of random dots moving upward and downward on one side of the fixation (the attended side) and one single field of upward or downward moving dots on the other side of fixation (the unattended side). Participants were asked to attend to a particular motion direction on the attended side and perform a speed discrimination task while ignoring the stimuli on the unattended side. The BOLD signal from the unattended side was stronger when the dots were moving in the same direction as the attended motion direction, indicating neural activation at the unattended location was also modulated by whether the motion direction was attended or not. The effect of feature modulation indeed occurred across the entire visual field and was independent of the attended location.

Much less is known about the behavioral consequences of direct selection by features. Liu, Stevens and Carrasco (2007) superimposed two fields of random dots that

moved in different directions on each side of the fixation. Participants detected a speed increment in one of the fields preceded by an endogenous cue that indicated either the motion direction or location of the target field. The stimulus-onset asynchrony (SOA) between the cue and the target stimuli was varied to assess the time course of the attentional effect. Liu et al. found both a location cueing effect and a motion direction cueing effect, indicating that both location and feature information facilitated motion speed detection. Furthermore, they found that it took longer for feature-based selection to express its influence than location-based selection, but the magnitude of facilitation eventually reached a similar extent at long SOAs.

In another experiment that encouraged feature-based selection, Vierck and Miller (2005, 2006) asked participants to discriminate the case of a prespecified target letter (e.g., H vs. h) in a rapid serial visual presentation (RSVP) task. The stimuli were colored letters presented briefly and sequentially in the same location. A color cue (e.g., a color patch) was given before the presentation of the letter stream. In the valid trials, a target letter appeared in the cued color. In the invalid trials, a distractor appeared in the cued color. The results showed that target discrimination was better in the valid trials than in the invalid trials, indicating participants used color information to facilitate target processing. Vierck and Miller concluded that direct selection by color was evident in a RSVP task because location-based selection failed to account for the effect of color modulation.

The interpretation of Vierck and Miler (2005, 2006), however, is questionable. The RSVP task may be more informative about selection in time than selection in space. It is not clear whether the process of attentional selection which takes place in a task with

objects simultaneously presented in multiple locations is equivalent to the process that takes place in a task with successive objects presented at different time points. The results of Vierck and Miller (2005, 2006) may reflect how feature information guides the temporal aspect of attentional selection, rather than direct selection by a feature. It is possible that there is a spatiotemporal gate at the attended location and color information serves as a temporal cue to indicate when to open or close the gate in a task like RSVP. When a stimulus is in the cued color, the gate will open to process the stimulus at the attended location. When a stimulus is not in the cued color, the gate will close and the stimulus at this location will not be processed. In this account, attentional selection is spatiotemporal, and not directly color-based.

To sum up, neuroimaging findings have demonstrated that stimuli can be selected based on a feature property, and attending to a feature can modulate neural responses across the visual field. The behavioral consequences of the *space-independent hypothesis*, however, receive little empirical examination. It is the goal of the current study to investigate the behavioral consequences of direct selection by features in order to provide more complete evidence for the *space-independent hypothesis*.

Strategic Selection vs. Automatic Selection

An important issue in the literature of attentional selection is whether the use of location or features in control of selection occurs automatically or is completely driven by top-down influence, such as task demands. It is widely accepted that attention is adaptive to the task demands and selection can be goal-driven. The studies discussed in Chapter 1 demonstrate that attention is flexible in using different stimulus properties (e.g., location or features) and such flexibility can be controlled by either feature or location

cues. One may argue that it is not surprising to observe a location or feature cueing effect when location cues or feature cues provide useful information about the upcoming target. Participants have incentives to actively use the location or features of the stimuli to select targets among distractors due to the processing advantage associated with the cues. The use of location or features should be considered as a deliberate and strategic process when location or feature information is task-relevant (Vierck & Miller, 2006; Yantis, 2000). Automatic selection can only be examined when location or feature information is task-irrelevant and automatic selection is beyond the strategic control of participants (Lamy & Tsal, 2000; Tsal & Lavie, 1993; Vierck & Miller; Yantis & Egeth, 1999). The central question is whether location or feature information is used automatically when location or features are task-irrelevant.

A common approach to investigate automatic selection is to use exogenous cues. Exogenous cues are usually presented peripherally (e.g., abrupt onsets or luminance increment) and are often uninformative or nonpredictive of the upcoming target (task-irrelevant). They are believed to trigger exogenous orienting, which refers to the process of orienting attention involuntarily or reflexively to a salient change in the environment (Jonides, 1981). Following Posner's (1980) cueing paradigm, Posner and Cohen (1984) presented one central box and two peripheral boxes and asked participants to detect a target that appeared in one of the boxes. An exogenous cue, which was the brightening of a box, was presented with lower probability on the peripheral boxes than on the central box. A peripheral target was detected faster when it was preceded by an exogenous onset cue at its location compared to when it appeared in an uncued location. The results suggested that attention was captured by the exogenous cue automatically to the location

of the cue and the visual processing of the upcoming stimulus at the cued location was facilitated as a result. Such attentional orienting to the location of the cue was involuntary and automatic because the location of the cue was task-irrelevant and nonpredictive of the target location.

Just as Posner (1980) used an exogenous location cue, Vierck and Miller (2006, Experiment 3 and 4) used an exogenous color cue in a study mentioned above. Their experiments showed that color was used automatically in selection. Participants were to discriminate whether the prespecified target letter was presented in upper or lowercase in a RSVP task. The cue color was randomly picked from a set of six colors to serve as a cue in the beginning of each trial, with one third of the total trials being valid. The incentive to use color cues was low since color cues did not predict the target color reliably. Participants were told that cues sometimes had the same color as the targets, and that attending to the color cues was optional. The results showed a small but significant color cueing effect (2.1 % improvement in accuracy), indicating that participants used color cues even when the color cues were nonpredictive and task-irrelevant. Vierck and Miller further reduced the cue validity to completely uninformative (at the chance level of 6.67%) and asked participants to ignore cues. Yet a significant color cueing effect remained (1.5% improvement in accuracy). The authors argued that since participants had no incentive to attend to the color of the stimuli, the small but significant color cueing effect must reflect an automatic process of using color of the stimuli to select targets. Vierck and Miller concluded that selection by color was partially automatic because a color cueing effect was observed even when color was completely uninformative and should be ignored. Selection by color was also partially strategic

because when the cue validity was increased, the magnitude of the cueing effect was greater.

Tsal and Lavie (1993) examined whether location and color were used automatically by manipulating the relevance of location or color. They presented a cue display followed by a two-letter display, one on each side of fixation. The cue display consisted of a black dot and a colored dot (either pink or blue), each adjacent to one of the letters. The task was to respond to the letter F in the two-letter display only when the colored dot was pink. The colored dot appeared either on the same side of the target letter or on the opposite side. Letter detection was better when the target appeared on the same side of the colored dot as well as when the target shared the same color with the colored dot. The authors concluded that location was used automatically in selection because the location of the cue was completely task-irrelevant since participants did not respond to the location of cues. However, the use of color in selection was not automatic because the color of the cues was task-relevant and attended.

With a similar logic, Lamy and Tsai (2000) provided further evidence for the strategic use of features and automatic use of location. Participants viewed two objects, one on each side of the fixation, with different shapes and colors (e.g., a green rectangle and a red hourglass) and were asked to detect the presence of a filled white square at one of the corners of the two objects. The two objects swapped locations in some of the trials. An onset cue, a thick outline white square, appeared at one of the four corners 200 ms before the filled square. In different experiments, this square could cue either location or shape and color. Participants were asked to attend either to the location of the cue (exogenous and endogenous cueing for location because the cue directly indicated a

location at which the target was most likely to appear and participants were supposed to attend to the location) or to the features of the object being cued (endogenous cueing for features because the cue did not directly represent the features of the object that most likely contained a target, so the cue needed to be interpreted). The results showed that in the location cue experiment in which a cue indicated the likely location of the target, target detection was better in the cued locations. However, whether the target appeared on the object with the cued features or on the object with the uncued features did not affect performance, indicating that the object features were not used for selection. In the feature cue experiment in which a cue directed attention to the features of the object on which the target most likely appeared, target detection was better when the target appeared on the object with the cued features as well as when it appeared at the location of the cue, indicating both features and location were used for selection. Lamy and Tsal concluded that location-based selection occurred automatically because attending to a feature entailed its location being selected even when location was task-irrelevant. In contrast, feature-based selection only occurred when participants were asked to attend to the feature (task-relevant), but disappeared when participants were not required to attend to the feature (task-irrelevant). Therefore, feature-based selection was not automatic.

The previous studies examine the automatic use of location or features in a cueing paradigm in which the cues are usually exogenous and uninformative (Lamy & Tsal, 2000; Tsal & Lavie, 1993; Vierck & Miller, 2006). Another way to study this topic is through probability manipulation. The logic is similar to the uninformative cues in that location or feature modulation should be evident for automatic selection by features or by location when location or feature probability is low and participants have no incentives to

attend to feature or location information. For example, Lavie and Driver (1996) examined whether the selection based on perceptual grouping of connectedness was automatic. As discussed earlier, Lavie and Driver presented two distinct lines formed according to connectedness and the two targets were either on the same line (*object* condition), on different lines and distant from each other (*far* condition) or on different lines and close in space (*near* condition) with equal probability. The locations of the two targets and whether they would be in the same or different lines was unknown. The authors manipulated the probability of each condition to vary the incentive to attend to an object representation or a location. The same-object effect (the better performance in the *object* condition than in the *far* condition) arose spontaneously when neither instruction nor task requirements specified attention to objects (equal probability for three conditions). Lavie and Driver further reduced the probability of the *object* condition from 33% to 25% and the results again showed significant same-object effect. Their findings suggested attentional selection based on object representation or connectedness was automatic when there was no strategic motivation for using objects.

Summary of Chapter 2

An ongoing debate concerns whether selection by features is completely mediated by location. To eliminate the confounding of location, overlapping stimuli have been adopted in neuroimaging and psychophysics to examine the *space-independent hypothesis*. In some circumstances, location-based selection fails to account for the effect of feature modulation in the attended location and the results indicate that feature information is used directly to control stimulus selection. Neuroimaging studies further show that such feature modulation occurs across the visual field: the visual processing of

an unattended stimulus in an unattended location is modulated according to whether it shares the same feature with the attended stimulus. Given that most of the current literature focuses on the effect of feature-based selection on neural activity, the current study is interested in the behavioral consequences of the *space-independent hypothesis* in order to provide more complete evidence for direct selection by features.

The second question we are interested in is whether attention uses feature information to select relevant stimuli automatically, or selection by features is completely driven by top-down influence. Lavie and Driver (1996) showed that attention was affected by grouping based on connectedness automatically even when there was no top-down influence to bias attention to use perceptual grouping. Other studies approach this question with uninformative exogenous cues (Lamy & Tsal, 2000; Tsal & Lavie, 1993; Vierck & Miller, 2006). Contradicting results are found, with some supporting automatic selection by color while others do not. The current study examines if features are used automatically in selection when uninformative exogenous cues are presented when there is no top-down or bottom-up influence to bias attention.

CHAPTER 3

THE RELATIONSHIP BETWEEN SELECTING FEATURES AND LOCATIONS

Evidence for different forms of attentional selection has been reported, including attention on the basis of location and features. However, it is not clear how the attention system utilizes and integrates different forms of information to control behaviors. The functional relationship between different forms of attentional selection is an important topic, for not only does it shed light on whether different forms of attention are mediated by discrete or unified neural mechanisms, but it also helps to build a complete picture of how the attention system operates. There are two possible reasons for why this puzzle has not been solved. First, not many studies have compared the two forms of attentional selection within the same experimental paradigm simultaneously. Secondly, many studies have used non-overlapping stimuli (Anllo-Vento & Hillyard, 1996; Cooper & Juola, 1990; Dunai, Castiello & Rossetti, 2001; Egner et al., 2008; Laarni, 1999; Lambert & Corban, 1992). As explained earlier, it is difficult to know if feature-based selection is involved with non-overlapping stimuli. The feature modulation may result from feature-based selection, feature-driven location selection, or a combination of both. Thus, to provide a clearer picture of the functional relationship between location-based and feature-based selection, the current study used overlapping stimuli to ensure that feature modulation is better accounted for by selection based on features, and not selection based on location. In addition, we compared the effect of selection based on location or features within the same task simultaneously and independently.

There are two dominant views on the relationship between location-based and feature-based selection in the literature. The first view, called the *independent hypothesis*, suggests that selection on the basis of location and features are two independent and parallel processes, with task demands determining what type of information drives selection (Lamy & Tsal, 2000; Treue & Martinez-Trujillo, 1999). The second view, the *interactive hypothesis*, suggests that location-based and feature-based selection operate in an interactive manner (Anllo-Vento & Hillyard, 1996; Hillyard & Munte, 1984).

The Independent Hypothesis

Several studies have examined how selection on the basis of location and features operate at the level of neural activities in monkeys and humans. As mentioned in Chapter 2, Treue and Martinez-Trujillo (1999) measured neural responses of direction-sensitive neurons in MT as a function of stimulus motion direction under attentional selection by location or by features. These neurons showed an increase in firing rate when the motion was in its preferred direction over when it was in a perpendicular direction (directional gain). In the location-based selection condition, two random dot patterns were presented, with one inside and one outside the receptive field. Both random dot patterns moved in the same direction (no feature differences). Monkeys attended to either the pattern inside or outside the receptive field. The directional gain on average increased by 10% (without sharpening the tuning curves) when attention was directed inside the receptive field compared to when attention was directed outside the receptive field. This attentional modulation of neural responses reflected a pure effect of location-based selection since the only difference between the two conditions was whether attention was directed to the location that contained the stimuli inside the receptive field. The authors further

measured the tuning curves in the feature-based selection condition. A similar design was used except that the dots outside the receptive field moved either in the same or opposite direction as the dots inside the receptive field. Monkeys were trained to attend to the dots outside the receptive field. The directional gain on average increased by 13% when attended dots moved in the same direction as the unattended dots compared to when the two moved in the opposite directions. The results reflected feature-based attentional modulation since the difference between the two conditions was whether the motion direction of the unattended stimuli contained the attended or ignored feature. Moreover, feature-based attentional modulation was spatially independent because it was observed in an unattended location.

More critically, Treue and Martinez-Trujillo (1999) showed that attentional modulation based on both location and features were observed in the same neurons and that the modulation effects were additive. When the effects of attending to features and to location were combined (attending to the preferred direction inside the receptive field vs. attending to the non-preferred direction outside the receptive field), the overall effect was the sum of the individual components. This additivity implies that selection based on location and features are two independent processes. Treue and Martinez-Trujillo proposed a *feature similarity gain model* in which both location and feature information were equally important in controlling attentional selection (Location was viewed as one of the features). The modulation of the sensory gain of neurons was controlled by the similarity of the features that were relevant to the current behaviors. Selecting based on location and based on features were parallel and independent.

Behavioral evidence as well as functional imaging evidence for the *independent hypothesis* was also provided by Egnér and colleagues (2008), who varied the cue validity and the level of cue informativeness (50%, 70% or 90% valid cues) for both location and color information simultaneously in a visual search task. The search array consisted of four diamond-like stimuli, two on the left and two on the right side of the display. Participants were asked to find if the top or the bottom corner of a target diamond was missing. A central endogenous cue was presented for 4 to 8 seconds before the search array on each trial. Each cue carried location (an arrow pointing to the left or right side of the screen) and color (a central letter indicating “R” for red or “B” for blue) information about the upcoming target. The proportion of valid location and color cues was manipulated independently from 50%, 70% to 90%, resulting in a 3 x 3 factorial design. The results showed significant cueing effects for both location and color cues, and the size of the cueing effects were comparable, suggesting that participants deployed their attention to locations and to colors according to the level of cue informativeness. In addition, the location cueing effect neither interacted with the validity of color cues nor the level of color cue informativeness and vice versa, suggesting the two types of cues were used independently. The authors further analyzed data based on validly cued trials and found that additional location cue information facilitated performance when the color cue was 50%, 70% and even 90% informative. Likewise, additional color cue information facilitated performance when the location cue was from 50% to 90% informative. The results indicated an additivity between the location cueing effect and the color cueing effect, and that selection based on location was independent from selection based on colors.

The Interactive Hypothesis

Contrary to the independent view, other studies have suggested that selection by location and by features interact (Anllo-Vento & Hillyard, 1996; Cooper & Juola, 1990; Hillyard & Munte, 1984; Stoppel et al., 2007). However, the *interactive hypothesis* does not give a clear prediction of what the interaction should look like, and at least three different patterns of interaction have been reported in the literature. For example, Cooper and Juola examined the relative effectiveness of endogenous location and feature cues in a letter recognition task. Participants viewed eight letters arranged in an “X” pattern and found one of two prespecified target letters. Each letter varied on three dimensions: location (foveal or parafoveal location), size (small or large) and color (red or blue). Before the letters were presented, a combined cue was presented (e.g., “outside blue” or “inside red”) that could identify two letters in each display. Each participant received one combination of cue types throughout the entire experiment (e.g., shape and location cues for group 1; color and location cues for group 2). Cue validity of each dimension was varied independently so that on any trial, either both dimensions were valid, one dimension was valid and the other was invalid, or both were invalid. The results showed that both location and feature cueing effects were significant, indicating that each cue dimension was used in selection. The interaction between location and feature cues was also significant, with the cueing effect for one cue dimension being larger if the other cue was valid rather than invalid. However, there was no interaction between color and size cues. The results suggested interactions between location and features, but independence between feature dimensions.

The second pattern of interaction was observed by Stoppel et al. (2007). The authors presented two surfaces of superimposed red and green dots in the left and right visual fields. One surface of dots either moved slowly or fast. A central colored arrow (e.g., a red arrow pointing to the left) was used to direct attention to a particular color surface in a particular location. The task was to detect a fast movement of the attended surface in the attended location. The results showed that the highest enhancement of BOLD signals (an index of attentional modulation) was found when the selection was based on location. Adding feature information on top of location information did not lead to a higher BOLD response than the location information alone. This might indicate that selecting features had no additional benefit on top of selecting location. Alternatively, it was possible that the BOLD activation was at ceiling and the measurement of signal enhancement was not sensitive enough to reflect the difference. The authors also found that feature modulation was observed only at the unattended location in motion-sensitive cortical areas. Stoppel et al. concluded that the combined effects of location-based selection and feature-based selection were nonadditive because additional feature information did not increase the BOLD signals and the effect of feature-based selection was more likely to occur when location information was uninformative (at the unattended locations).

The third pattern of interaction was termed the *hierarchical organization hypothesis* and was put forward by Hillyard and colleagues (Anllo-Vento & Hillyard, 1996; Hillyard and Munte, 1984). According to this hypothesis, the relation between location-based and feature-based attention is hierarchical and serial, with location being dominant in the selection process. In their studies, participants viewed a red or blue bar

moving horizontally or vertically either on the left or right visual field in random order. They were asked to direct attention either to a specific color or specific motion direction in either the right or left hemifield. The task was to detect slower moving targets that contained the attended combination of feature and location. ERPs were compared for stimuli in the attended vs. unattended hemifield as well as for stimuli with the attended vs. unattended feature. The ERP results showed that compared to the stimuli in the unattended location, stimuli in the attended location elicited higher amplitude P1, N1 and N2 components over the hemisphere contralateral to the attended visual field, regardless of the color of the stimuli. The higher amplitudes of P1, N1 and N2 components were indices for location-based selection. Stimuli with the attended feature also elicited higher amplitude SN and SP components compared to the stimuli with the unattended feature. The higher amplitudes of SN and SP were indices for feature-based selection. Surprisingly, the enlarged SN and SP components were reduced or even absent when the stimuli appeared in the unattended location, suggesting feature modulation interacted with location. The results indicated that feature-based selection was contingent on location-based selection and the relation between the two was hierarchical. The *hierarchical organization hypothesis* also implies that there are two selection processes, with the initial stage based on locations of the stimuli and the second stage based on feature properties of the stimuli.

Endogenous and Exogenous Control of Attention

We also consider the influence of the modes of attentional orienting in the functional relationship between selection based on location and features. As mentioned earlier, covert orienting of attention without eye movements can be found both with

exogenous and endogenous location cues (Klein, 2000; Posner, 1980). Endogenous cues are usually symbolic signs presented at a non-target location (e.g., usually at the center) that require interpretation (e.g., “L” meaning the upcoming target will appear on the left side of the screen). Endogenous cues are usually highly task-relevant (validity higher than chance level) and thus are informative on the location of the upcoming target. In this case, participants have incentives to attend to the cue and actively use it to find targets. Therefore, endogenous cues are believed to trigger voluntary or top-down control of attentional orienting that responds to internal expectancies or intentions of the participants.

Exogenous location cues, on the contrary, are presented directly at a likely target location and often consist of abrupt onsets or luminance changes. Exogenous cues can be task-irrelevant and uninformative about the upcoming target location or feature. In fact, a pure exogenous cueing effect can only be measured when the cue is uninformative. An informative exogenous cue will also activate endogenous orienting. Exogenous cueing effects have been reported even when participants have no incentives to use them, suggesting that the cue is used automatically. Therefore, exogenous cues are responsive to the salience of the stimuli and they trigger reflexive or bottom-up control of attentional orienting.

Endogenous orienting and exogenous orienting differ in many aspects. For example, Jonides (1981) compared the location cueing effects of exogenous and endogenous cues and found that: (1) exogenous orienting was less affected by cognitive load than endogenous orienting, (2) the manipulation of cue validity affected endogenous orienting more than exogenous orienting, and (3) participants were able to ignore

endogenous cues but were unable to ignore exogenous cues (although the claim of automatic attentional capture by exogenous cue was rejected later in Yantis & Jonides, 1990). Another intrinsic difference between the two modes of attentional orienting is in the time course of attentional development. Location-based endogenous orienting develops gradually with an initial broad focus followed by a narrow focus, whereas location-based exogenous orienting develops more rapidly from early facilitation to later inhibition (Shepherd & Muller, 1989). The later inhibition is termed *inhibition of return* (IOR) and is believed to play an important role in preventing attention from permanently focusing or revisiting the most salient stimulus (Klein, 2000). The differences between endogenous and exogenous orienting have led to a debate over whether the two modes are generated by a unitary system or by two separate systems (Berger, Henik & Rafal, 2005; Funes, Lupianez & Milliken, 2007).

Most studies have investigated endogenous orienting of attention with location cues or feature cues, indicating that attention uses location and feature information to select targets in a top-down manner (Cooper & Juola, 1990; Egeton et al., 2008; Klein, 2000; Liu et al., 2007; Posner, 1980; Vierck & Miller, 2005, 2006). As mentioned in the previous paragraph, exogenous orienting of attention triggered by location cues has also been studied, indicating that attention can be captured to the location of the cue (Folk, Remington, & Johnston, 1993; Jonides, 1981; Theeuwes, 1991; Yantis, & Jonides, 1990). The understanding of exogenous orienting of attention triggered by feature cues, however, is relatively little. Furthermore, none of these studies have systematically tested whether the mode of attentional orienting affects the functional relationship between using location and using features: some studies used endogenous location cues and endogenous

feature cues (Cooper & Juola, 1990; Egner et al., 2008), some used exogenous location and exogenous color cues (Dunai, Castiello & Rossetti, 2001), and some even used endogenous location cues and exogenous color cues (Lamy & Tsal, 2000; Stoppel et al., 2007). Since there is evidence for separate mechanisms for exogenous and endogenous orienting (Berger, Henik & Rafal, 2005; Funes, Lupianez & Milliken, 2007; Jonides, 1981; Klein, 2000; Shepherd & Muller, 1989), we examined whether the mode of attentional orienting to some degree accounts for the discrepancies between the *independent hypothesis* and the *interactive hypothesis*.

Summary of Chapter 3

We have discussed the evidence for attentional selection based on location and features in Chapter 2. However, the functional relationship between location and features is unclear. The *independent hypothesis* proposes that features and location are equally important and are used independently (Egner et al., 2008; Treue & Martinez-Trujillo, 1999). The *hierarchical organization hypothesis* proposes that location is unique in the selection process and feature information can only be used inside the spotlight of attention (Anllo-Vento & Hillyard, 1996; Hillyard & Munte, 1984). One possibility of why the discrepancy exists is that most studies have failed to control for the confounding of location with features. Furthermore, the question of whether the functional relationship between location and features varies with endogenous and exogenous orienting remains unsolved. The current study is aimed to investigate the relationship between using location and using features with a better control by adopting overlapping stimuli, and in doing so to measure the relationship in both endogenous and exogenous orienting of attention.

CHAPTER 4

THE CURRENT STUDY

The current study investigates how feature and location information are used to direct attention in selecting targets in a single task, and also tests the flexibility of attentional selection. We adopted a design similar to Lavie and Driver's (1996) in which the same-object effect was found (judging the properties of two targets is more efficient when they are on the same object than on different objects). This design allows us to directly compare the effects of using location and using features concurrently in the same task. However, the objects are defined intuitively in Lavie and Driver (e.g., a connected line made up of small line segments) and the same-object effect might have resulted from the effect of grouping by connectedness. Moreover, since the line segments can be easily perceived as a connected line through low spatial frequency channels in the visual system, perceptual grouping may not even be needed in Lavie and Driver (Driver et al., 2001; Han, Humphreys & Chen, 1999). To further dissociate from object-based attention, instead of making targets part of an object as in Lavie and Driver, we use letters and digits that are distinctive from each other perceptually and conceptually. Stimuli can only be grouped based on their features (e.g., color), not based on being part of an object and the grouping effect cannot be achieved through low spatial frequency channels. We are more confident that the color modulation is caused by perceptual grouping, rather than other factors in our study.

Although the same-object effect in Lavie and Driver (1996) may be attributed to the selection of a location-independent object representation, it can also be explained by

the *grouped-array hypothesis* (Vecera, 1994, 1997). The *grouped-array hypothesis* proposes that attentional selection occurs within a representation organized by location in which the locations of the stimuli are selected according to whether they belong to the same object. Object structure or perceptual grouping influences attention not because objects or perceptual groups are directly selected, but because they affect how locations are segmented and grouped. Selection ultimately is based on grouped locations. The same-object effect is caused by the grouped locations of an object being selected simultaneously, rather than a location-independent object representation being selected. According to this account, it is inappropriate to interpret the findings on the influence of perceptual grouping on attention as supporting evidence for selection from a spatially invariant object representation. The possibility of this alternative grouped-array account makes it important to demonstrate that selection based on nonspatial properties is not mediated by location but is truly spatially independent.

The task in the current study is to compare the properties of the two targets (See Method in the next chapter for details). The distance between the two targets as well as the colors of the two targets is manipulated. Location-based selection predicts a proximity advantage in which judging the two targets sharing the same location should be more efficient than two targets far apart, regardless of the colors of the targets. Feature-based selection, on the contrary, predicts a same-color advantage in which judging two targets with the same color should be more efficient than two targets with different colors, regardless of the distance between the targets. Whether attentional selection based on location or color of the stimuli is further biased by changing the probability of location or color relevance in the task. This method allows us to compare task-relevant and task-

irrelevant information in the same paradigm without a shift in the paradigm and procedure as in post-display probe tasks (Kim & Cave, 1995, 2001; Vecera & Farah, 1994). Probability manipulation also prevents attention from being directed by a location probe as in the post-display probe tasks (thus, participants are more likely to adopt location-based selection).

The current study is designed to examine the behavioral predictions of the *space-independent hypothesis* in order to provide more complete evidence for direct use of features in attentional selection. To demonstrate that direct use of features in selection is spatially independent, the challenge is to minimize the confounding of location with features, and to avoid the high correlation between features and locations. Three important factors prevented the confounding from selection by location in the current study. First, overlapping stimuli were used, with two different features in the same location (See Figure 1). A pure location model of attentional selection predicts no effect of feature modulation for the overlapping stimuli inside the spotlight because it assumes that selection is insensitive to the feature properties of the stimuli. When a location is attended, all of the stimuli occupying the same location are selected and are processed to the same degree. If the feature properties of the stimuli in this location modulate task performance, the feature effect cannot be attributed solely to selection by location. Rather, selection must be based on features (Busse et al., 2006; Liu et al., 2007; Muller et al., 2006; Saenz et al., 2002; Stoppel et al., 2007; Vierck & Miller, 2005, 2006; Zhang & Luck, 2009).

Second, many studies supporting direct selection by features have presented stimuli made up of collections of moving dots or colored dots, so that different features

are intermixed within a region (Liu et al., 2007; Saenz et al., 2002; Stoppel et al., 2007; Treue & Martinez-Trujillo, 1999; Zhang & Luck, 2009). Since stimuli with different features did not completely overlap in these displays, one may argue that the feature effect can possibly be accounted for by feature-driven location selection if the size of the spotlight could be small enough to select a small region where one pattern did not overlap the other pattern. The overlapping stimuli may fail to prevent selection mediated by location in this extreme case. For example, there were 50 red and green dots randomly intermixed in a circular aperture (radius 5 °) in Saenz et al., and each red dot was not necessarily overlapped with a green dot at each single location. Participants could have attended a location of a red dot that did not overlap with a green dot. Nevertheless, Saenz et al. showed that BOLD activation at the unattended location was modulated by whether the stimuli at the unattended location shared the same feature as the attended stimuli at the attended location, suggesting that participants did not adopt location-based selection and that feature-based selection occurred even when stimuli with different features did not completely overlap. Furthermore, it has been suggested that the size of spotlight can be no smaller than one degree of visual angle (Eriksen & Hoffman, 1973). Several studies have successfully ruled out location-based selection by presenting overlapping stimuli smaller than one degree of visual angle (Duncan, 1984; Harms & Bundesen, 1983; Humphreys, 1981; Vecera & Farah, 1994). Following the same logic, the size of each stimulus was controlled to be around one degree of visual angle, and the area of overlap was maximized in our study, to ensure the co-selection of the overlapping stimuli when attention was directed to a location. In this case, any feature modulation in our study is difficult to attribute to feature-based selection.

Third, the exact target identities on each trial were unknown in advance to prevent a strategy of only attending to the non-overlapping part of a stimulus. There were a range of possible targets (e.g., digits from two to nine) so that participants could not perform the task by holding a certain target template in visual working memory and simply matching the target template with the non-overlapping partial shape of a stimulus. In addition, distractors looked similar to targets. A high level of accuracy could not be achieved in this task by attending to only the non-overlapping parts of stimuli and identifying partial shapes. With this design, the entire shape of the stimulus, rather than part of it, would need to be attended for full identification, and if the stimulus was selected with a spatial spotlight, the other overlapping stimulus would be partly selected as well.

The first goal of the current study is to investigate how feature information affects attentional selection when there is no explicit top-down bias to features in selecting relevant stimuli. Several studies have shown that stimulus color affects attention through image segmentation and perceptual grouping even when color is task-irrelevant (Baylis & Driver, 1992; Driver & Baylis, 1989; Harms & Bundesen, 1983; Humphreys, 1981; Kramer & Jacobson, 1991). In Experiment 1 of the current study, the two targets either occupied the same location or different locations. They were either in the same color or in different colors. A same-color effect is expected in which selecting two targets with the same color is more efficient than selecting two targets with different colors. This is because when the two targets share the same color, they will be grouped together and selection will operate on the entire color group; when the two targets are in different colors, they should not be grouped. There is a cost for attention to select between

different groups, as predicted by the same-object effect (Baylis, 1994; Duncan, 1984; Lavie & Driver, 1996; Vecera & Farah, 1994). Therefore, the same-color effect should result from stimuli being grouped by color similarity and the entire color group is selected by attention. Most critically, we tested the *space-independent hypothesis* of attentional selection, which has not been successfully demonstrated in earlier behavioral studies. With overlapping stimuli, the same-color effect should reflect that attention directly selects the entire feature group without being mediated by the locations of the selected group. Thus, stimulus color is used directly in selection, independent of the location information.

The second goal was to examine whether feature information was used automatically or strategically in perceptual grouping and in attentional selection. The findings on the influence of perceptual grouping on attention are usually discussed under the scope of how bottom-up factors (e.g., perceptual grouping or figure-ground segmentation) constrain attentional selection. However, the interactive account proposes that perceptual grouping should not be viewed as a pure bottom-up process. Rather, perceptual grouping is modulated by top-down influence (Ben-Av et al., 1992; Driver et al., 2001; Freeman et al., 2001; Han et al., 2005; Mack et al., 1992; Vecera, 2000). Experiments 2 and 3 adopted the same design as Experiment 1 but varied the degree of task relevance of feature and location information. Varying the degree of feature relevance in the task allowed us to examine to what extent color grouping was modulated by goal-driven, top-down control. In Experiment 2, the probability of feature relevance was reduced to the chance level. There was no incentive to attend to the colors of the stimuli because color information could not help perform the task. A significant same-

color effect will indicate that color grouping is formed automatically and is also used in attentional selection automatically. On the contrary, the lack of the same-object effect will indicate that color grouping is not formed when colors of the stimuli are not informative, and that color grouping is modulated by top-down influence. In Experiment 3, feature and location information were both informative and task-relevant (slightly above the chance level). The incentive to use the colors or the location of the stimuli for selection was equal. Attention could use color, location or both types of information to select targets. Flexibility of attention in using different types of information could be reflected by the presence of the same-color effect or the proximity effect across Experiments 1, 2 and 3.

Experiments 1, 2 and 3 examined how color information affected attentional selection when attention was not biased to any particular color. The same-color effect is expected if color is used in a general way in which both colors are involved, as when red stimuli are combined to form one group and the green stimuli are simultaneously combined to form a separate group. When there is no specific top-down bias to select one color over the other, it is reasonable to assume that each color group is selected with equal probability.

Experiment 4 further investigated how color affected selection when there was an explicit top-down bias given by the color cues (See Figure 4). In this case, color information was used more specifically, so that stimuli with the validly cued color could be selected with higher priority compared to the stimuli with the invalidly cued color. Experiment 4 allowed us to investigate how the specific use of color in biasing selection interacted with the general use of color in grouping.

The third goal of the current study further examined the flexibility of attention in using color and location information when attention was directed to a color or a location in a top-down or bottom-up manner. In addition, the functional relationship between using color and using location in controlling the selection process was investigated. The experimental designs of Experiments 5 and 6 were similar to Experiment 4 with two modifications. First, there was only one target presented among the four characters on each trial. Attention might have been divided across the entire stimulus region in Experiments 1 to 4 since one of the two targets could appear on each location. It was possible that stimuli were processed under divided attention, and the same-color effect might be arising only under divided attention. In this case, feature-based selection is contingent upon location-based selection and the two are dependent. To demonstrate the independence of using color and using location, a color cueing effect should be found regardless of whether the color was at the attended or unattended location. Presenting a single target at a location in Experiments 5 and 6 allowed us to dissociate the effect of location-based selection and color-based selection. Second, attention was directed to a location or a color by cues. Each cue contained both color and location information about the upcoming target simultaneously and the validity of each cue type (e.g., 50% validity in Experiment 5 and 60% and 80% validity in Experiment 6) was manipulated independently. Therefore, the relationship between using color and using location could be measured in the single task and the flexibility of using color and location information could be examined.

Furthermore, we considered the influence of exogenous and endogenous control of attention on the relationship between using color and location separately. The

endogenous cues carried different levels of cue informativeness, while the exogenous cues were always uninformative in our study. The manipulation of different levels of cue informativeness allowed us to investigate the flexibility of top-down control in using color and location (Experiment 6; See Figure 6). By using uninformative exogenous cues (Experiments 5; See Figure 5), we were able to examine whether using location and color was automatic. If using location and using color were independent, no interaction is expected. We are particularly interested in testing the *hierarchical organization hypothesis*, which predicts that the color cueing effect should only be found in the attended location, not in the unattended location.

CHAPTER 5

EXPERIMENT 1: THE INFLUENCE OF COLOR GROUPING ON ATTENTIONAL SELECTION

Experiment 1 was designed to investigate how color affected attentional selection when attention was not biased to select a particular color by an explicit top-down command. In addition, it was aimed to examine the behavioral consequences of the *space-independent hypothesis*, which was a critical prediction for any selection based on nonspatial properties. The design was modeled after that of Lavie and Driver (1996) because it allowed us to examine how attention used spatial property and nonspatial property of the stimuli in a single task. The design was also informative about the roles of automatic and strategic processes in attentional selection.

To make sure that color modulation could not be accounted for by location-based selection, we adopted overlapping stimuli. Stimuli were two letters and two digits, with two stimuli partially overlapping in the same location on each side of the fixation point. The digits were the targets and the letters were distractors. In order to discriminate overlapping stimuli clearly, the two stimuli that overlapped in the same location always appeared in different colors (See Figure 1). Participants were asked to find the two digits and made a same or different category judgment according to the identities of the two targets (e.g., if both digits were odd or even, they were in the same category; if one odd and one even, they were in different categories). As in Lavie and Driver (1996), there were three conditions. When the two targets were in different locations, they were either in the same color (*feature* condition), or in different colors (*far* condition); when the two targets occupied the same location, they were in two different colors (*near* condition).

Since no studies in the literature had ever used exactly the same design as the current study, the two targets were made to appear in the same color (*feature* condition) more often than in different colors in order to make sure our design was capable of yielding a same-color advantage when attention was biased to select on the basis of features. Of the total trials, 80% were in the *feature* condition, 10% were in the *far* condition and 10% were in the *near* condition. Note that the color of the stimuli was task-relevant and informative since the two targets appeared in the same color for a high percentage of trials. However, participants were not informed about the feature probabilities in Experiment 1, so that the knowledge of features being relevant would have to be learned in the course of the experiment.

Selection by features and selection by location make contrasting predictions in Experiment 1. Based on the previous findings on perceptual grouping and attention, we expect that stimuli should be organized into two separate perceptual groups according to color similarity and that attention should select an entire perceptual group (Baylis & Driver, 1992; Driver & Baylis, 1989; Harms & Bundesen, 1983; Humphreys, 1981; Kim & Cave, 2001; Kramer & Jacobson, 1991). A same-color effect is expected in which processing two stimuli in the same color group (*feature* condition) should be more efficient than processing two stimuli in different color groups (*far* condition), controlling for the distance between the two targets. This same-color effect is predicted because when a color group is selected, all of the stimuli in the group should receive facilitated processing. Since the two targets in the *feature* condition always had the same color and thus were grouped together, they should be selected concurrently. In the *far* condition, the two targets were always in different colors and thus in different groups, so that one would

be in the selected group while the other was not. There should be a cost in switching attention between two groups (Baylis, 1994; Baylis & Driver, 1992; Duncan, 1984; Lavie & Driver, 1996; Law & Abrams, 2002; Vecera & Farah, 1994; Watson & Kramer, 1999). Therefore, color grouping predicts that the performance in the *far* condition should be worse than that in the *feature* condition.

On the contrary, location-based selection predicts that task performance depends on the spatial distance between the two targets, rather than the color of the targets. The distance between the two targets was less in the *near* condition than in the *far* or *feature* conditions. If attention uses location information of the stimuli, then performance in the *near* condition would be better than that in the *far* condition after the color of the two targets was controlled.

Method

Participants.

Participants were 18 undergraduate students at the University of Massachusetts Amherst. The entire experiment took fifty to fifty-five minutes. All participants had normal or corrected-to-normal vision and received academic credit as compensation for their time.

Apparatus.

The stimuli were presented on a 15-inch VGA color monitor attached to a PC computer. E-Prime experimental software (Schneider, Eschman, & Zuccolotto, 2002) was used for controlling the timing of events, generating stimuli and recording responses. All responses were recorded through a keyboard. Participants were seated approximately 65 cm from the monitor with the entire display subtending 26.9° x 21°.

Design and Stimuli.

The stimulus display was composed of a central fixation square and four stimuli occupying two locations. The two locations were approximately 3.5° to the left and the right of the fixation. Two stimuli were partially overlapped in the same location with the stimulus in the back offset 0.27° lower than the stimulus in the front. In the left location, the stimulus in the back was also offset 0.27° to the right of the front stimulus, and in the right location the stimulus in the back was offset 0.27° to the left of the front stimulus. To make the overlapping stimuli at the same location more discriminable, the two stimuli were always colored differently (one red and one green) on each trial. The order of the position (front or back) and the color of the stimulus were randomly determined for each location on each trial.

The stimuli were either letters or digits in Courier font and either in red (RGB 255, 0, 0) or green (RGB 0, 245, 0). Each object subtended 0.88° in width and 1.1° in height. The letters were uppercase B, D, E, H, R, S, T and U. The digits were 2, 3, 4, 5, 6, 7, 8 and 9. The task was to judge if the two targets were in the same or different categories. For example, if the two targets were both odd or both even numbers, they should be classified as being in the same category. If one was odd and one even, they should be labeled as being in different categories. Two letters and two digits were randomly selected on each trial with the constraints that there were equal numbers of “same” and “different” responses. The occurrence of each digit or letter was approximately equal across trials and no two letters or digits were repeated in the same trial. The central fixation square subtended 0.35° in width and height and was colored in white. All stimuli were presented on a dark background.

There were three conditions in Experiment 1: *near*, *far*, and *feature* (see Figure 1). In the *near* condition, two digits with different colors appeared in the same location. In the *far* condition, the two digits were in different locations and in different colors. In the *feature* condition, the two digits were in different locations and in the same color. 80% of the total trials were in the *feature* condition and the remaining trials were split between the other two conditions equally.

Procedure.

The experiment was conducted in a testing room with normal lighting. Each trial began with the fixation display for 1000ms (see Figure 2). Participants were asked to find the two digits and performed a categorization task. Participants viewed an example of each condition and were told that the digits could appear in the front or in the back, and in the same location or different locations. They were encouraged to attend to all of the stimuli, including the ones in the back, and make their judgments based on the entire contour of the stimuli. Participants were told to divide attention between both sides of the display while maintaining their eyes on the fixation at all times.

The stimulus display immediately followed the fixation display and was presented for 235 ms. A pilot study showed that the average accuracy was low when the stimulus display was presented for 201ms, so the stimulus display was adjusted to 235ms to keep the overall accuracy higher. The stimulus display was then followed by a response display instructing participants to make a response as quickly and accurately as possible. The response display stayed on the screen until a response was made. The task was to judge whether two digits were in the same or different categories. If two digits were in the same category (e.g., both even or both odd), participants pressed the 'Z' key. If two

digits were in different categories (e.g., one even and the other odd), participants pressed the 'M' key. Auditory feedback with a beep sound for 500ms was provided for incorrect responses. The next trial began with an inter-trial-interval of 800 ms.

A block of 30 practice trials were conducted before the experiment. The experiment consisted of 12 blocks with 60 trials per block (80% *feature*, 10% *far* and 10% *near* in each block). Participants could take a break after each block.

Results

Two participants with accuracy around the chance level were excluded from data analyses (M=51% and 54%, respectively; the average accuracy for the remaining participants was 82.3%). Trials with response times longer than 3000ms and shorter than 300ms were excluded from RT analyses, resulting in 2.6% of the total trials being removed. Data from same and different response categories were pooled together since the overall pattern looked similar between the two response categories. The average accuracies and RTs for the three conditions are summarized in Table 1.

The average accuracy (%) for *far*, *feature* and *near* condition was 82.9, 86.6 and 76.0 respectively ($F(2,30)=22.21, p<.05$). In planned comparisons, the accuracy in the *feature* condition was higher than that of the *far* condition (M=3.7%, $t(15)=3.40, p<.05$), indicating a benefit for judging two targets with the same color over judging two targets with different colors. The accuracies in the *far* condition and the *feature* condition were both higher than the *near* condition (M=6.9%, $t(15)=3.49, p<.05$ and M=10.6%, $t(15)=6.43, p<.05$, respectively), suggesting that there was no advantage for processing two targets close in space in the current study.

The same kinds of analyses were carried out for the mean reaction times for correct trials. The mean reaction times (ms) for the *far*, *feature* and *near* condition were 1292, 1209 and 1423 respectively ($F(2,30)=31.13, p<.05$). The mean reaction time in the *feature* condition was faster than the *far* condition (mean= 83ms, $t(15)=4.16, p<.05$), suggesting a benefit for two targets in the same color than in different colors. The mean reaction time in the *far* condition was faster than the *near* condition (mean= 131ms, $t(15)=4.10, p<.05$). The mean reaction time in the *feature* condition was also faster than the *near* condition (mean= 212ms, $t(15)=7.45, p<.05$). Consistent with the accuracy results, the mean reaction time in the *near* condition was the slowest, suggesting no advantage for two targets close in space.

Discussion

Our findings are consistent with the literature on the effect of grouping on attention in that the color of the stimuli affects attentional selection through perceptual grouping even when an explicit top-down bias to color is not present (Baylis & Driver, 1992; Driver & Baylis, 1989; Harms & Bundesen, 1983; Humphreys, 1981; Kim & Cave, 2001; Kramer & Jacobson, 1991). The same-color effect indicates that color is used to segment stimuli into different groups, and that a color group is then selected between the two. We hypothesize that each color group has equal probability being selected on each trial since there is no bottom-up or top-down bias for attention to select one color over the other. The use of color information is not color-specific because both red and green items have equal probability to be selected. We will further discuss the specific use of color in Experiment 4. Processing targets in the same group (*feature* condition) is more efficient than processing targets in different groups (*far* condition) because there is a cost in

switching attention between groups (Baylis, 1994; Baylis & Driver, 1992; Duncan, 1984; Lavie & Driver, 1996; Law & Abrams, 2002; Vecera & Farah, 1994; Watson & Kramer, 1999).

Alternatively, one may argue that the same-color effect could have been caused by a perceptual effect, not attentional effect, such as processing two stimuli in the same color is somehow more perceptually efficient than two stimuli in different colors. We will examine this issue in Experiment 2. We will show that the same-color effect cannot be accounted for by a perceptual advantage and it reflects an attentional effect. The size of the same-color effect (83ms in RT and 3.7% in accuracy) observed in the current study is greater than the same-object effect observed in other studies (28ms in RT in Lavie & Driver, 1996; 15ms in RT in Law & Abrams, 2002). Possible explanations for this larger effect include differences in stimuli, task difficulty and the presence of distractors. For example, the average accuracy in the current study is lower compared to that in Lavie and Driver and in Law and Abrams (around 90% in both studies), indicating that our task with overlapping digits is more difficult and that participants might have relied more on the color information. Another possibility is that two distractors were presented in the current study while no distractors were presented in Lavie and Driver or in Law and Abrams. Distractor interference is greater when distractors are grouped with the target due to the co-selection of the target and the distractor (Baylis & Driver, 1992; Kramer & Jacobson, 1991). When a group is selected in the *far* condition, additional processing is required to inhibit stronger distractor interference due to grouping, resulting in even a slower or less accurate response in the *far* condition.

As discussed in the introduction, the current design with the overlapping stimuli discourages color modulation being mediated by location. The results suggest that stimulus color is directly used to direct attentional selection without selection of the stimulus locations. A behavioral advantage is found when the targets share the same color across space. Thus, the findings of Experiment 1 support the *space-independent hypothesis* and provide more complete behavioral evidence for it. Processing two stimuli sharing the same location (the *near* condition) is less efficient than processing two stimuli far apart in distance (the *feature* condition), suggesting that participants did not use the locations of the stimuli in selection in Experiment 1 and that selecting one stimulus did not cause the second stimulus at the same location to be selected automatically. The fact that location-based selection is inefficient further strengthens the conclusions that the same-color effect observed in Experiment 1 is best accounted for by selection based on feature information and that the designs of the current study successfully measures the effect of feature-based attention without confounding with location-based selection. Lavie and Driver (1996) also reported poor performance when the two targets were close in distance. They suggested that the relatively poor performance in the *near* condition was probably caused by the fact that the two targets appeared on opposite sides for a large proportion of the trials. This possibility will be discussed in details in Experiment 3.

In our study, the two targets appeared in the same color with a high probability (80%) and thus color provided useful information about the upcoming targets. Since the colors of the stimuli were relevant, the same-color effect may be driven by either the automatic or the strategic use of color in perceptual grouping and in selection. Vierck and Miller (2006) varied the validity of color cues in a RSVP task and found that color cueing

effect was greater when the validity was higher even when participants were not explicitly informed about the validity, showing that the color cueing effect could be driven in a top-down manner. Although our task and procedure are quite different from those of Vierck and Miller, it is possible that our participants might also have inferred color relevance in the course of the experiment even though they were not informed about the color probability. At the end of the experiment, we asked participants if they were aware that digits appeared in the same color frequently. Excluding the one participant who did not answer this question, eight out of 15 noticed higher color probability during the experiment. However, there was no difference in the strength of the same-color effect (*far* vs. *feature*) between the two groups ($t(13)=-.35, p>.5$ for accuracy; $t(13)=.30, p>.5$ for RT). We conclude that the knowledge of color relevance can be acquired either implicitly or explicitly on different participants, and that the influence on attentional selection is similar. Whether using color in perceptual grouping and in attentional selection was automatic or strategic was unclear because feature information was relevant in Experiment 1. We further clarified this issue in Experiment 2.

CHAPTER 6

EXPERIMENT 2: AUTOMATIC OR STRATEGIC USE OF COLOR IN SELECTION

Lavie and Driver (1996) reported that objects were selected automatically when object information was completely task-irrelevant. In their study, the two target gaps were sometimes on the same object, as defined by the Gestalt principle of connectedness. We modified Lavie and Driver's design and extended their findings to grouping by color similarity in Experiment 1 and showed that color-based selection was spatially independent. However, the same-color effect could be attributed to a color group being selected either automatically or strategically (with implicit or explicit knowledge) because color was task-relevant in Experiment 1. Experiment 2 reduced the incentive to use color in selecting targets to examine if color affects attention automatically. The number of trials in the *feature* condition was equal to the other two conditions, so that the two targets appeared in the same color in only one third of the total trials. Participants had little motivation to select targets based on their colors since the two targets would appear in different colors for most of the trials. If the same-color effect is observed when color information is not useful, we will conclude that color information is used to affect selection automatically through color grouping. If the same-color effect disappears, we will conclude that the use of color is modulated by task demands in the selection process.

We also consider the top-down influence on perceptual grouping. Some researchers view perceptual grouping as a bottom-up or preattentive process that operates before attentional selection (Baylis & Driver, 1992; Duncan, 1984; Humphreys, 1981; Kanwisher & Driver, 1992; Kramer & Jacobson, 1991; Lamy, Segal & Ruderman, 2006;

Moore & Egeth, 1997). Lavie and Driver's findings imply that probability manipulation may only affect the selection process of attention because it reduces the motivation to attend to object information. Probability manipulation does not affect perceptual grouping because grouping is formed preattentively. Based on this logic, the lack of a same-color effect in our study would indicate that color is used in perceptual grouping automatically but attention does not select from color groups. On the other hand, more recent studies have proposed that perceptual grouping is modulated by top-down factors (e.g., attention or familiarity; Ben-Av et al., 1992; Freeman et al., 2001; Han et al., 2005; Linnell & Humphreys, 2007; Mack et al., 1992;). Probability manipulation not only affects the selection process, but also perceptual grouping because of the link between attention and grouping. Thus, a lack of the same-color effect in Experiment 2 should indicate that color is not used automatically to form perceptual groups, and that grouping does not automatically affect the selection process.

Method

Participants.

Participants were 23 undergraduate students at the University of Massachusetts Amherst. The entire experiment took fifty to fifty-five minutes. All participants had normal or corrected-to-normal vision and received academic credit as compensation for their time.

Apparatus.

Same as Experiment 1.

Design and Stimuli.

All aspects of the design were the same as those in the Experiment 1, except that the proportion of trials in each of the three conditions (*feature*, *far*, and *near*) was the same (33%).

Procedure.

The procedure was identical to Experiment 1. Participants were not informed about the probability of each condition in advance. A block of 30 practice trials were conducted before the experiment started. The experiment consisted of 12 blocks with 60 trials per block.

Results

Two participants with accuracy around the chance level were excluded from data analyses (M=49% for both; the average accuracy for the remaining participants was 82.3%). Trials with response times longer than 3000ms and shorter than 300ms were excluded from RT analyses, resulting in 1.9% of the trials being removed. Data from same and different response categories were pooled together since the overall pattern looked similar between the two response categories. The average accuracies and RTs for the three conditions are summarized in Table 1.

The average accuracy (%) for *far*, *feature* and *near* conditions was 83.3, 82.0 and 81.7 respectively ($F(2,40)=2.55, p>.05$). In planned comparisons, there was no difference between the *feature* and *far* conditions ($t(20)=1.84, p>.05$), showing no benefit for judging two targets with the same color. The performance in the *far* condition was slightly better than the *near* condition (M=1.6%, $t(20)=2.74, p<.05$). There was no difference between the *feature* and the *near* condition ($t(20)=.41, p>.5$).

The same kinds of analyses were carried out for the mean reaction times for correct trials. The mean reaction times (ms) for the *far*, *feature* and *near* conditions were 1158, 1156 and 1178 respectively ($F(2,40)=3.26, p<.05$). There was no difference between the *feature* and *far* conditions ($t(20)=.32, p>.5$), suggesting no benefit for two targets with the same color. The mean reaction time in the *near* condition was slightly slower than the *far* condition ($M=20$ ms, $t(20)=1.85, p=.08$) and slower than the *feature* condition ($M=22$ ms, $t(20)=1.92, p=.07$), clearly indicating that there was no advantage of two targets being close in space.

Discussion

When the probability of same-color targets is reduced to the chance level, there is no top-down signal biasing attention to select targets based on color groups, the disappearance of the same-color effect in Experiment 2 suggests that color of the stimuli does not affect attentional selection when color is task-irrelevant and that selection based on color grouping is not automatic. The findings also confirm that the same-color effect is caused by attention, rather than nonattentional factors discussed in Experiment 1. If it was caused by perceptual factors, such as a higher efficiency for processing two stimuli in the same color, the same-color effect should have appeared even when the probability of same-color targets was low. Together with the results of Experiment 1, we conclude that color of the stimuli influences the selection process only when it provides useful information in the task, and that attention does not use color grouping as a selection basis automatically. Our findings are consistent with the view that the nature of the task determines which representation can be activated for attentional selection (Kramer & Jacobson, 1991; Lamy & Tsal, 2000; Vecera & Farah, 1994). For example, Lamy and

Tsal propose that a feature-based representation is activated only when that feature information is task-relevant.

In addition, our findings support the view that perceptual grouping is modulated by attention. The lack of the same-color effect can be interpreted as stimuli are not grouped based on color similarity in the first place, since attending to color is not useful in Experiment 2. As a result, attention does not use color grouping as the selection basis. As noted earlier, some studies have emphasized the importance of top-down influence on perceptual grouping (Driver et al., 2001; Linnell & Humphreys, 2007; Vecera, 2000). Based on this interactive account of perceptual grouping and attention, we hypothesize that manipulating color probability not only affects the attentional process but also the process of perceptual grouping. Therefore, the effect of color grouping observed in the current study is most likely driven in a top-down manner, not in a pure bottom-up manner. Just as attention may affect grouping, grouping may also be able to affect the allocation of attention, leading to a complex interaction between the two. It is worth noting that this view differs somewhat from the assumption of Lavie and Driver (1996), who concluded that object-based selection was automatic and that perceptual grouping based on connectedness was formed preattentively. This issue will be discussed later.

In Experiments 1 and 2, processing two targets sharing the same location (*near* condition) is inefficient. The results suggest that participants do not adopt location-based selection in the current task. However, the difference between the *far* and *near* conditions is greatly reduced in Experiment 2 (M=-20 ms in RT; M=1.6% in accuracy) compared to Experiment 1 (M=-131 ms in RT; M=6.9% in accuracy) which indicates that the use of location information in selection is modulated by task demands. When the two targets

appear in the same location with a low probability, selection by location is discouraged, resulting in a much poorer performance in the *near* condition as shown in Experiment 1. However, the relatively poor performance in the *near* condition in Experiments 1 and 2 raises doubts as to whether the current design can effectively measure the effect of location-based selection. We will test this question in Experiment 3.

To sum up, the results of Experiments 1 and 2 successfully demonstrate that color of the stimuli affects attention through perceptual grouping and that attentional selection based on color grouping is independent of location. Attention is sensitive to the probability of the occurrence for different stimulus types, and the use of color or location is tuned to the task demands. When color information is informative, it is used as a selection basis for attention by grouping stimuli based on color similarity. When color is uninformative, color grouping does not occur and attention does not select from the color groups. Likewise, the use of location as a selection basis is modulated by the probability of stimulus types. Participants tend to adopt location-based selection when two targets are more likely to appear together at the same location.

CHAPTER 7

EXPERIMENT 3: THE FLEXIBILITY OF USING LOCATION AND COLOR IN ATTENTIONAL SELECTION

The purpose of Experiment 3 was twofold. First, the performance in the *near* condition in Experiments 1 and 2 was relatively low. This could be caused either by perceptual difficulties in processing two overlapping targets, or by an attentional bias weighting against using location of the stimuli in selection due to the low probability of two targets at the same location. The improved performance in the *near* condition in Experiment 2 seemed to indicate the latter. To distinguish the two possibilities, the proportion of the *near* trials was increased in Experiment 3 in order to bias attention to select by location. If the poor performance was caused by perceptual difficulties, probability manipulation should not affect the results. On the contrary, if the poor performance was caused by attentional bias, the high probability of two targets sharing a location should favor location-based selection, resulting in a better performance in the *near* condition.

Second, Lamy and Tsal (2000, 2001) suggested that location and feature information could be used to bias attentional selection simultaneously and that task demands determined if a location or a color would be used. As discussed earlier, Lavie and Driver's (1996) design makes it possible for attention to use feature and location information in a single task. Experiment 3 maximized the proportion of the *feature* trials and the *near* trials so that the incentive to use color or location was equivalent. The design allowed us to compare the flexibility of attention in using color and using location in the same task.

Method

Participants.

Participants were 24 undergraduate students at the University of Massachusetts Amherst. The entire experiment took fifty to fifty-five minutes. All participants had normal or corrected-to-normal vision and received academic credit as compensation for their time.

Apparatus.

Same as Experiment 1.

Design and Stimuli.

All aspects of the design were the same as those in Experiment 1, except that the proportions of trials in the *feature*, *far* and *near* conditions were 45%, 10% and 45% respectively.

Procedure.

The procedure was identical to Experiment 1.

Results

Four participants with accuracy around the chance level were excluded from data analyses (M=54%, 59%, 53% and 52%, respectively; the average accuracy for the remaining participants was 81.5%). Trials with response times longer than 3000ms and shorter than 300ms were excluded from RT analyses, resulting in 4.8% of the trials being removed. Data from same and different response categories were pooled together since the overall pattern looked similar between the two response categories. The average accuracies and RTs for the three conditions are summarized in Table 1.

The average accuracies (%) for *far*, *feature* and *near* conditions were 81.5, 82.6 and 80.5 respectively ($F(2,38)=1.83, p>.05$). In planned comparisons, there was no difference in the accuracy between the *feature* condition and the *far* condition ($t(19)=1.15, p>.1$), indicating no benefit for judging two targets with the same color compared to judging two targets with different colors. There was no difference in the accuracy between the *far* and the *near* condition ($t(19)=.82, p>.2$), indicating processing two targets close in space was no more efficient than processing two targets far apart. The accuracy in the *feature* condition was marginally higher than that in the *near* condition ($t(19)=1.94, p=.07$), suggesting there might be a slight advantage for two targets being the same color compared to two targets being close in space.

The same kinds of analyses were carried out for the mean reaction times for correct trials. The mean reaction times (ms) for the *far*, *feature* and *near* condition was 1200, 1191 and 1169 respectively ($F(2,38)=2.67, p=.08$). There was no difference in the mean reaction times between the *feature* and *far* condition ($t(19)=.52, p>.5$), suggesting no benefit for processing two targets in the same color than in different colors. The mean reaction time in the *near* condition was faster than the *far* condition ($t(19)=2.51, p<.05$) and the *feature* condition ($t(19)=2.08, p=.05$), suggesting a benefit for the two targets sharing the same location.

Discussion

Compared to the previous two experiments, there is an advantage for processing targets at the same location in Experiment 3, after controlling for the colors of the targets: participants were faster in judging the *near* condition compared to the *far* condition. The results of Experiment 3 clearly indicate that the poor performance in the *near* condition in

Experiments 1 and 2 was not caused by perceptual difficulties in processing overlapping stimuli but by a top-down bias weighting attention against using stimulus location as the selection basis since location information was not useful in finding targets. The current study successfully demonstrates that the probability of different stimulus arrangements biases attentional selection. Along with the findings of the previous two experiments, we conclude that attention is sensitive to the location probability and is flexible in using stimulus location as the basis of selection. When the location of the stimulus is predictive of the upcoming target, attention is biased by this information, either to select a stimulus based on the location of the stimulus as shown in Experiment 3 or to prevent selection based on location information as in Experiment 1. Note that the two targets appeared on the opposite sides of the display somewhat more frequently (55%) than on the same side (45%) in Experiment 3. It is likely that the performance in the *near* condition can be further improved if the *near* probability is further increased.

Contrary to the effect of location probability manipulation, Experiment 3 shows little evidence for the same-color effect, suggesting that color does not consistently affect attentional selection when the probability of two targets of the same color is somewhat higher than the chance level (45%). This finding is similar to that in Experiment 2 in which color information is completely uninformative (33% probability of same-color targets) and does not affect attention in selection. Note that Experiments 1, 2 and 3 only differ in the probability of occurrence for different types of conditions. The results show that attention is responsive to the probability of the stimulus' types and is flexible in using the relevant or informative dimension (e.g., location or color) in selection. Nevertheless, the findings of Experiments 2 and 3 suggest that a small amount of increase

in color probability (from 33% to 45%) was not enough to drive attention to use color as the selection basis in a top-down manner. Attention seems to be less sensitive to the color probability manipulation than the location probability manipulation since the same amount of increase in location probability (from 33% to 45% in Experiments 2 and 3) is enough to bias attention to use location of the stimuli as the selection basis. Therefore, in the realm of event probability in biasing attentional selection, attention may be less prone to adopt feature-based selection compared to location-based selection.

It has been proposed that attention may activate different representations as selection bases, depending on task demands (Lamy & Tsal, 2000; Vecera & Farah, 1994). For example, Lamy and Tsal showed that when a location was cued, a location cueing effect was observed; with the same design, when object features were cued, a feature cueing effect was observed. The authors suggested that attention might be best described as a pattern of activation that involved several representations and the distribution of activation varied according to the tasks. Although the current study is theoretically able to measure the effect of color modulation and the effect of location modulation in a single task, Experiment 3 demonstrates the effect of location-based selection but fails to show the effect of feature-based selection. An important difference between Lamy and Tsal and our study is that the former uses cues to direct attention to location or feature of the stimuli explicitly while the latter did not present any cue to direct attention. Participants might have attended to the most available or salient information (e.g., location in this case) and ignored other relevant information. To ensure that participants attend to both color and location of the stimuli simultaneously, we presented location and color cues in the next two experiments to direct attention to color and location information.

CHAPTER 8

EXPERIMENT 4: TOP-DOWN BIAS IN USING COLOR IN SELECTION

The previous three experiments investigated how color information was used in controlling attentional selection when attention was not directed to a specific color value. We showed that color was used even when the specific color of the targets was not known. We also demonstrated the importance of the grouping factor: stimuli with the same color were grouped together and color groups became the basis for selection. Since attention was not biased to one particular color in advance, both the red and green color groups had equal probability of being selected by attention. Before the processing of the stimulus began, selection was not color-specific.

Experiment 4 further investigated the use of color information to control attention in a more specific way by providing foreknowledge of the probable target color. Studies have shown that a color cue can direct attention to a stimulus with the cued color, so that the stimulus with the cued color is selected with higher priority compared to a stimulus with an uncued color (Cooper & Juola, 1990; Laarni, 1999; Lamy & Tsal, 2000; Vierck & Miller, 2006). When there is a clear color bias, selection on the basis of color predicts that all of the stimuli with the attended color should benefit from attentional modulation, whereas the visual processing of the stimuli with the unattended color should be unaffected. Selection should be color-specific in this sense.

The task in Experiment 4 was the same as the previous ones except that an exogenous color cue was presented in the beginning of each trial to direct attention to a particular color in advance. A cue was considered valid only when both targets appeared

in the cued color. The color cue was 70% valid, meaning that the two targets appeared in the cued color in 70% of the total trials (referred to the *valid-feature* condition). The rest were invalid trials (10% *invalid-feature*, *far* and *near* conditions, respectively). Note that color information was task-relevant. Participants were informed about the probability of valid cues and were asked to pay attention to the cue.

The previous three experiments have shown how color is used in perceptual grouping and it affects attentional selection in a top-down manner. Experiment 4 investigates how top-down color grouping interacts with another top-down explicit color bias (e.g., color cues) to control attentional selection. It is possible that the explicit top-down command driven by color cues is dominant and that only the stimuli with the cued color would be processed and selected. The strong bias to one particular color could override the other top-down bias based on perceptual grouping, resulting in the disappearance of the grouping effect. This extreme version of cue dominance predicts that performance in the *valid-feature* condition should be better than that in the *invalid-feature* and *far* conditions because both the *invalid-feature* and *far* trials are invalid. Such a result would suggest that an explicit top-down command is efficient in biasing attention only to the stimuli with the cued color. Furthermore, it predicts that there should be either no differences between *invalid-feature* and *far* conditions or a slightly better performance in the *far* condition than in the *invalid-feature* condition because one target appears in the cued color in the *far* condition whereas no targets appear in the cued color in the *invalid-feature* condition. According to this prediction, the same-color advantage will be only observed in the *valid-feature* condition, and not in the *invalid-feature* condition.

On the contrary, the use of color may be driven by the top-down color grouping and the top-down cue bias at the same time. The same-color advantage may appear in both the *valid-feature* and the *invalid-feature* conditions compared to the *far* condition, indicating an effect of color grouping. A color cueing effect may also appear since attention is cued to select one color over the other on a trial-by-trial basis. If so, the group with the cued color will be selected with a higher priority, resulting in a better performance in the *valid-feature* condition compared to the *invalid-feature* condition. Furthermore, we expect the performance in the *near* condition to be similar to the results in Experiment 1 because the probability of the *near* trials is the same. This will suggest that location-based selection is not adopted in this task.

Method

Participants.

Participants were 31 undergraduate students at the University of Massachusetts Amherst. The entire experiment took fifty to fifty-five minutes. All participants had normal or corrected-to-normal vision and received academic credit as compensation for their time.

Apparatus.

Same as Experiment 1.

Design and Stimuli.

All aspects of the design were the same as those in Experiment 1, except for the following. The central square in the fixation display was colored either red or green to serve as a color cue and fixation point at the beginning of each trial. The colored square remained on the screen until the response display. The color of the cue was randomly

selected on each trial with the constraint that red and green cues were equally likely to appear. Four conditions were used: *near*, *far*, *valid-feature* and *invalid-feature* (see Figure 3). The two targets both appeared in the same color as the cue in the *valid-feature* condition, whereas the two targets both appeared in a different color than the cue in the *invalid-feature* condition. 70% of the total trials were in the *valid-feature* condition and the remaining trials were split across the other three conditions equally.

Procedure.

The procedure was identical to Experiment 1 except for the following. Each trial began with the cue display for 1000ms (see Figure 4). Participants were informed about the validity of the color cue (70%) in the beginning of the experiment. They were encouraged to attend to the color of the cue and to use color to find the two targets. Participants viewed an example of a *near* trial and an example of a *valid-feature* trial in the practice session.

Results

Three participants with average accuracy around the chance level were excluded from data analyses (M=59%, 48% and 60%, respectively; the average accuracy for the remaining participants was 80.2%). Trials with response times longer than 3000ms and shorter than 300ms were excluded from RT analyses, resulting in 2.6% of the trials being removed. Data from same and different response categories were pooled together since the overall pattern looked similar between the two response categories. The average accuracies and RTs for four conditions are summarized in Table 2.

The average accuracies (%) for *near*, *far*, *valid-feature* and *invalid-feature* condition were 75.1, 79.5, 84.3 and 81.9 respectively ($F(3,81)=19.70$, $p<.05$). We further

carried out planned comparisons based on the predictions made by feature-based selection, location-based selection and perceptual grouping. A color cueing effect was found in which the *valid-feature* condition was more accurate than the *invalid-feature* condition ($M=2.4\%$, $t(27)=2.31$, $p<.05$), showing that participants used color cues in the task. The *valid-feature* condition was more accurate than the *far* condition ($M=4.8\%$, $t(27)=3.83$, $p<.05$), showing a benefit for processing two targets with the cued color over one with the cued color and the other with a different color. The *invalid-feature* condition was marginally more accurate than the *far* condition ($M=2.4\%$, $t(27)=1.81$, $p=.08$), suggesting an effect of perceptual grouping, independent of color cueing effect. The *near* condition was less accurate than the *far* condition ($M=4.4\%$, $t(27)=2.31$, $p<.05$), indicating that there was no advantage for two targets sharing the same location.

The same kinds of analyses were carried out for the mean reaction times for correct trials. The mean reaction times (ms) for the *near*, *far*, *valid-feature* and *invalid-feature* condition were 1270, 1201, 1101 and 1129 respectively ($F(3,81)=26.82$, $p<.05$). The mean reaction time in the *valid-feature* condition was faster than the *invalid-feature* condition ($M=28\text{ms}$, $t(27)=2.28$, $p<.05$), showing that participants used the color of the cue in selecting targets. The mean reaction time in the *valid-feature* condition was faster than the *far* condition ($M=100\text{ms}$, $t(27)=5.01$, $p<.05$), again showing the benefit for processing the two targets with the cued color. The mean reaction time in the *invalid-feature* condition was faster than the *far* condition ($M=72\text{ms}$, $t(27)=4.00$, $p<.05$), suggesting a grouping effect, with an advantage in processing two targets in the same color compared to two targets in different colors. The mean reaction time in the *near*

condition was slower than the *far* condition ($M=69$, $t(27)=3.55$, $p<.05$), indicating there was no advantage with two targets that shared the same location.

Discussion

Similar to our previous findings, a same-color advantage was observed in which processing two stimuli in the same color (both the *valid-feature* and the *invalid-feature* conditions) was more efficient than processing two stimuli in different colors (the *far* condition). This indicates that stimuli are grouped by color similarity, and that color grouping affects attentional selection even when attention is explicitly directed to a specific color in advance. This aspect of selection is color-nonspecific. The comparison between the *far* condition and the *invalid-feature* condition provides a measure of the grouping effect that is independent of the color cue effect, and the better performance in the *invalid-feature* condition than in the *far* condition suggests a strong grouping influence in the current experiment. The influence of color grouping does not disappear when there is another explicit top-down signal biasing attention only to select stimuli with a particular color.

The better performance in the *valid-feature* condition than the *invalid-feature* condition shows an effect of explicit top-down bias in controlling attention to select based on a particular color. Participants attended to the color cue and selected stimuli with the cued color. The visual processing was more efficient when the two targets were in the cued color compared to when they were both in the uncued color (the *invalid-feature* condition) or when one target was in the cued color and the other was in the uncued color (the *far* condition). In the previous experiments in which stimuli formed two color groups, attention was presumed to select one of the two color groups at random

since there was no clear bias to select one over the other. With a color cue, Experiment 4 shows that attention is further biased to select one particular color group with a higher priority on a trial-by-trial basis and visual processing of the stimuli in the selected color group is enhanced. When the targets are not found in the first color group, attention shifts to the second color group. Selection thus is color-specific. To sum up, the findings in Experiment 4 clearly demonstrates that two sources of top-down control co-direct attention in the same task, with the general use of color reflected by the grouping effect and the specific use of color reflected by the color cueing effect.

The poor performance in the *near* condition suggests that participants did not use the location of the stimuli as the selection basis. This is consistent with the findings of our previous experiments in which attention was not biased to use location information when the two targets were unlikely to share a single location.

CHAPTER 9

EXPERIMENT 5: THE RELATIONSHIP BETWEEN USING LOCATION AND USING COLOR IN EXOGENOUS ORIENTING

Experiments 5 and 6 investigated the relationship between using location and using color in selection. The *independent hypothesis* predicts that using location should be independent of using color. No interaction between the two is expected. The *interactive hypothesis*, on the other hand, predicts an interaction between the type of cues and the size of cueing effect. The exact pattern, however, is not clear in the literature. Among the many observed patterns, we are especially interested in the *hierarchical organization hypothesis*, which proposes that location information is unique because it controls what feature information will direct attention. Under this hypothesis, feature-based selection is contingent on location-based selection so that a feature cueing effect should only occur at the attended location.

We further consider the influence of two components of attentional control, exogenous orienting and endogenous orienting, on the relationship between using color and location since exogenous and endogenous orienting are qualitatively different (Folk, Remington, & Johnston, 1992; Jonides, 1981; Posner, 1980). The endogenous or voluntary component, usually driven by symbolic cues, reflects a top-down or goal-directed process. It takes longer to orient attention since interpretation of the symbolic cues takes time. Exogenous orienting of attention, usually triggered by peripheral onset cues, occurs rapidly and in at least some circumstances is resistant to interruption. It reflects an automatic or stimulus-driven process. Since different components of attentional orienting are determined by the nature of the cues and the tasks, exogenous

onset cues will be used in Experiment 5 and endogenous cues will be used in Experiment 6. The results of Experiments 5 and 6 will be compared to see if the functional relationship between using location and using color differs according to the endogenous orienting and exogenous orienting of attentional control.

One possible reason for the controversy in the literature is that many studies confound feature-based selection and location-based selection, because each feature occupies a distinctive location, so that feature modulation can result from either the feature being selected or the location of the feature being selected. Overlapping stimuli are used to serve as a better control in Experiments 5 and 6. The experimental design of Experiments 5 and 6 is similar to that of Experiment 4 with two modifications. First, there is only one target presented among the four characters on each trial (See Figures 5 and 6). Attention might have been divided across the entire stimulus region in Experiments 1 to 4 since targets could appear on both locations. It is possible that stimuli were processed under divided attention, and the same-color effect arose only under divided attention. In this case, feature-based selection is contingent upon location-based selection and the two are dependent. To dissociate the effect of selection by features and by location, we presented a single target and manipulated the validity of location cues and color cues independently, so that a target with validly cued color can appear at the validly cued location or at the invalidly cued location. Second, attention is directed to a stimulus at a particular location or with a particular color by cues. Each cue contains both color and location information about the upcoming target simultaneously and the validity of each cue type is manipulated independently. Therefore, the relationship between using

color and using location can be measured and the flexibility of using color and location information can be examined in the single task.

A crossover pattern is often observed in the literature for exogenous location cueing with facilitation of attention at the short SOA and inhibition at the long SOA (location-based inhibition of return, or IOR; see Klein, 2000 for a review). The results for feature-based IOR are controversial, with some studies finding color-based IOR (Law, Pratt & Abrams, 1995) and some not (Busse et al., 2006; Kwak & Egeth, 1992). Busse et al. varied the SOA between the exogenous cues and the target display to examine the time course of location-based and color-based IOR. The target display was made up of two overlapping fields of gray random dots moving in different directions at each side of the central fixation. The task was to detect a brief change in the direction of motion. One field of the random dots at either the right or left side of the display suddenly changed its color to red, serving as an exogenous location cue and color cue. The validity of the cue was manipulated independently for location and color. Busse et al. found location-based IOR but no evidence for color-based IOR. The onset of IOR varied with the task difficulty.

Since the current study only investigates facilitation of attention, the SOA between the exogenous cues and stimulus display was chosen to avoid IOR based on the results of a pilot study. Note that the exogenous cues in Busse et al. (2006) were the task stimuli themselves (random dots), which might have made the uninformative exogenous cues more salient compared to the exogenous cues used in our study. The exogenous cues in our study were not part of the task stimuli, so that participants could completely ignore the cues.

Method

Participants.

23 undergraduate students participated in Experiments 5. All participants had normal or corrected-to-normal vision. Participants in Experiment 5 received extra credits as compensation. Experiment 5 took approximately 45-50 minutes.

Apparatus.

To avoid the confounding of overt orienting, eye movements were monitored in both of the experiments. The stimuli were presented on a 19-inch Viewsonic CRT monitor attached to a PC interfaced with an SR Research Limited Eye-Link 2 eye tracking system. Participants were seated 66 cm from the monitor with their heads in a chin rest. The entire display subtended $25.7^\circ \times 32.5^\circ$ of visual angle. All responses were recorded through a response box.

Design and Stimuli.

The designs of Experiment 5 were similar to Experiment 4 except for the following differences. There was only one digit presented on each trial, along with three letter distractors. The task was to judge if the digit was odd or even. An outlined square surrounding the two overlapping stimuli on one side of the display served as an onset cue. The cue was either on the left or right location and was either red or green. The location and the color of the onset cue were randomly chosen and were not predictive of the target location and color (See Figure 5).

Each trial consisted of a cue display for 129 ms, a blank display for either 247 or 318 ms in different blocks, the stimulus display for 141 ms, and the response display lasting until a response was made. The time intervals of the stimulus display, the blank

display and the cue display were chosen to reach the facilitatory cueing effect according to the results of a pilot study.

Cue validity (valid vs. invalid) and the type of cue (location cue vs. color cue) were manipulated independently and simultaneously. Two intervals between the cue and the stimulus displays (SOA) were used (376 and 447 ms) to assess if the relationship between using location and using color varied over time. In a pilot study in which we varied SOAs from short to long, the two SOAs chosen for the current study yielded facilitatory cueing effect for location cues. No color-based IOR was observed in the pilot study. A total of four blocks of 56 trials each for a SOA was conducted. The order of SOA in the eight blocks was randomly determined so that a block may have either short or long SOA, with the constraints that there were four short SOA blocks and four long SOA blocks.

Procedure.

The procedure was the same as Experiment 4 except for the following differences. Participants were told that the location and the color of the cues were unpredictable of the target location or target color. Participants pressed the left button on a response box with the left index finger if the digit was odd and pressed the right button with the right index finger if the digit was even. They were asked to press the response buttons as quickly and as accurately as possible. They were instructed to maintain fixation on the central square and their eye movements were monitored throughout the entire experiment.

Results

Trials with response times longer than 2000ms or shorter than 200ms, and trials with eye movements larger than 1.5 ° away from the fixation point while the stimulus

display was on the screen were excluded from further analyses, resulting in 6.1% of the total trials being removed. Data from odd and even response categories were pooled together because the overall pattern looked similar. Tables 3 and 4 summarize the results for 376 ms SOA condition and 447 ms SOA condition, respectively.

The mean reaction times for correct trials were subjected to a 2 (Location Cue Validity: valid vs. invalid) x 2 (Color Cue Validity: valid vs. invalid) repeated-measures ANOVA for each SOA condition (See Figure 7a). For the 376 ms SOA, a location cueing effect (Location cue validity) was observed ($M=11\text{ms}$, $F(1,22)=6.80$, $p<.05$), showing that responses to the targets were faster at the cued location than at the uncued location. Neither the color cueing effect (Color cue validity) nor the interaction were significant ($F(1,22)<1$ and $F(1,22)=1.65$, $p=.23$, respectively). For the 447 ms SOA, a location cueing effect was observed ($M=20\text{ms}$, $F(1,22)=4.39$, $p<.05$). Neither the color cueing effect nor the interaction were significant ($F(1,22)<1$ in both cases).

The average accuracy for the 376 ms SOA and 447ms SOA was 82.8% and 82.3%, respectively (See Figure 7b). The same kinds of analyses were carried out for the accuracy scores. For the 376 ms SOA, neither the location cueing effect, the color cueing effect, nor the interaction were significant ($F(1,22)<1$ for all three). For the 447 ms SOA, a location cueing effect was observed but not a color cueing effect ($M=2.9\%$, $F(1,22)=4.39$, $p<.05$ and $F(1,22)<1$, respectively), showing that responses to the targets at the cued location were more accurate than at the uncued location, whereas responses to the targets with the cued color did not differ from those with the uncued color. However, the interaction between location cueing effect and color cueing effect was significant ($F(1,22)=8.03$, $p<.05$). Post hoc comparisons revealed that the mean accuracy for the

color-valid trials was higher than that for the color-invalid trials at the validly cued location ($M=4.3\%$, $t(22)=3.1$, $p<.05$). No other comparisons were significant. The results of the mean accuracy scores suggest that the effect of color cues is contingent on location information.

Discussion

We show that attention is directed by an exogenous onset cue without confounding selection by location and selection by color. No location-based or color-based IOR was found in the current study, which confirms that the two SOAs used successfully measure the facilitatory effect of attention. Attention is drawn to the validly cued location and task performance becomes more accurate at the validly cued location than at the invalidly cued location for both short and long SOAs. Such facilitatory effect is purely spatial, regardless of the color of the target. Furthermore, the two factors interact, with task performance more accurate when targets appear in the validly cued color compared to the invalidly cued color at the validly cued location with the longer SOA. That is, color cueing effect is found at the validly cued location, but not at the invalidly cued location. The results suggest that in exogenous cuing, color modulation is contingent on location information and that the use of color in directing attention is dependent on the use of location. Our results of the exogenous orienting of attention are consistent with the *hierarchical organization hypothesis*, which proposes that attention uses location as the selection basis and location further controls what feature information can be processed in the visual system.

Busse et al. (2006) also reported similar findings with a significant effect of location cue validity and an interaction between location cue validity and color cue

validity. Responses to the targets were fastest when targets appeared at the validly cued location and in the validly cued feature. Moreover, the interaction was evident even at the earliest SOA bin (100-300ms). Analyses in accuracy scores were not reported in Busse et al.. As we pointed out earlier, Busse et al. used a brief color change of the motion stimuli as an exogenous location cue and color cue. One possible reason why Busse et al. observed an earlier interaction between location cue validity and color cue validity is that because the exogenous cues were part of the target stimuli, which might make cues more salient and less able to be ignored even the cues were uninformative about the targets. Exogenous orienting of attention may be contaminated with endogenous orienting. Another possibility is that the properties of their motion stimuli (e.g., judging motion direction) may be more salient than our shape stimuli (e.g., letters to be discriminated). The time course of the effect of stimulus-driven control of attention may vary according to the type of stimuli.

The orienting of attention triggered by location or color cues in the exogenous condition is automatic or stimulus-driven, since the onset cues are unpredictable of the location or color of the targets and participants have no incentive to use them. This is confirmed by the subjective report from all participants, who said that they did not attend to the onset cues during the experiment. Nevertheless, their performance was affected by the location and the color of the onset cues. In addition, the finding that the color cueing effect only occurs at the validly cued locations at the longer SOA but not at the shorter SOA indicates that unpredictable location cues exert an earlier influence on the exogenous process of attention, while unpredictable color cues take longer to express their influence

on the exogenous process of attention. Thus, our results suggest that location cues differ from color cues in the ability to capture attention at different points in time.

CHAPTER 10

EXPERIMENT 6: THE RELATIONSHIP BETWEEN USING LOCATION AND USING COLOR IN ENDOGENOUS ORIENTING

Experiment 6 extended the investigation of the relationship between using location and using color information to a task in which attention was controlled in a goal-driven or endogenous manner. As mentioned in the introduction, Egner et al. (2008) presented an endogenous location and color cue in a visual search task and varied the cue validity (valid vs. invalid) and the level of cue informativeness (50%, 70% or 90% validity) for both location and color cues independently on the same group of participants. They found a location cueing effect and a color cueing effect, and both cueing effects were larger for the 90% validity condition than the 70% validity condition. No interaction between these factors was observed. The authors concluded that advance knowledge of location and color produced independent effects on visual search performance.

We adopted a similar design to Egner et al. (2008) but with overlapping stimuli. An endogenous cue, containing both location and color information, was presented simultaneously in the beginning of a trial. The cueing validity (valid vs. invalid) for location and color cues was independently manipulated. The level of cue informativeness (60% vs. 80%) was further varied independently across location and color cues. For example, an endogenous cue might inform participants that the target will appear at the left location with 60% probability and will be red with 80% probability. This design allows us to assess the flexibility of voluntary control of attention in using color and location across different levels of cue informativeness. Uninformative cues (e.g., 50%

validity) were not used because they would not provide additional knowledge in understanding the relationship between location and color in directing endogenous attention. All these factors resulted in a 2 (Location Cue Informativeness: 60% vs. 80%) x 2 (Color Cue Informativeness: 60% vs. 80%) x 2 (Location Cue Validity: valid vs. invalid) x 2 (Color Cue Validity: valid vs. invalid) repeated-measures design.

One difference between Experiments 5 and 6 was that the participants in Experiment 6 were more experienced than those in Experiment 5, spending multiple hours performing the task. Subjects were given more practice because the design of Experiment 6 was more complex, with four conditions of cue type and the level of cue informativeness. The four conditions were repeated three times on the same group of participants in a random order to reach stable and optimal observations (See Method section for details). This large number of total trials also helped participants to learn how informative each cue was in different conditions. Having the same group of participants perform the task in different conditions also allowed us to compare the flexibility of the voluntary control of attention.

As mentioned earlier, Liu, Stevens and Carrasco (2007) showed that feature-based selection exhibited a slower influence than location-based selection, but the efficacy of endogenous feature cues was eventually equivalent to that of endogenous location cues. To ensure that there was enough time for attention to fully process both location and color cues, the endogenous cues were presented for 1000ms, followed by a blank interval of 200 ms. The duration of the cue display was determined by subjective reports in a pilot study. The results of Experiments 5 and 6 will be compared to see if the functional

relationship between using location and using color differs according to the endogenous orienting and exogenous orienting of attentional control.

Method

Participants.

Seven graduate and undergraduate students at the University of Massachusetts Amherst participated in Experiment 6. All participants had normal or corrected-to-normal vision. Participants in Experiment 6 received cash as compensation. Experiment 6 took approximately four hours to complete and was distributed across four separate days.

Apparatus.

Same as Experiment 5.

Design and Stimuli.

Similar to Experiment 5 except for the following differences. A central white arrow was used to drive endogenous orienting. The arrow either pointed to the right or to the left side of the screen, directing attention to a particular location. A letter was presented inside the arrow (“R” for red, “G” for green) to direct attention to a particular color. Each trial consisted of a cue display for 1000 ms, a blank display for 200 ms, the stimulus display for 141 ms and the response display lasting until a response was made (See Figure 6). The time intervals of the stimulus display, the blank display and the cue display were chosen to reach the facilitatory cueing effect according to the results of a pilot study.

The level of cue informativeness (60% and 80%) was manipulated independently across the type of cue (location cue vs. color cue), resulting in four conditions. The four conditions were repeated for three times to reach a stable observation, resulting in 12

blocks of 150 trials each. The order of the four conditions was randomly determined for each repetition and for each participant. Each condition was tested within a single block. Procedure.

The procedure was similar to Experiment 5 except that participants were informed about the level of the cue informativeness for location and color cues in the beginning of each block. The combination of location and color cue informativeness was kept the same throughout the entire block. Participants were instructed to allocate attention according to both the location cues and color cues.

Results

Trials with response times longer than 2000ms or shorter than 200ms, and trials in which the eyes deviated more than 1.5 ° from a fixation point while the stimulus display was on the screen, were excluded from further analyses, resulting in 6.2 % of the total trials being removed. Data from odd and even response categories were pooled together because the overall pattern looked similar. Figures 8 and 9 show the results for RT and accuracy respectively in the four experimental conditions.

The mean reaction times for correct trials were subjected to a 2 (Location Cue Informativeness: 60% vs. 80%) x 2 (Color Cue Informativeness: 60% vs. 80%) x 2 (Location Cue Validity: valid vs. invalid) x 2 (Color Cue Validity: valid vs. invalid) repeated-measures ANOVA. First of all, a main effect of location validity was evident, with shorter RT on validly cued trials than invalidly cued trials ($M=25$ ms, $F(1,6)=13.23$, $p<.05$). A main effect of color validity was also evident, with shorter RT on the validly cued trials than invalidly cued trials ($M=20$ ms, $F(1,6)=17.58$, $p<.05$). These effects suggested that attention was successfully directed by the location cues and color cues.

Note that the main effect of location validity and the main effect of color validity can be interpreted as a location cueing effect and a color cueing effect, respectively. Furthermore, location validity (or location cueing effect) marginally interacted with location cue informativeness, with a greater effect when location cues were 80% valid than 60% valid ($F(1,6)=4.92, p=.06$). Color validity (or color cueing effect) did not interact with color cue informativeness ($F(1,6)=2.63, p=.16$). The results indicated that the size of location cueing effect tended to increase when the location cue informativeness increased, but the size of the color cueing effect did not vary systematically with color cue informativeness. Most critically, the location validity neither interacted with color validity nor color cue informativeness ($F(1,6)<1$ for both cases), showing that the location cueing effect did not vary with either the color cue validity or the color cue informativeness. Color validity did not interact with location cue informativeness ($F(1,6)<1$), showing color cueing effect did not vary with location cue informativeness. These results suggest that the effect of location cues and color cues are independent.

The average accuracy was high ($M=85.2\%$). The same kinds of analyses were carried out for accuracy scores. No differences were found among the measures except that the location validity was marginally significant ($M=2.5\%$, $F(1,6)=5.01, p=.07$), indicating that the mean accuracy was higher when the target appeared at the validly cued location than at the invalidly cued location.

Discussion

Experiment 6 investigated how attention was directed by location cues and color cues in a top-down manner. The significant location and color cueing effects observed in Experiment 6 indicate that both location and color information can be used as the

selection bases. Moreover, no interaction is evident across different levels of factors when both types of cues are presented simultaneously, suggesting that location cues and color cues can be used independently in the selection process. Thus, the relationship between using color and using location is parallel and independent when attention is controlled in a top-down manner, supporting the *independent hypothesis* (Egner et al., 2008; Treue & Martinez-Trujillo, 1999). Our findings are consistent with the view that multiple representations can be activated concurrently, depending on the task requirements (Lamy & Tsal, 2000; Tsal & Lavie, 1993; Vecera & Farah, 1994).

Across different conditions, the size of the location cueing effect does not significantly differ from that of the color cueing effect ($M=5\text{ms}$, $t(6)= 1.59$, $p=.16$ for RT; $M= 2.2\%$, $t(6)= 1.21$, $p=.27$ for accuracy), suggesting that attention can be equally efficient in using location and color information. This result is consistent with Liu, Stevens and Carrasco (2007)'s finding that endogenous location cues and color cues improved task performance to a similar degree at a longer SOA. However, there is a tendency for the location cueing effect to vary systematically as a function of the level of location cue informativeness (60% vs. 80%), with a greater location cueing effect when location cue informativeness is higher. The color cueing effect fails to show this pattern. This seems to suggest that top-down control of attention may be more flexible in adjusting the amount of attentional resource based on location information than color information.

Compared to Experiment 5, the participants in Experiment 6 were more experienced in performing the task. Each participant repeated the four conditions three times in Experiment 6 in a random order. We aggregated the RTs across the four

conditions in each repetition to evaluate the impact of experience in the task. A 3 (Repetition) x 2 (Location Validity: valid vs. invalid) x 2 (Color Validity: valid vs. invalid) repeated-measures ANOVA was conducted. Repetition was not significant ($F(1,2) < 1$), indicating that responses to the targets did not get faster with practice. This is probably because by the end of the first repetition, participants had completed 600 trials and their task performance had reached a stable level. Location validity was significant and color validity was marginally significant ($F(1,6) = 7.25, p < .05$ and $F(1,6) = 4.21, p = .08$, respectively), indicating that the location cueing effect and the color cueing effect were evident. Again, location validity did not interact with color validity ($F(1,6) < 1$). Most importantly, repetition did not interact with any of the factors, suggesting that experience with the task did not systematically change the relationship between using location cues and using color cues. Thus, the experience of the task has little influence on how location cues and color cues are used by top-down control of attention in the current experiment.

By varying the nature of the cues in Experiments 5 and 6, we show how attention is directed by location cues and color cues endogenously and exogenously without confounding selection by location and selection by color. The relationship between using location and using color information can vary according to the mode of attentional orienting. On one hand, the use of location and the use of color can be independent when attention is controlled in a top-down manner. Both location and color information can be used as the selection basis and task demands modulate what relevant information is selected. On the other hand, the use of color is dependent on selection by location when attention is triggered by the salience of the stimuli. Location plays a dominant role in exogenous orienting of attention.

CHAPTER 11

GENERAL DISCUSSION

Direct Selection Based on Nonspatial Properties

A long standing debate over the basis on which visual attention operates concerns whether information can be selected directly according to features of the stimuli or selection by features is mediated by selection by location. The location-unique view proposes that the function of features is to guide attention to the location of the relevant stimulus and that all selection is ultimately mediated by location (Kim & Cave, 1995; Moore & Egeth, 1998; Shih & Sperling, 1996; Wolfe et al., 1989). Other studies suggest that spatial location is not the only basis for selection; nonspatial properties can be used directly as selection bases as well (Baylis & Driver, 1992; Driver & Baylis, 1989; Duncan, 1984; Harms & Bundesen, 1983; Humphreys, 1981; Vecera & Farah, 1994). One important reason why the controversial results exist may be that features usually occupy distinct locations in many studies and thus the effect of feature modulation can be attributed to selection on the basis of location, features, or a combination of both.

To dissociate features from locations, the current study investigates this issue by overlapping a red stimulus with a green stimulus in a location. A location-based theory such as the spotlight model of attention predicts that since both stimuli are inside the focus of attention, they should be selected and processed to the same degree, regardless of their colors. Thus, the color of the stimuli is not directly used in the modulation of attention. On the contrary, feature-based selection predicts that the color of the stimuli influences task performance with enhanced responses for the stimuli with the attended

feature, regardless of their locations. Any effect of feature modulation with the overlapping stimuli is best attributed to feature-based selection, not location-based selection (Liu et al., 2007; Saenz et al., 2002; Stoppel et al., 2007; Vierck & Miller, 2005, 2006; O'Craven et al., 1999; Zhang & Luck, 2009).

In addition to overlapping stimuli, we adopt a two-target task modified from Lavie and Driver (1996) in which the distance between the two targets as well as the colors of the two targets can be manipulated, which allows us to measure the distance effect and color effect concurrently in the same task. A same-color advantage (processing two targets with the same color is more efficient than two targets in different colors) reflects an influence of perceptual grouping on attention when color information is used in a general way: stimuli are grouped based on color similarity and attentional selection occurs on the basis of color groups. A proximity effect (processing two targets in the same location is more efficient than two targets far apart) reflects location-based selection because the distance between the two targets modulates the task performance.

Attentional selection by location or color is further biased by changing the probability of location or color relevance in the task. This method allows us to compare task-relevant and task-irrelevant dimensions in the same paradigm compared to other studies in which paradigm and procedures shift between the task-relevant and task-irrelevant dimension (Kim & Cave, 1995, 2001; Vecera & Farah, 1994). Probability manipulation also prevents attention from biasing toward location information due to the presence of a location cue (e.g., post-display spatial probes in Kim & Cave).

Across experiments, we observed the influence of color on attentional selection. First of all, the color of the stimuli affects attentional selection through perceptual

grouping, as reflected by the same-color effect. Stimuli are organized into two color groups and attentional selection facilitates the processing of an entire color group. The two color groups have equal probability to be selected since there is no bottom-up or top-down color bias. Thus, color information is used in a general way to affect attention. Second, top-down or bottom-up signals can further bias attention to select stimuli with a particular color as reflected by the endogenous or exogenous color cueing effect. This use of color information is color-specific because there is a particular color having higher priority to be selected compared to other colors. In Experiment 4, in which a color cue was presented in a two-target task, the same-color effect reflected a combined effect of color grouping and color cueing. As in Experiment 1, stimuli were organized into two color groups. In addition, the selection process was biased by the color cues, resulting in the validly cued color group being selected with a higher priority compared to the invalidly cued color group. The specific use of color information was also found in Experiments 5 and 6. Stimuli with the cued color were selected endogenously or exogenously with a higher priority. As a result, better performance was observed when the target shared the same color with the cue.

Our findings provide evidence for the *space-independent hypothesis*, which is an important prediction that distinguishes selection by features from selection by location. According to the *space-independent hypothesis*, feature modulation should be spatially independent and thus should occur throughout the entire visual field. The *space-independent hypothesis* has been examined in functional imaging and physiological studies by showing that neural responses of an ignored stimulus at an unattended location are modulated by whether it shares the same feature as the attended stimulus at an

attended location (Saenz et al., 2002; Treue & Martinez Trujillo, 1999). Behavioral evidence for the critical *space-independent hypothesis* is very limited and far from clear in the literature (Vecera & Farah, 1994; but see Kramer, Weber & Watson, 1997 and Lavie & Driver, 1996 for criticism). With overlapping stimuli, the same-color effect and the color cueing effect in the current study provide evidence supporting the claim that feature-based selection can be truly space-independent.

Furthermore, the manipulation of the distance of the targets in the two-target task (Experiments 1 to 4) strengthens our conclusion that feature-based selection occurs without being mediated by location. We show that processing two targets that have the same color but are far apart in space (7°) is more efficient than processing two targets that share the same location but are different in colors. This indicates that the effect of color modulation occurs across space under some conditions, overriding the location factor. Furthermore, if participants only attend to the non-overlapping part of the stimuli, a proximity advantage (better performance when two targets share the same location than when they occupy two distant locations) should be found, indicating that the location of the stimuli is selected. We find evidence for a same-color advantage but not for a proximity advantage. Together with the effects of color modulation, our findings provide more complete behavioral evidence for the feature-based selection. We conclude that both spatial and nonspatial properties (e.g., color of the stimuli) can be used directly as the selection basis.

Differences in experimental design may be partly responsible for the incongruence between studies supporting selection mediated by location and selection by features. A general concern in studying the basis of attentional selection is how to make

selection by features as efficient as selection by location. In many studies in which a stimulus occupies a location, there tends to be more possible stimulus locations than possible stimulus features (e.g., four colors occupy eight locations). When attention uses location information as the selection basis, each selection deals with one stimulus at the attended location. When attention uses feature information as the selection basis, however, each selection may deal with more than one stimulus with the attended feature. When location uncertainty is higher than feature uncertainty, selection by location is usually reported since stimuli can be easily distinguished based on their locations (Cave & Pashler, 1995; Kim & Cave, 1995, 1999; Moore & Egeth, 1998; Shih & Sperling, 1996; Tsal & Lavie, 1993). The reason why selection based on spatial properties is dominant in these experiments is probably because selection based on nonspatial properties is overshadowed by the dominance of location in this case (Vierck & Miller, 2005). On the contrary, the overlapping stimuli used in the experiments presented here makes stimuli harder to distinguish solely based on their locations, and thus selection by location is no more efficient than selection by color in these experiments. This is especially true in our design in which there are two possible target locations and two possible target colors. When a location is selected, attention processes two stimuli at the location. Similarly, when a color is selected, attention processes two stimuli with the same color across the visual field. This may explain why studies with overlapping stimuli successfully demonstrate a color modulation effect when the dominance of location in selection is prevented (Liu et al., 2007; Saenz et al., 2002; Vierck & Miller, 2005, 2006).

The Influence of Color Grouping

Color affects attentional selection in multiple ways in our study. One way is through perceptual grouping. The same-color effect demonstrates that the colors of the stimuli are used to organize stimuli into two color groups, one red and one green, and these color groups become the selection bases. As discussed earlier, the use of color in this aspect of selection is not color-specific, since both red and green colors are involved in the grouping process and each color has equal probability to be selected. When attention is directed to a color group, all stimuli inside the color group are selected as a whole and visual processing is enhanced. As a result, task performance is better when two targets are in the same group compared to when two targets are in different groups.

Our findings are consistent with other studies that show nonspatial grouping factors affect attentional selection (Baylis & Driver, 1992; Duncan, 1984; Harms & Bundesen, 1983; Humphreys, 1981; Kramer & Watson, 1995; Lavie & Driver, 1996; Vecera & Farah, 1994). For example, in a central letter categorization task, Baylis and Driver showed that response competition was greater when the incongruent distractors shared the same color with the central target, or were connected with the central target by dashed lines. Baylis and Driver attributed the greater distractor interference effect to grouping between distractors and targets by color similarity or by connectedness. Although Baylis and Driver, as well as other researchers, interpret object or grouping effects as evidence for selecting from a spatially-invariant representation, they usually fail to exclude the alternative account of location-based selection. By adopting overlapping stimuli and by manipulating the colors and the locations of the two targets,

we show that color groups can be used as the selection basis and the selection is spatially-invariant.

In the experiments described above, the same-color effect occurs even when stimuli are overlapped in the same location. It is possible that participants actually perceive the overlapping stimuli as being located on two different depth planes. If depth perception did occur in our study, then since the front or back position is assigned to each item randomly, the two targets are on the same depth plane on only half of the trials, and participants had no advance knowledge about which plane would contain the targets. The same-color effect suggests that color grouping occurs across depth planes and is not constrained by the spatial factors. Baylis and Driver (1992) also observed that color grouping occurred when distractors were not spatially adjacent to the target. Spatial continuity between two stimuli is not necessary, and nonspatial grouping factors can sometimes override spatial distance.

Since many color grouping studies have tested how color grouping affects attention when attention is not biased to any color in advance (Baylis & Driver, 1992; Duncan, 1984; Harms & Bundesen, 1983; Humphreys, 1981; Kim & Cave, 2001), the results may lead to the conclusion that perceptual grouping affects the selection process only when attention is not set on any particular color value. We dismiss this possibility by showing that the same-color advantage is found in both the *valid-feature* condition and the *invalid-feature* condition in Experiment 4, in which attention is cued to use a particular color in selection. The results of Experiment 4 suggest that not only the stimuli with the cued color but also the stimuli with the uncued color are organized as a group, reflecting a strong influence of color grouping even under a top-down color bias. We

conclude that color grouping has a strong influence on visual attention when an explicit top-down color bias is available and when it is not available. Note that even though we find a strong effect of color grouping, color grouping in our study reflects a top-down modulated process rather than one that is automatic. This point will be further illustrated in the next section.

The role of perceptual grouping on attention is often discussed in the context of object-based selection or object recognition because the products of perceptual grouping are usually viewed as being more or less equivalent to the conceptual objects we experience. As other studies have pointed out, most studies on object-based attention in fact deal with image segmentation and parsing, rather than the conceptual objects in our daily life (Driver et al., 2001; Watson & Kramer, 1999). Real-world objects, however, are usually defined intuitively and may not be the same as the perceptual chunks based on Gestalt principles. We show that perceptual grouping affects feature-based attention, not object-based attention. The stimuli in our study are digits and letters that can be individualized as separate and distinctive objects perceptually and conceptually. It is unlikely that participants had treated the two stimuli sharing the same color as parts of a single object. It is based on the color of the two objects that perceptual grouping and attentional selection operate. Our findings suggest that attention can operate on the basis of features and that it is probably inappropriate to view the products of perceptual grouping equal to the conceptual objects.

Top-down Perceptual Grouping

The robust effect of perceptual grouping on selection even when grouping factors are task-irrelevant has led many researchers to presume that stimuli are grouped together

at the preattentive stage, and that this early perceptual grouping constrains attentional allocation and selection (Baylis & Driver, 1992; Duncan, 1984; Humphreys, 1981; Kanwisher & Driver, 1992; Kramer & Jacobson, 1991; Moore & Egeth, 1997). However, by manipulating the degree of color relevance to the task, we find that the same-color effect is observed only when color information is useful and task-relevant and it disappears when color information is unpredictable of the upcoming targets. This indicates that stimuli are not grouped based on color similarity automatically, and thus attention does not always select from perceptual groups. The use of color in perceptual grouping and in attentional selection is modulated in a top-down manner. Our findings are consistent with the view that perceptual grouping can be modulated by top-down factors, such as attention and task relevance (Ben-Av et al., 1992; Driver et al., 2001; Freeman et al., 2001; Han et al., 2005; Mack et al., 1992; Vecera, 2000).

Alternatively, one may argue that probability manipulation only affects the attentional process, not perceptual grouping. In this view, color is used to form perceptual groups automatically, but attention does not select from color groups when color is irrelevant to the task. Lavie and Driver (1996) varied the probability of two targets being on the same connected lines to measure if selecting on the basis of object was automatic. They found the same-object advantage even when selecting from the same line was task-irrelevant. The authors concluded that attentional selection is based on objects automatically. Their study implies that grouping by connectedness occurs automatically and that probability manipulation only affects the attentional process. While this conclusion is appropriate for Lavie and Driver's study, we reject this alternative account for our experiments because of the following two reasons. First, accumulating evidence

indicates that perceptual grouping should not be treated as a pure bottom-up process but should be viewed as an interactive process that can be modulated by top-down factors, thus challenging the preattentive grouping view (Ben-Av et al., 1992; Freeman et al., 2001; Han et al., 2005; Linnell & Humphreys, 2007; Mack et al., 1992). According to this view, color grouping probably does not occur when color is not relevant to the task. Second, our findings with color grouping differ from those of Lavie and Driver in grouping based on connectedness in an important way: when color information is informative in our experiments, color is used to group stimuli and the grouped stimuli become the selection bases for attention. When color is task-irrelevant, color is not used to form color groups and color groups are not used as a selection basis. In our view, if color information is not used in segmentation, it is also not used in selection, whereas the alternative account presumes that color is used in the grouping process but somehow not used in the attentional process. Our account offers a more parsimonious and consistent explanation of how color is used in different levels of visual processing than the alternative account, and it probably illustrates a fundamental difference between color grouping and grouping based on connectedness.

Different Principles of Perceptual Grouping

In some theories, the visual field is segmented into organized chunks that correspond to the objects in the environment based on figure-ground segmentation rules or Gestalt principles (Driver et al., 2001; Duncan, 1984; Duncan & Humphreys, 1989; Treisman, 1982; Vecera, 2000). Common Gestalt principles of grouping include proximity, similarity, common fate and connectedness. Although researchers tend to treat different grouping principles as one general mechanism, the accumulating evidence

suggests not all grouping principles are the same (Han et al, 1999; Han et al., 2005; Han, Ding & Song, 2002; Kimchi & Peterson, 2008; Kimchi & Razpurker-Apfeld, 2004; Palmer & Rock, 1994). For example, recognition of a letter formed by proximity or connectedness was faster and more accurate than recognition of a letter formed by similarity of shape, indicating that processing proximity or connectedness was more efficient than processing shape similarity (Han et al., 1999). Event-related brain potential (ERP) results also show that grouping by proximity elicits an earlier activity than grouping by shape similarity, suggesting distinct neural substrates underlying different grouping principles (Han et al., 2002).

As mentioned previously, Lavie and Driver (1996) conclude that grouping by connectedness occurs automatically, while we conclude that color grouping is modulated by top-down influence. Since the design and logic are similar between the two studies, the inconsistency may result from how stimuli are grouped (different principles of perceptual grouping). Lavie and Driver's stimuli are many line segments, forming two long lines. Although Lavie and Driver referred to the grouping effect to the same-object effect, the grouping is in fact based on line segments being connected into a line (grouping by connectedness). Dashed lines can be easily perceived as an unbroken line through low spatial frequency channels in the visual system so that grouping by connectedness may not even be needed (Driver et al., 2001; Han et al, 1999). Thus, the same-object effect observed in Lavie and Driver may not necessarily reflect the effect of selection based on perceptual grouping. In our experiments, however, we use individual digits and letters that are distinctive from each other perceptually and conceptually. Stimuli can only be grouped based on color similarity, which cannot be achieved through

low spatial frequency channels. We are confident that the same-color effect in our study is caused by perceptual grouping.

Furthermore, Han, Humphreys and Chen (1999) compared the task performance of discriminating letters formed by many solid small rectangles and letters formed by solid long lines. In the former, local elements were grouped into a global shape based on proximity (although the authors referred it to grouping by proximity, the small solid rectangles were similar to line segments and could be interpreted as grouping by connectedness). In the latter, global shapes were formed by connected lines and thus no grouping was needed. Letter discrimination was equally efficient in the two conditions, indicating that the effect of grouping by connectedness was strong. Therefore, grouping by connectedness may be stronger than grouping by many other grouping principles, including color similarity, and might be less affected by top-down influence, as shown in Lavie and Driver (1996). According to theories of object-based attention, the visual field is organized into perceptual chunks or objects so that attention can be allocated accordingly to recognize the object. Image segmentation can be achieved through bottom-up processes, such as figure-ground segmentation and certain principles of perceptual grouping. Bottom-up processes further constrain attentional allocation and selection. Several studies have provided evidence supporting bottom-up image segmentation (Driver et al., 2001; Kimchi & Peterson, 2008; Moore & Egeth, 1997). Moore and Egeth (1997) took advantage of illusions (e.g., Ponzo and Muller-Lyer illusions) and manipulated whether the task-irrelevant background elements (e.g., black and white circles) were grouped by similarity in contrast polarity to induce the visual illusion. The task was to judge the relative length of the two horizontal target lines. If

grouping occurred without attention, line judgment should be biased by the illusion. The authors found that background elements induced visual illusions so that participants tended to report one target line longer than the other even when they were of the same length, suggesting that similarity grouping by contrast polarity occurs without attention (Note that the stimuli in Moore and Egeth also may be easily perceived as unbroken lines through low spatial frequency channels in the visual system so that grouping process may not even be needed). Kimchi and Peterson hypothesized that figure-ground segmentation occurred preattentively and adopted similar logic in a change detection task. Two successive displays were presented, each containing a small target matrix of black and white random squares centered in a background scene consisting of alternating regions that were organized into figures and grounds by convexity. The target matrix was either unchanged or switching the location of a black square with a white square in the two successive displays. The task was to detect if the target matrix changed or not. The figure and ground regions in the background scene either stayed the same in the two successive displays or switched locations so that the central target matrix was either positioned on a figure (or a ground) successively, or one on a figure and one on a ground, or vice versa. If figure-ground segmentation occurred without attention, then responses to the targets (same or different) should be affected by the background scene (same or different) so that responses to the same targets should be faster or more accurate when the background scene stayed unchanged, or responses to the different targets should be faster or more accurate when the background scene changed (the congruency effect). The results confirmed the authors' hypothesis and provided evidence for bottom-up process of figure-ground segmentation.

As discussed earlier, another group of researchers suggest that perceptual grouping is probably a result of statistical regularities in the environment, and that top-down factors can influence the process of image segmentation (Beck & Palmer, 2002; Freeman et al., 2001; Han et al., 2005; Linnell & Humphreys, 2007; Mack et al., 1992; Vecera & Farah, 1997). Following the logic of the same-object effect, Vecera and Farah presented participants two overlapping letters and asked them to judge if two probes were on the same or different shapes. The two overlapping letters were either presented upright (familiar) or rotated (unfamiliar). Responses were faster with the upright letters than the rotated letters. The authors concluded that image segmentation was an interactive process because top-down knowledge (familiarity) influenced how image was segmented. Our findings support the interactive view of perceptual grouping and attention. Certain principles of perceptual grouping or figure-ground segmentation may be stronger than others (e.g., convex, connectedness or proximity), resulting in less modulation by top-down influence. However, top-down factors can have a strong impact on how the image will be segmented and what parts will be selected by attention. Whether these top-down factors can always override the bottom-up source or vice-versa is still an open question.

Selection Based on Location Information

In addition to the evidence for feature-based selection, we show that attention can use location information as the selection basis in our tasks. First, when the two targets are close in space as in Experiment 3, task performance is faster than when the two targets are far apart, indicating that when a location or a small region is selected, visual processing of the second stimulus benefits from being close to the selected location. Such a location effect has been interpreted as evidence for selection based on location

(Hoffman & Nelson, 1981; Kim & Cave, 1995; Tsal & Lavie, 1993). Note that participants did not know which of the two locations contained a target in advance (although the two targets appear together at a level above chance). Spatial attention probably shifts to one of the two locations randomly since the two locations have equal probability to contain targets. Second, a classical location cueing effect is also found in Experiments 5 and 6 when endogenous or exogenous location cues are presented. Task performance is better for the target at the validly cued location than at the invalidly cued location, indicating that attention is directed to the location of the cue and selects the stimulus at the attended location. Consistent with other studies, we show that advance knowledge about the target location can facilitate the target processing (Lamy & Tsal, 2000; Posner, Snyder & Davidson, 1980; Theeuwes & Van der Brug, 2007).

One of the critical functions of selective attention is that visual processing of the selected stimulus is enhanced compared to that of the unattended stimulus (Kastner & Ungerleider, 2000; Desimone & Duncan, 1995). Some researchers have argued for a unique role of location in selection based on the findings that spatial attention enhances the visual processing of the attended stimulus while selection by features does not (Moore & Egeth, 1998; Shih & Sperling, 1996; Theeuwes & Van der Brug, 2007). Theeuwes and Van der Brug employed signal detection theory with briefly presented visual search displays to examine if cueing affected sensory gain. The logic was that if cueing affected early sensory processing, a sensitivity increase was expected. If cueing only affected later decision-related processing, sensitivity was not expected to change. The search display consisted of six objects arranged on an imaginary circle: five identical green distractor outlined circles and one target singleton that differed either in color

(color singleton) or in shape (shape singleton). There was a gray oriented line segment inside each object, and the task was to discriminate the orientation of the line segment inside the target singleton (e.g., vertical or horizontal). An endogenous cue, giving either location, color or shape information about the singleton, was presented with 80 % validity to direct attention to a particular dimension in separate experiments. Mean sensitivity (A') increased from the invalid condition to the valid condition when a location cue was presented. However, mean sensitivity did not vary according to the validity of the color or shape cue. The authors concluded that knowing the location of the target singleton facilitated selectivity of attention on the target, whereas knowing the color or shape of the singleton did not facilitate the sensory processing of the target.

Liu et al. (2007) provide contrasting results, showing that attending to a feature cue increases the sensitivity of target processing. As mentioned earlier, the authors superimposed two fields of random dots that moved in different directions on each side of the fixation and asked participants to detect a speed increment in one of the fields. An endogenous location cue or motion direction cue was given on each trial and the SOA between the cue display and the stimulus display was varied between 150ms, 300, and 500ms, separated by blocks. The authors found increased sensitivity (d') for the valid trials compared to the invalid trials for both location cues and motion direction cues. The response bias measure (C) was close to 0 and exhibited no systematic pattern. Furthermore, sensitivity was enhanced by the location cue at three SOAs but sensitivity was not enhanced by motion direction cue until 500ms SOA. Liu et al. conclude that both spatial attention and feature-based attention increase the efficacy of the visual processing

of the stimulus. However, location may be unique in the sense that its effect on attentional selection is exerted earlier than feature information.

The inconsistencies between Theeuwes and Van der Brug (2007) and Liu et al. (2007) may arise because the design in the former study discouraged the use of feature-based attention, while the overlapping stimuli in the latter prevented feature-based selection from being overshadowed by location-based selection. In Theeuwes and Van der Brug, the objects containing the line segments differed in either color or shape, but the line segments were always gray. Knowing the color or the shape in advance did not facilitate the target processing because the target never shared the same property with the feature cues. The target only shared the same property with the location cues (e.g., the location of the target). Thus, Theeuwes and Van der Brug did not observe any sensitivity increase when feature cues were presented. The target stimuli in Liu et al., on the contrary, shared the same feature or location with the feature cues or the location cues. Thus, in their study, both types of cues increased the sensitivity of target processing, because feature-based selection was not overshadowed by location-based selection.

Although our design could not allow us to directly examine whether the color effects are driven by a sensitivity change or by a response bias, the effects of selection by color most likely reflect a sensitivity increase, rather than a response bias for the following reasons. The target digits range from 2 to 9 and the task depends on identification of the targets. The color of the stimulus is randomly determined on each trial and there is no consistent mapping between the color of the stimulus and the identity of the stimulus. Sensory priming cannot explain our results since the task cannot be done by simply attending to the color of the stimulus. Furthermore, the strategy of holding a

target template that combines color and shape in working memory (e.g., red 3) does not help perform the task more efficiently. Response to the targets would not be systematically biased by such a working memory template in any way that would improve performance. It is thus unlikely that color information causes systematic response biases in our study.

Automatic vs. Top-Down Modulated Selection

Another reason why some researchers assign a unique role for location in selection is based on the observation that the location of the stimulus is automatically selected when attention is directed to feature information (Kim & Cave, 1995; Lamy & Tsal, 2000; Tsal & Lavie, 1993). Our findings show that one cannot have a full understanding of this issue without taking the sources of attentional orienting into consideration. As discussed in the introduction, there are two ways to control attentional allocation: bottom-up or stimulus-driven and top-down or goal-driven (Desimone & Duncan, 1995; Vecera, 2000; Yantis, 2000). Stimulus-driven direction of attention refers to the process by which attention is captured by the properties of the stimuli within the image, such as a salient singleton or an onset. Goal-driven direction of attention refers to the process by which attention is allocated according to the internal goals or expectations of an observer, as when the cueing effect increases as the cue validity increases. The use of location or color in selection is a deliberate and strategic process when location or color is task-relevant, because there is incentive to actively use location or color information in this case. Automatic or bottom-up selection can only be examined when location or feature information is task-irrelevant and unpredictable, so that the use of location or feature information is beyond the strategic control of participants (Vierck &

Miller, 2006; Yantis, 2000; Yantis & Egeth, 1999). A location or color modulation effect is observed in the current study (Experiments 1, 3, 4 and 6) when the location or color of the stimuli is predictive about the upcoming target. Participants learn about the predictability of the location or color information either implicitly or explicitly and thus have incentives to use this information to direct attention. In this task, location or color modulation disappears when location or color does not provide useful target information, as shown in Experiment 2. This suggests that the use of location or color information can be controlled in a top-down manner, adjusted by the goal of the task. Moreover, when color is predictive while location is not (e.g., Experiment 1 and 3), only color modulation is observed, suggesting that when attention is controlled in a goal-driven manner, only the relevant dimension is selected and used. The fact that location information is not used automatically when it is not task-relevant further strengthens our conclusion that attentional selection is modulated by task demands and location is not unique in this sense. Our findings are consistent with the view that there are multiple representations that can be used as the selection bases, and that task demands determine which information will direct selection (Lamy & Tsal, 2000; Tsal & Lavie, 1993; Vecera & Farah, 1994). Location-based selection and feature-based selection are not mutually exclusive when attentional allocation is controlled in a top-down manner.

When attention is controlled in a stimulus-driven fashion, we show that attention is automatically captured by the onset cues regardless of the observer's intention. Participants were informed that location cues and color cues were task-irrelevant and unpredictable in Experiment 5. However, this knowledge did not prevent attention being drawn to the location of the onset cue, resulting in more efficient responses to the targets

at the validly cued location than at the invalidly cued location, regardless of the color. Despite the effects of the location cue, all participants reported that they did not attend to the onset cues in the course of the experiment. Some even reported that they forgot the presence of the onset cues. Since the use of location seems to be beyond strategic control in this experiment, we conclude that attention is automatically drawn to the location of the onset cue. Location-based attentional capture probably arises from a retinotopic representation that codes the location of the salient stimulus. Furthermore, the color of the onset cue also affects attention, resulting in the highest accuracy for processing targets that share the same color with the cue at the validly cued location. Similarly, the knowledge that color cue is unpredictable of the target does not prevent attention being drawn by the color cue. However, the effect of color is only found at the validly cued location in long SOA condition, indicating that the influence of color in selection develops later and is dependent on the selection by location. Feature-based attentional capture probably arises from a representation that is feature-specific and is organized retinotopically. Consistent with the view of stimulus-driven attentional capture, we conclude that attention is automatically affected by the location and the color of a salient but uninformative onset cue (Busse et al., 2006; Jonides, 1981; Posner & Cohen, 1984; Vierck & Miller, 2006; Yantis, 2000; Yantis & Jonides, 1984). Location does play a unique role in stimulus-driven attentional orienting. How the representation used in location-based attentional capture is related to that in feature-based attentional capture and how they interact at different time points needs more investigation.

Note that some studies have proposed that stimulus-captured attention is contingent on the attentional set (Folk, Remington & Johnston, 1992; Bacon & Egeth,

1994; Folk & Remington, 2006). Folk and colleagues suggest that any given task goal can create an attentional set and any stimulus feature that matches the attentional set can control attentional allocation. For example, a task-irrelevant salient stimulus captures attention when it shares a feature with the target (e.g., color or onset). The same salient stimulus does not capture attention when it does not share any feature with the target. Bottom-up attentional capture is not entirely immune from top-down modulation. Their argument raises doubts about whether a pure stimulus-driven control of attention is possible, and suggests that top-down control influences bottom-up process. Nevertheless, how top-down control interacts with bottom-up control of attention is beyond the scope of the current discussion. We focus our discussion on the differences between when location or color information is informative and when it is uninformative, and how attentional selection differs in these two conditions.

Our findings on the distinction between top-down and bottom-up sources of attentional control may explain discrepancies in the literature. Researchers have assigned location a unique role in selection by arguing that attending to a feature entails attending to its location (Kim & Cave, 1995; Lamy & Tsal, 2000, 2001; Tsal & Lavie, 1993). For example, Lamy and Tsal presented a white onset cue on one of the corners of two objects that differed in location, color and shape. Participants were asked to either attend to the location of the cue or the color and shape of the object on which the cue appeared. A location cueing effect was found when attention was directed to the location of the cue and a feature cueing effect was found when attention was directed to color and shape of an object. The results showed that task relevance modulated what type of information was used as the selection basis, reflecting a top-down control of attentional selection.

However, a location cueing effect was also found when attention was directed to color and shape, but a feature cueing effect was not found when attention was directed to location. The authors concluded that selection by location was automatic, because the location cueing effect was observed even when it was task-irrelevant. Selection by features was not automatic because the effect disappeared when feature information was task-irrelevant.

We propose that Lamy and Tsal's (2000) pattern of results can be explained by the design of the stimuli and the task demands in their experiments. The salient white onset cues in Lamy and Tsal are effective to drive top-down control of attention in both location and color dimensions since participants were asked to actively attend to location or feature information. We have shown that selection is modulated by task demands when attention is controlled in a top-down manner and this explains why the task-modulated location cueing effect and feature cueing effect are both evident in Lamy and Tsal. However, the white onset cues can only trigger stimulus-driven control of attention in the location dimension, and not in the feature dimension, because the white onset cue does not share any feature with the objects. It is not surprising to find that only the location cueing effect is stimulus driven in this study, due to this asymmetry in the cue information.

Taken together, we suggest that the source of attentional control plays a critical role in the relationship between using location and using color in selection. Color or location information can be used either in a top-down or in a bottom-up manner, depending on the nature of the task and how attention is directed in the task. Task demands can modulate attentional selection and how relevant information is used in

selection. Location is not unique when attention is directed in a top-down manner because location and color information can be used independently and in parallel. Attention can also be captured by a salient but task-irrelevant stimulus. The use of location or color is automatic in these situations since it is beyond observers' control. Location is unique in selection when attention is directed in a bottom-up manner because the effect of color on attention depends upon the selection by location.

The Flexibility of Attention

Selective attention is a mechanism that allows the visual system to select part of the visual information for further processing and action. What information is used for attention in the selection process is a central issue in the studies of selective attention. The roles of location and features have been studied and implemented in many theories of visual attention, with a dominant view that all selection is mediated by location (Treisman & Gelade, 1980; Wolfe, 1994; Wolfe et al., 1989). Attention clearly uses spatial properties in selection, as shown in the current study and previous studies (Eriksen & Hoffman, 1973; Kim & Cave, 1995; Posner, Snyder & Davidson, 1980; Shih & Sperling, 1996). We observe location-based selection in the probability manipulation task and a location cueing effect in the cueing task. With the same design and procedures, we also find that attentional selection can operate on nonspatial properties, including perceptual grouping and a specific color value (Baylis & Driver, 1992; Duncan, 1984; Kramer & Jacobson, 1991; Vecera & Farah, 1994). Such selection is not mediated by the location of the stimuli.

With the appropriate control over the stimuli, the effect of feature-based selection is dissociated from that of location-based selection in the current study. Our findings

suggest that both spatial properties and nonspatial properties can be used as the basis of selection. However, as many studies point out, the nature of the task and cues determines what type of information controls the allocation of attention and what mode of attentional orienting is engaged (Jonides, 1981; Klein, 2000; Posner, 1980). We show that the source of attentional control (or the mode of attentional orienting) should be taken into consideration when discussing how spatial and nonspatial properties are used by attention. When attention is controlled in a top-down manner, attention is sensitive to the task demands and is flexible in using the relevant information at hand to select targets. Either location or color can be used as the selection basis, as long as it is informative or task-relevant. Thus, the use of location or color is modulated by task relevance, and is not automatic. The direction of attention by location and color are independent or parallel and selection by location is not dominant over selection by features in this case (Egner et al., 2008; Treue & Martinez-Trujillo, 1999). The relative contribution between the two types of selection is most likely to be determined by task demands or strategies of the observer.

Attention is insensitive to the task factors and is responsive to the salience of the visual stimulus under some circumstances. When attention is controlled in a bottom-up manner, selection is automatic because attentional capture is beyond voluntary control. In these circumstances, attention is first automatically drawn to the location of an onset cue, with a later influence of cued color at the validly cued location, as reflected in the SOA manipulation. The selection of color is contingent on the prior selection of location and the relationship between the two is hierarchical and serial. Our findings on the bottom-up process of attention support the *hierarchical organization hypothesis* in which location is dominant because it acts as a gate mechanism that controls analysis of visual features

coming from the attended locations (Anllo-Vento & Hillyard, 1996; Hillyard & Munte, 1984).

In sum, we provide evidence that under the right conditions, feature-based selection is not mediated by location, and that multiple dimensions can serve as the selection bases. There can be multiple selection stages at different levels of visual processing, especially when attention is directed in a bottom-up manner (Vecera & Farah, 1994). Which dimension is used as the basis for attentional selection is probably determined by a number of factors, including task demands or the mode of attention engaged in the task. Therefore, it is not surprising to observe a pure location-based selection, a pure feature-based selection, or an interactive selection (e.g., *grouped-array hypothesis* in which object structure constrains the spatial distribution of attention). A general theory dealing with attentional selection should incorporate selection based on spatial and nonspatial properties in the same framework and should have the flexibility in adjusting the relative contribution among different types of selection basis according to the task demands, goal of the observers and the mode of attentional control.

APPENDIX A

THE TABLES

Table 1. Mean reaction times (in milliseconds) and accuracy (percentage) in three conditions for Experiments 1-3

	Feature		Far		Near	
	RT	%	RT	%	RT	%
Experiment 1	1209	86.6	1292	82.9	1423	76.0
Experiment 2	1156	82.0	1158	83.3	1178	81.7
Experiment 3	1191	82.6	1200	81.5	1169	80.5

Table 2. Mean reaction times (in milliseconds) and accuracy (percentage) in four conditions in Experiment 4

Valid		Invalid					
Feature		Feature		Far		Near	
RT	%	RT	%	RT	%	RT	%
1101	84.3	1129	81.9	1201	79.5	1270	75.1

Table 3. Mean reaction times (in milliseconds) and accuracy (percentage) in four conditions for 376 SOA in Experiment 5

		Location Cue			
		Valid		Invalid	
		RT	%	RT	%
Color Cue	Valid	719	83.1	736	82.7
	Invalid	723	82.9	728	82.5

Table 4. Mean reaction times (in milliseconds) and accuracy (percentage) in four conditions for 447 SOA in Experiment 5

		Location Cue			
		Valid		Invalid	
		RT	%	RT	%
Color Cue	Valid	703	85.9	718	80.0
	Invalid	693	81.6	719	81.7

APPENDIX B

FIGURE CAPTIONS

Figure 1. Example stimuli in Experiments 1 to 3. The task was to compare if the two digits were in the same or different categories (See text for details). (a) An example of the *feature* condition in which the two digits shared the same color and were far apart. (b) An example of the *far* condition in which the two digits were in different colors and were far apart. (c) An example of the *near* condition in which the two target digits shared the same location and were in different colors. Displays are not to scale in this figure. See text for details.

Figure 2. Sequence of events on a trial in Experiments 1 to 3. This example represented a *feature* trial.

Figure 3. The four conditions in Experiment 4. The central square served as both the fixation point and the color cue on each trial. (a) An example of the *near (invalid)* condition. (b) An example of the *valid-feature* condition. (c) An example of the *invalid-feature* condition. (d) An example of the *far (invalid)* condition. Displays are not to scale in this figure. See text for details.

Figure 4. Sequence of events on a trial in Experiment 4. This example illustrated a *valid-feature* trial.

Figure 5. Sequence of events on a trial in Experiment 5. The target appeared at the validly cued location with the validly cued color in this example. However, both location cue and color cue were uninformative.

Figure 6. Sequence of events on a trial in Experiment 6. The target appeared at the invalidly cued location with the validly cued color. Location cue was 60% informative while the color cue was 80% informative in this example.

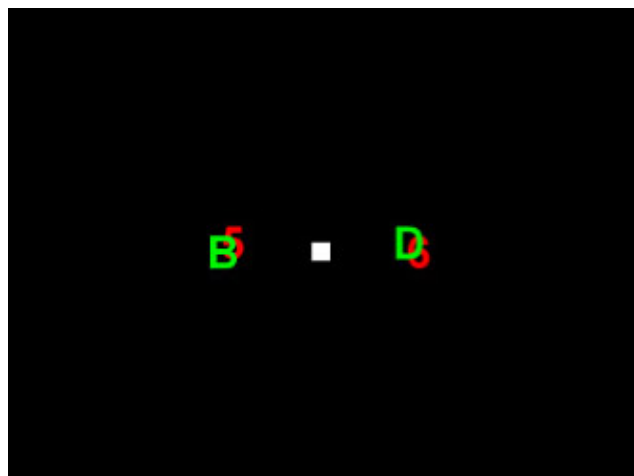
Figure 7. The results from Experiment 5. (a) Mean reaction times (in milliseconds) as a function of conditions and SOAs. (b) Mean accuracy (percentage) as a function of conditions and SOAs.

Figure 8. The mean reaction times (in milliseconds) from Experiment 6 as a function of level of cue informativeness and type of cue. (a) Location cue 60% and color cue 60%. (b) Location cue 60% and color cue 80%. (c) Location cue 80% and color cue 60%. (d) Location cue 80% and color cue 80%.

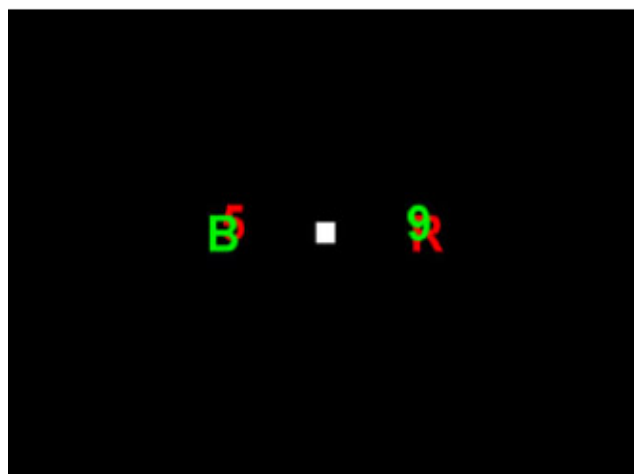
Figure 9. The mean accuracy (percent correct) from Experiment 6 as a function of level of cue informativeness and type of cue. (a) Location cue 60% and color cue 60%. (b) Location cue 60% and color cue 80%. (c) Location cue 80% and color cue 60%. (d) Location cue 80% and color cue 80%.

Figure 1

(a)



(b)



(c)

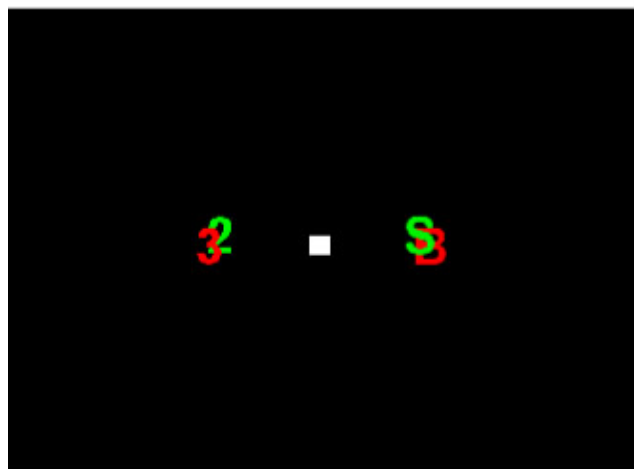


Figure 2

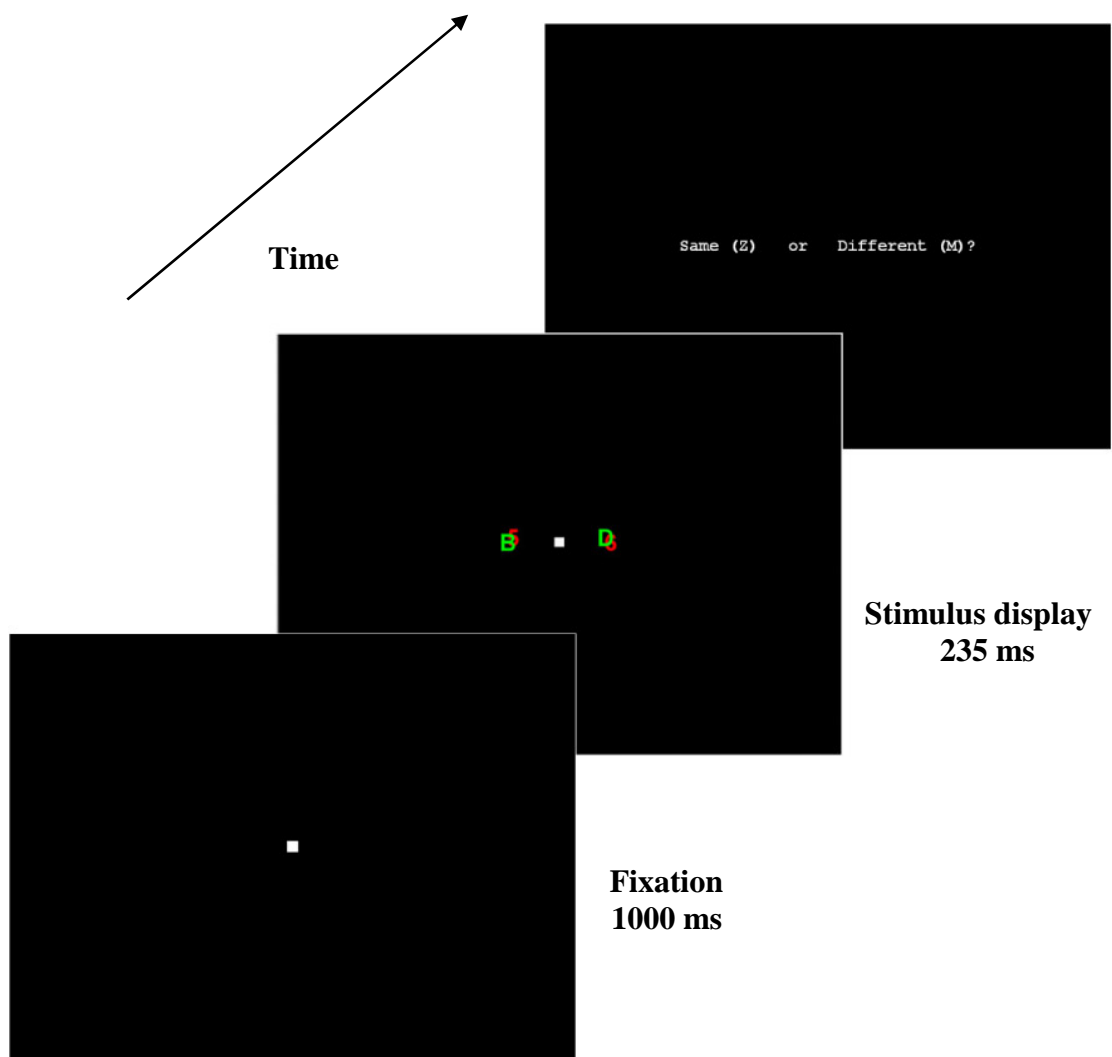
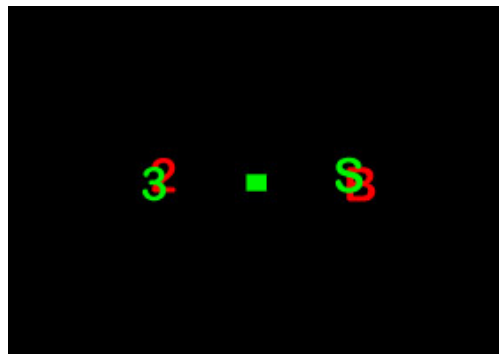
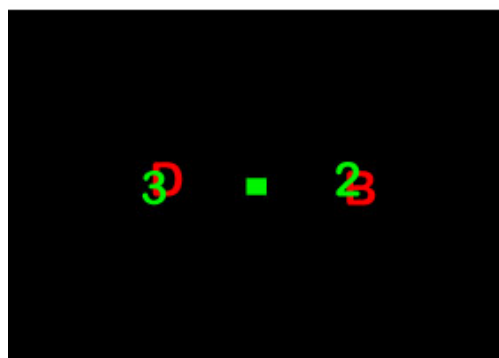


Figure 3

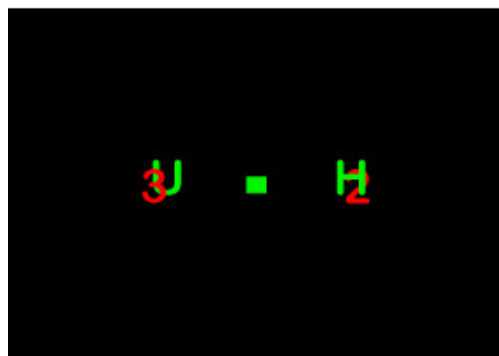
(a)



(b)



(c)



(d)

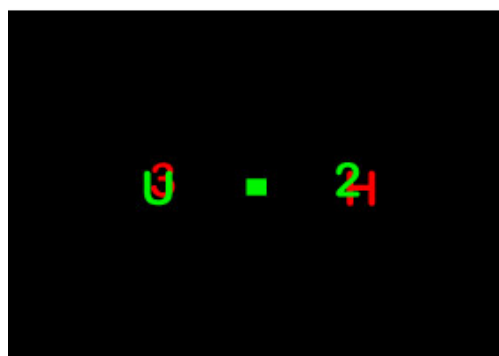


Figure 4

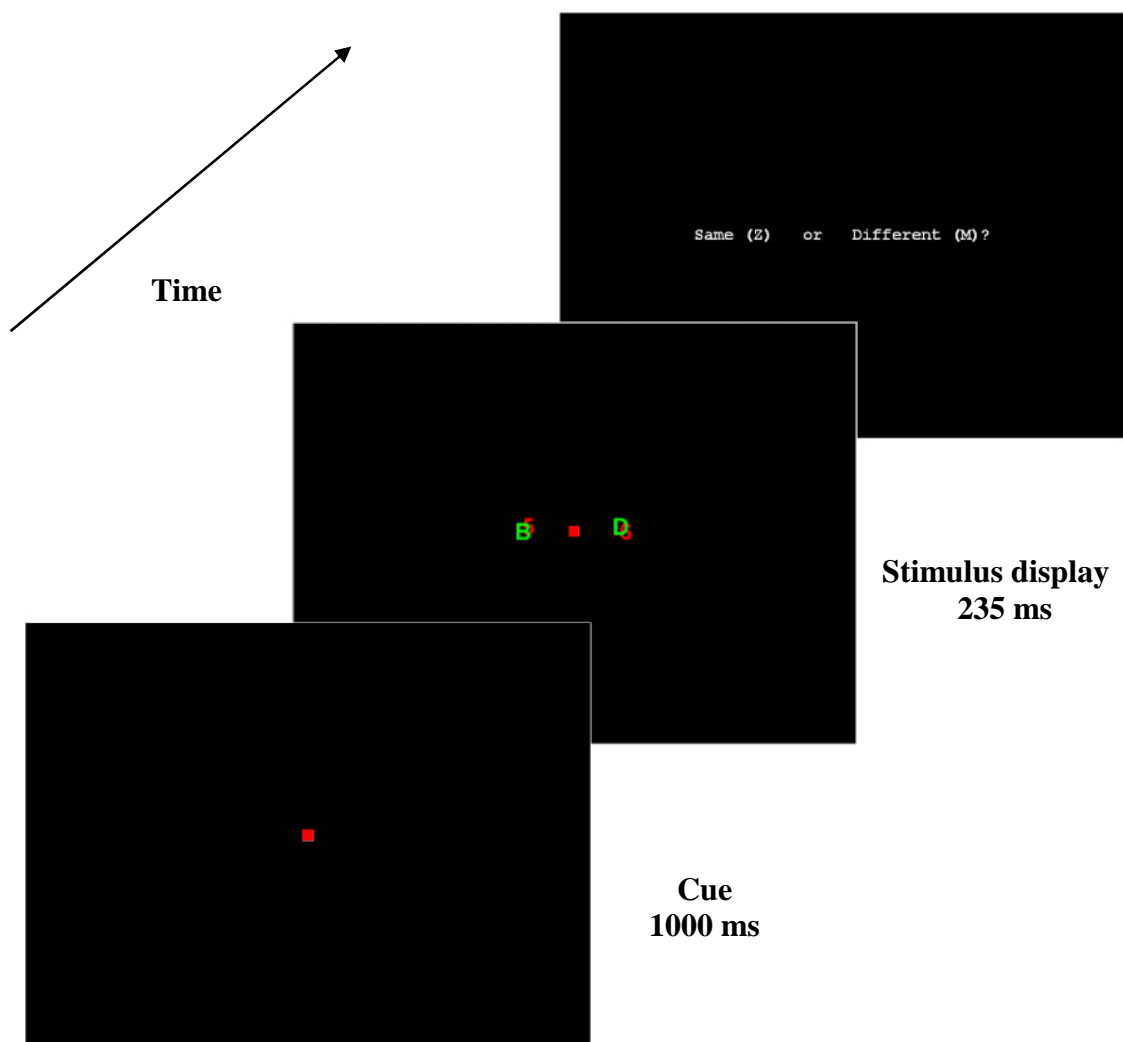


Figure 5

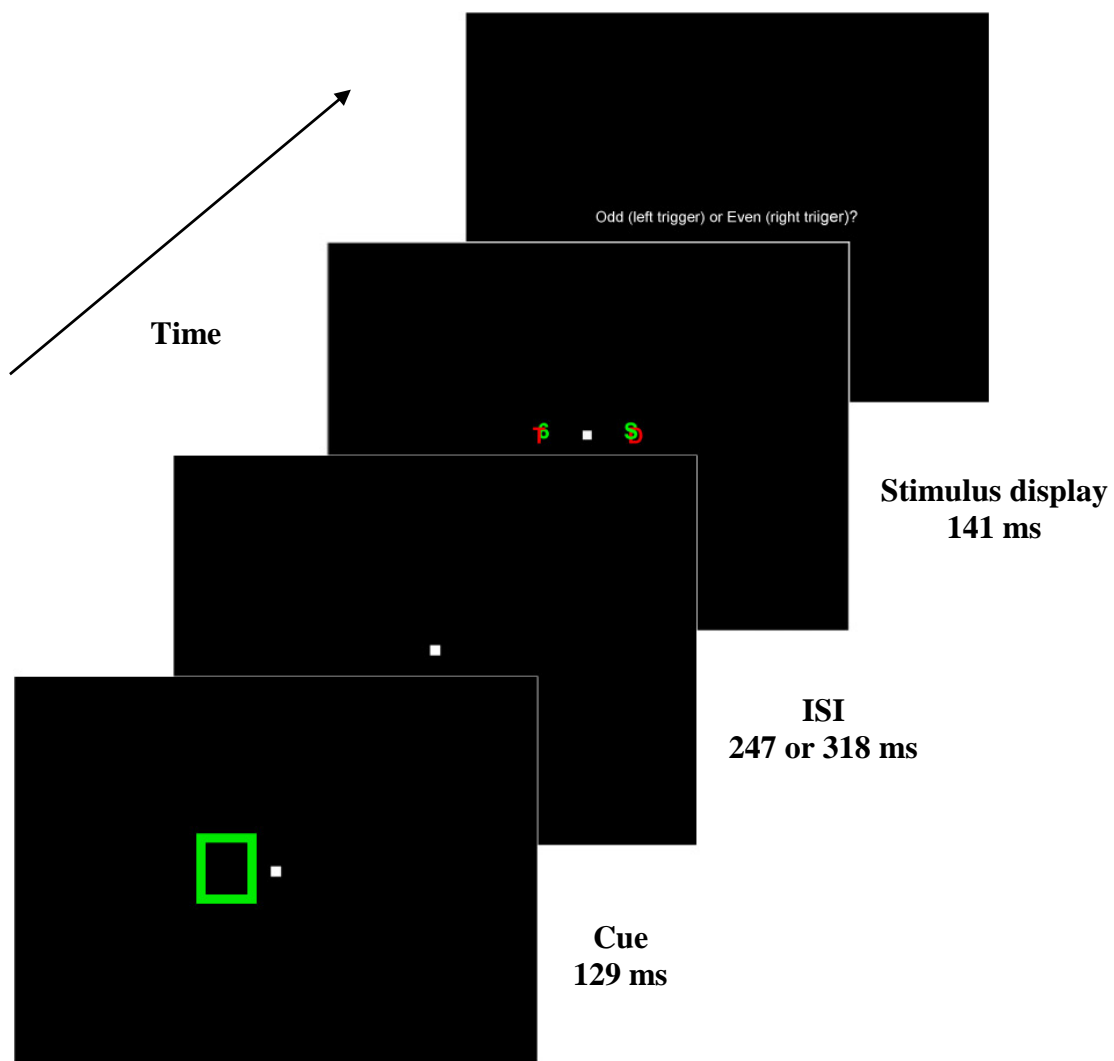


Figure 6

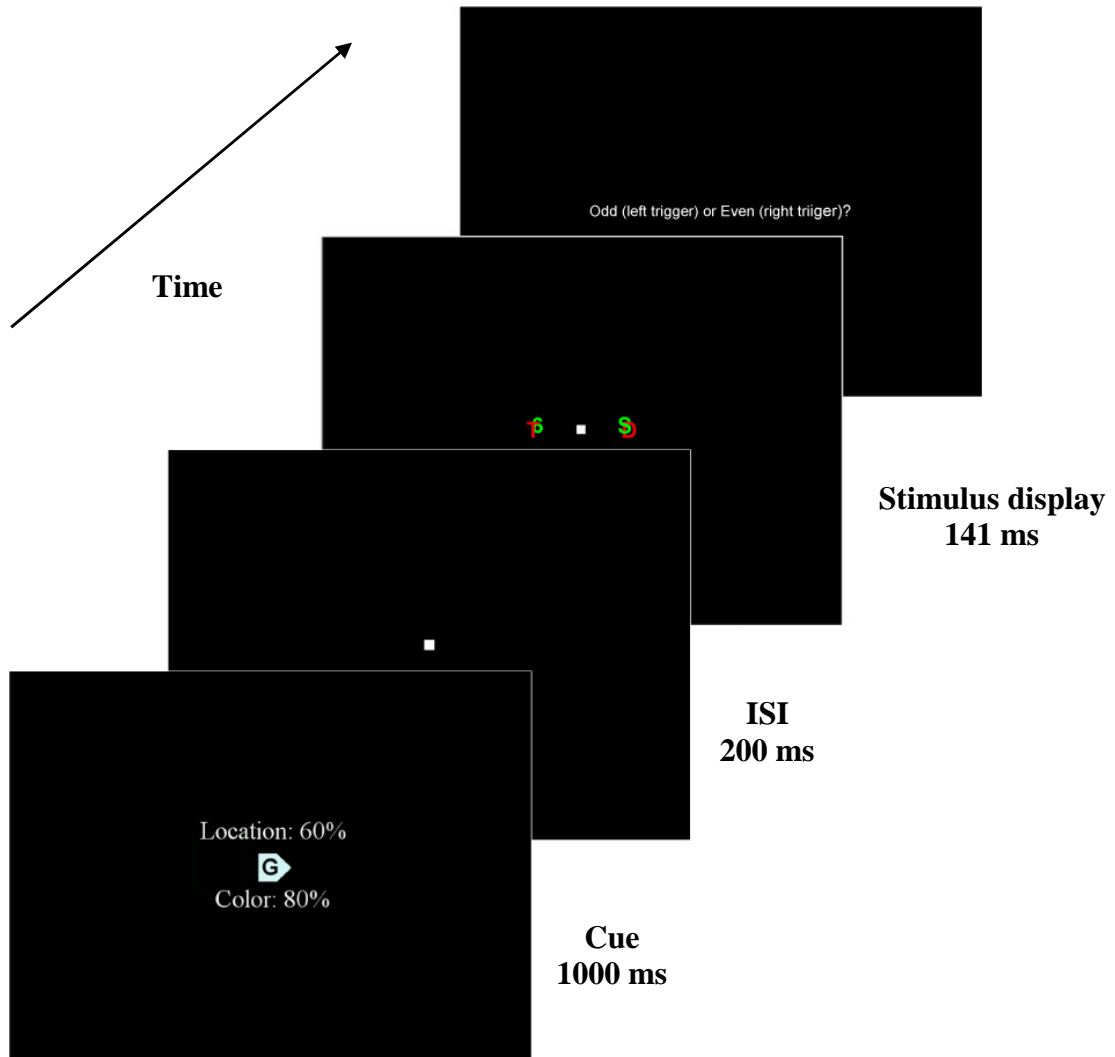
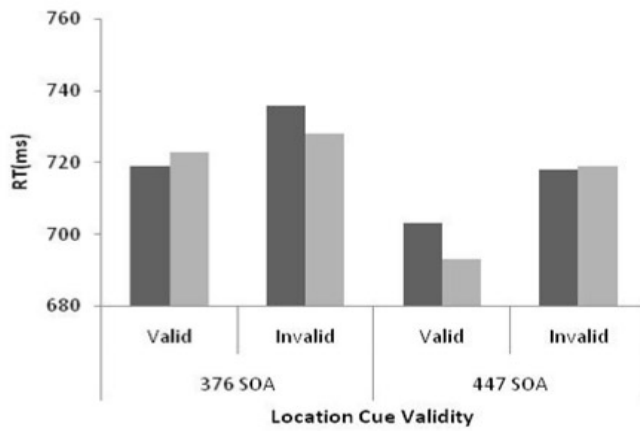
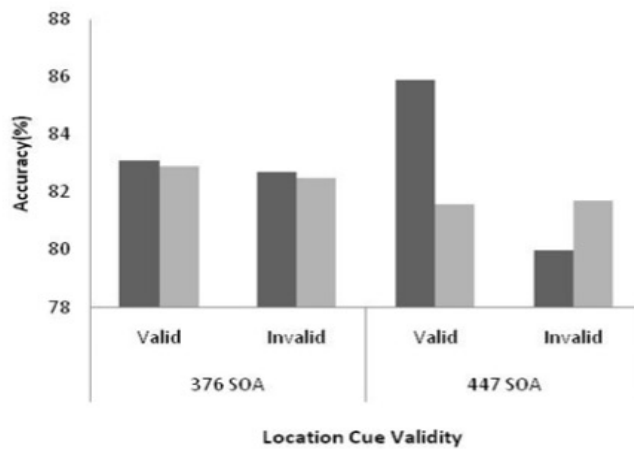


Figure 7

(a)



(b)



■ Valid Color Cue ■ Invalid Color Cue

Figure 8

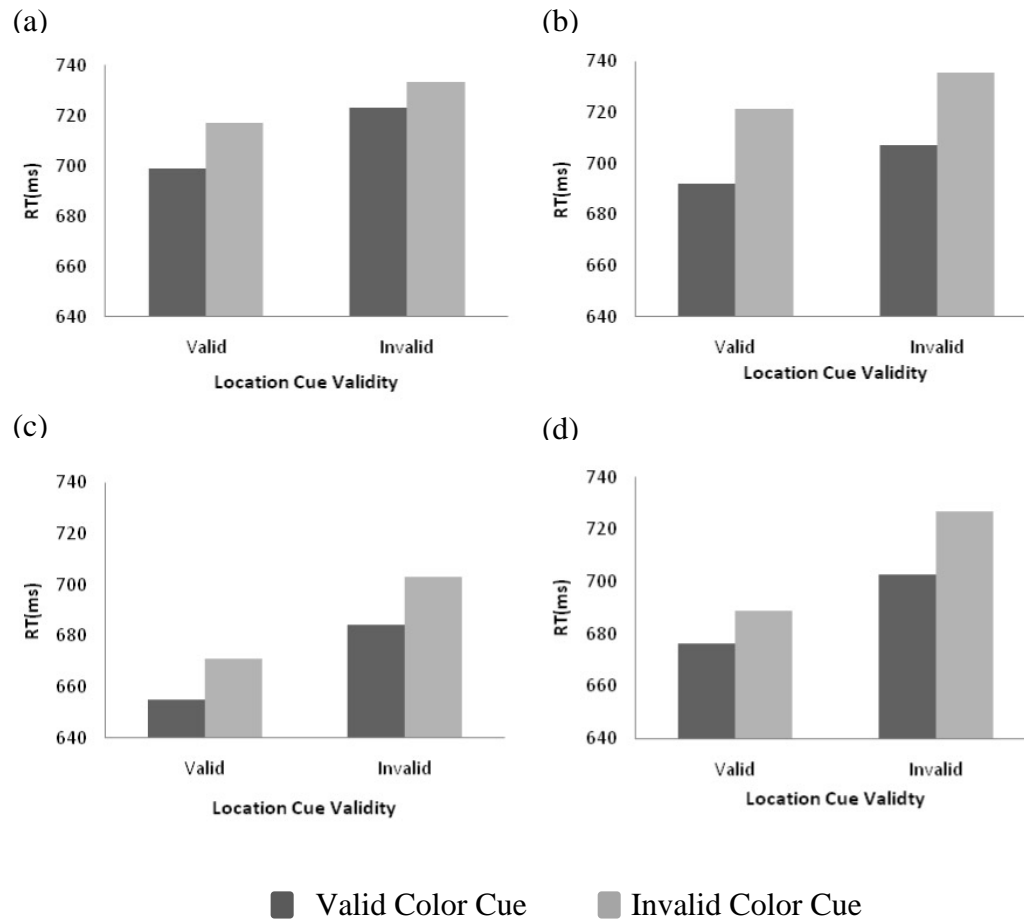
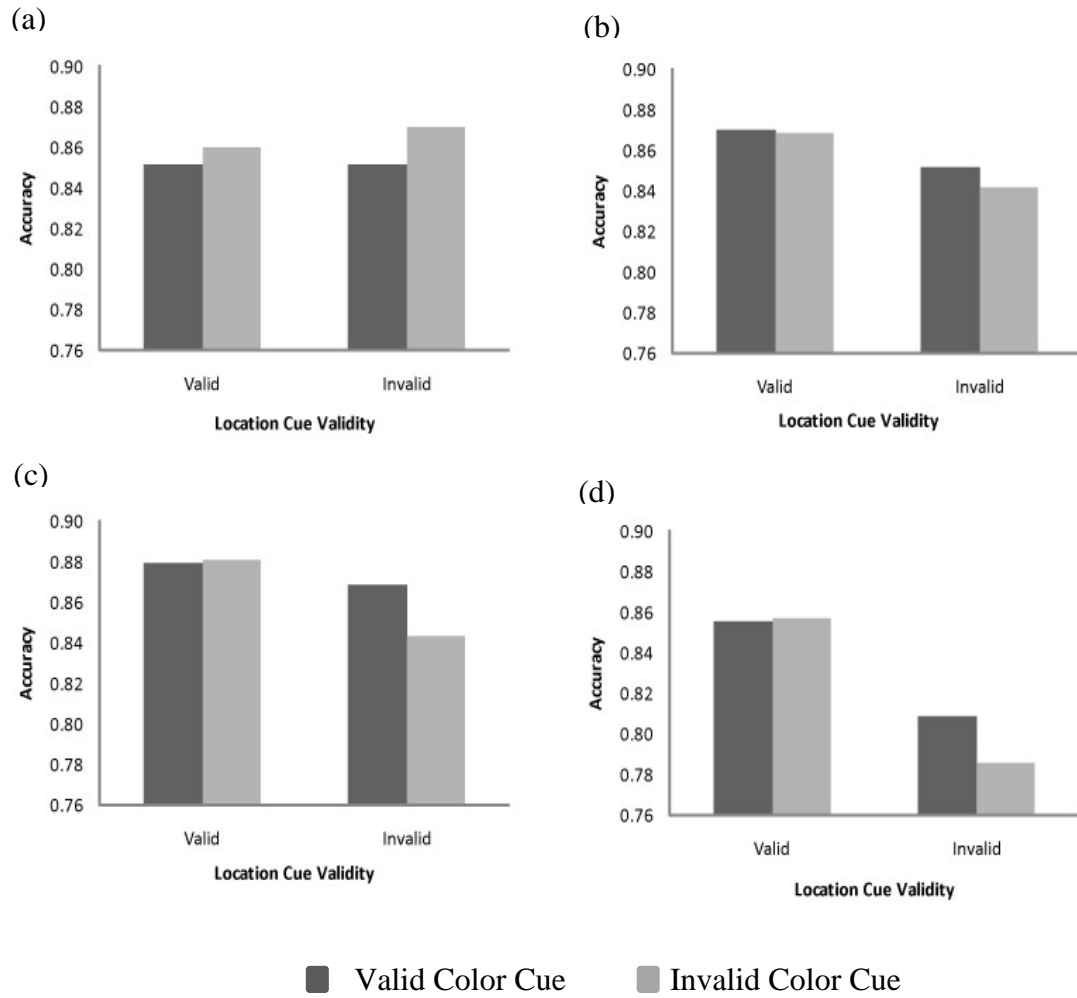


Figure 9



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