THE EFFECTS OF FEATURE-BASED ATTENTION ON PERCEPTION

by

XIAOHUA ZHUANG

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ABSTRACT OF THE DISSERTATION

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By XIAOHUA ZHUANG

Dissertation Director:

Thomas V. Papathomas

Feature-based attention is one of the mechanisms that can facilitate the processing of many aspects of our visual perception. A variety of paradigms were employed in the current dissertation to further investigate how feature-based attention modulates motion perception, visual search and temporal processing of stimuli.

The first set of experiments aimed to explore the effects of feature-based attention on the processing of motion speed and motion direction separately. Speed and direction discrimination tasks were used in separate experiments. Results showed that feature-based attention has more dramatic influence on direction perception than on speed perception. This may be taken as evidence that humans are more sensitive to motion speed change than to motion direction change.

The second set of experiments was designed to study how performance in color-orientation conjunctive searches changes when observers attend to a pre-cued location, or a pre-cued feature (color or orientation), as well as the temporal characteristics of these precue effects. Color (sensory and symbolic) and location precues improved search performance. The magnitude of improvement did not vary as the inter-stimulus interval (ISI) changed for color and location cues. The sensory color and location cues exhibited their effect in directing visual search as early as 0 ms of ISI. However, orientation precue did not facilitate nor inhibit the search processing. These results may imply that color is a better feature to base the segmentation processing on and thereby facilitate the visual search processing.

The third set of experiments explored the existence of feature-based attentional prior-entry effect, which refers to the hypothesis that attended objects are perceived prior to unattended ones. Temporal order judgment (TOJ) and simultaneity judgment (SJ) tasks were employed to test this hypothesis. Prior-entry effect for objects with attended feature was found in TOJ task, the most frequently used paradigm in the literature to claim the spatial prior-entry effect, but the effect was absent in the SJ task. This could be due to a second-order response bias in the TOJ task, or to the fact that the SJ task is not as sensitive as the TOJ task.

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Finally, I would like to dedicate this dissertation to my family, especially to my mother. My family has been very supportive throughout these years. It was their support that encouraged me to persist in finishing this journey.

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1. General Introduction

Our sensory systems are constantly “bombarded” with information coming from the external world. This is particularly true in the visual system. No matter what environment we are in, we are always surrounded by many different kinds of things, such as people, buildings, cars, trees, clouds, and so on. At any given moment, millions of receptors on our retina are stimulated by these elements in our visual field, and all the signals are then sent to higher stages in our visual system for further processing. However, can our visual system process these signals all at once? Would our visual system become overloaded to deal with all the information simultaneously? One may notice from their own experience that our visual system does not deal with all the information received simultaneously. Researchers also believe that not all information received by our retina is processed consciously, and there is a mechanism built in our brain to process information selectively. This mechanism is known as visual attention.

Visual attention has been thought to play the role of selecting what part of the visual input to process, given the limited capacity for processing information in the visual system (Desimone & Duncan, 1995). Due to the limitation of capacity, at any moment, only a small proportion of the information available in the retina can be processed in detail. Thus, behaviorally relevant information is selected by visual attention for special processing, whereas behaviorally irrelevant information is ignored, or even suppressed. Researchers have been investigating the mechanisms of selective visual attention. Single-cell recording studies in monkeys and brain imaging studies in humans have shown that attention can affect neural processing in visual cortex by a variety of ways, such as enhancing neural responses to attended stimuli (Colby et al 1996; Connor et al 1996, 1997; Luck et al 1997; McAdams & Maunsell 1999; Treue & Maunsell 1996, Treue & Martinez 1999), suppressing responses to distractors (Moran & Desimone. 1985; Reynolds et al, 1999; Kastner et al, 1998), and increasing baseline activities for neurons or visual areas (Luck et al 1997; Colby et al 1996; Kastner et al 1999; see review Kastner & Ungerleider, 2000, and Treue, 2001).

A central question in theories of visual attention is “what is selected”, i.e. what are the units of attention. Three different classes of theories propose that selective attention could be directed to a location, an object, or a feature. A common assumption under these three different kinds of theories is that, once a property is selected by attention, other information related to this property is automatically selected. However, different theories make different assumptions about what is automatically selected (O’Craven, Downing & Kanwisher, 1999). Spatial attention theories (Eriksen & Hoffman, 1974; Eriksen & James, 1986) suggest that, once a location is selected to be attended, anything located within a limited neighborhood of the attended location would be automatically selected to be processed. Object-based attention theories (O’Craven, Downing & Kanwisher, 1999; Blaser, Pylyshyn & Holcombe, 2000, Mitchell, Stoner & Reynolds, 2004) propose that, if an object is selected all the features of the object will be processed automatically. By contrast, feature-based attention theories (Treue & Martinez Trujillo, 1999; McAdams & Maunsell, 2000; Saenz, Buracas & Boynton, 2002, 2003; Corchs & Deco, 2004; Martinez-Trujillo & Treue, 2004; Melcher, Papathomas & Vidnyanszky, 2005) hold the idea that, if attention is directed to a single feature, say the color red, the processing of this feature will be automatically enhanced throughout the visual field, no matter whether the feature is inside or outside the attended aperture. These three accounts for what constitutes the unit of attentional selection (location, object, or feature) are not mutually exclusive. Namely, it is possible that all three attentional selection modes are active in parallel at the same time. Depending on the nature of the experiment, one or another mode manifests itself more strongly than the others.

Among these three classes, the earliest and dominant class is spatial attention (Hoffman & Nelson, 1981; Posner, Snyder & Davidson, 1980). The mechanisms and characteristics of spatial attention have been studied extensively. The perceptual consequence of spatial attention is that processing of everything proximal to the attended location is facilitated. The speed and sensitivity of detecting targets at the attended location are increased (Posner, Snyder & Davidson, 1980). Spatial attention is also thought to be important for directing our saccade system to make eye movements (Moore and Armstrong, 2003). Accumulated evidence also show modulation of spatial attention on neural processing. Neuron activities to stimuli at the attended location are enhanced compared with activities to stimuli at the unattended location (Colby et al 1996; Connor et al 1996, 1997; Luck et al 1997).

The effects of object-based attention are also well documented. The classical effect of object-based attention is the single-object advantage (Duncan, 1984, 1993). In Duncan’s classic study (1984), two overlapping objects were shown to observers, a box and a line. The box was either short or tall, and had a gap on its left or right side. The line was either dotted or dashed, and tilted to the left or right. Observers were instructed to report two of these four features. Their accuracies were higher when the two features were of the same object than when the two features were of different objects. This effect cannot be attributed to spatial attention. It is thought that the difference in accuracy was due to the distribution of attention to the same object or different objects. That is, observers' performance on multiple features that belong to a single object is better than performance on multiple features that belong to multiple objects. The processing of the task-irrelevant features of the attended object is enhanced compared with the processing of the task-irrelevant features of the unattended object (Sohn et al., 2004; O'Craven, Downing & Kanwisher, 1999).

In addition to location- and object-based attention theories, feature-based attention theories and findings have attracted more and more researchers in the field of visual attention. The behavioral consequences of feature-based attention are similar to those of spatial attention, and the magnitude of feature-based and spatial attentional modulation on neuronal activities are about equal in size (Treue and Martinez-Trujillo, 1999). The effects of feature-based attention can be understood from two aspects, local and global feature-based attention. Seidemann & Newsome (1999) presented two groups of moving dots within the receptive fields (RFs) of neurons being recorded. One group of dots moved in the preferred direction of the neurons, the other moved in the anti-preferred direction. Neurons' responses were larger when monkeys attended to the preferred direction than when they attended to the anti-preferred direction. This is called "local feature-based attention", because the effect is within the monkeys' focus of attention and within the neurons' RFs. A more interesting effect is the global feature-based attention, in which attention affects the processing of stimuli outside the focus of attention and outside the neurons' RFs. That is, once a feature is selected to be attended, visual processing of this feature is enhanced not only within the locus of attention but throughout the visual field. The global effect of feature-based attention has been observed in many psychophysical studies (Saenz, Buracas & Boynton, 2003; Boynton, Ciaramitar & Arman, 2006; Melcher, Papathomas & Vidnyanszky, 2005); single-cell recording studies (Treue & Martinez Trujillo, 1999; McAdams & Maunsell, 2000; Martinez-Trujillo & Treue, 2004) and functional brain imaging studies (Saenz, Buracas & Boynton, 2002; Sohn, Chong, Papathomas & Vidnyanszsky, 2005).

It has been shown that feature-based attention improves behavioral performance or otherwise enhances processing of stimuli that share the attended feature across the visual field (Saenz, Buracas & Boynton, 2003; Boynton, Ciaramitar & Arman, 2006). It is easier to divide attention to the same feature of multiple stimuli than to different features of multiple stimuli (Saenz, Buracas & Boynton, 2003). The sensitivity of detecting the cued feature is increased compared with detecting uncued features (Liu, Stevens & Carrasco, 2006). The speed of detecting targets increases if the targets are of the same feature on consecutive trials (Maljkovic and Nakayama, 1994). Stronger motion after effect was observes on the unattended motion field when its motion direction was the same as the direction of the attended motion, compared with when the directions were different (Boynton, Ciaramitar & Arman, 2006).

Neuronal correlates of feature-based attention have been measured in many different cortical areas. Single-cell recording in monkeys (e.g. Treue & Trujillo, 1999; McAdams & Maunsell, 2000; Bichot, Rossi & Desimone, 2005) and functional magnetic-resonance imaging (fMRI) studies in humans (e.g. Saenz et al., 2002) have shown that feature-based attention can globally influence visual cortical responses throughout the visual field. Attention to a given stimulus feature, say the color red, increases the responses of cortical visual areas to a spatially distant, ignored stimulus that shares the same feature. Treue and Martinez-Trujillo’s (1999) study found a non-spatial, feature-based attentional modulation of neuronal responses in direction-selective cells of macaque cortical middle temporal (MT) area. Attention to the preferred direction outside the receptive field of MT neurons increased their responses by about 13%, compared to attention to a null direction stimulus outside the receptive field. Bichot, Rossi & Desimone (2005) reported that during visual search, neurons in area V4 of monkeys were more activated to stimuli containing features to be searched, and this effect occurs throughout the visual field, regardless of the location of the monkeys’ focus of attention. Saenz et al.’s (2002) fMRI research recording cortical responses from human visual areas V1, V2, V3, V3A and MT+, showed that responses in these areas were enhanced when the motion direction of the ignored moving stimuli matched the attended motion direction.

In the literature, random-dot-patterns (RDP) that contain multiple features (colors or directions) are the most popular paradigm used to study feature-based attention and its effect on motion perception. It is thought that feature-based attention is most useful for visual search tasks, partly due to the fact that we usually search for an object based on a specific feature, such as the color, shape, or direction of motion of the object. In the current thesis, both RDP and visual search stimuli are used to investigate further some effects of feature-based attention. Meanwhile, one of the important aspects of feature-based attention on perception that has not been investigated extensively by researchers is how feature-based attention influences the temporal processing of perception. Therefore, we also explore this aspect of the effect of feature-based attention as well in the current thesis. Specifically, the main goals of this thesis are:

1. To investigate the effect of feature-based attention on the perception of motion direction and speed.

2. To examine how feature-based attention influences visual search tasks and the time course of the attentional effects.

3. To test if feature-based attention has an effect on the temporal processing of stimuli.

2. Experiment 1: Feature-based attention modulated motion processing

2.1. Introduction

Although motion perception was thought to involve low-level processing that does not require attention, it has now been generally accepted that motion perception includes both pre-attentive low-level processing and attentive high-level processing (Treisman and Gelade, 1980; Nakayama and Silverman, 1986; Cavanagh, 1995). In recent decades, numerous studies have shown a strong interaction between motion perception and the attention mechanisms (Chaudhuri, 1990; Cavanagh, 1992; Lankheet & Verstraten, 1995; Raymond, O'Donnell, & Tipper, 1998; Alais & Blake, 1999; Treue & Maunsell, 1996; Treue & Maunsell, 1999; Rees, Frith, Lavie, 1997; O’Craven, Rosen, Kwong, Treisman, & Savoy, 1997; Rezec, Krekelberg, Dobkins, 2004). For example, Cavanagh (1992) demonstrated that, in addition to a low-level mechanism that can detect motion signals automatically in the absence of attention, there also exists an attention-based motion process. Chaudhuri (1990) observed a significant reduction of motion aftereffect (MAE) duration on the non-attended background stimulus when attention was engaged to a non-motion task away from the moving background stimulus. O’Craven et al.’s (1997) fMRI study on human visual cortex found that neural activities of the visual areas, MT-MST, which are responsible for motion processing, were stronger while attention was directed to the moving elements than to the stationary elements of the same single visual stimulus. Several single-unit recording studies have reported that neural responses in the areas MT and MST of monkeys were enhanced while monkeys attended to motion stimuli inside the receptive fields of the neurons compared to while they attended to motion stimuli outside the receptive fields, and responses were stronger when they attended to motion in the preferred direction than the non-preferred direction inside the receptive fields of the neurons (Treue & Maunsell, 1996; Treue & Maunsell, 1999).

It has become clear that motion perception can be modulated by feature-based attention. Brain imaging and electrophysiological studies have demonstrated the influence of global feature-based attention on the activities of the visual cortical areas MT and MST (Treue & Trujillo, 1999; Saenz et al., 2002; Sohn et al., 2005). To measure the global effect of feature-based attention on motion perception, a paradigm was used commonly by researchers. In this paradigm, two apertures of motion stimuli are presented, one on each side of the fixation mark. Attention is directed to one of the features in one of the aperture, and neuronal activities to features on the unattended (ignored) aperture are then measured. Neuronal responses on the unattended stimulus are compared under two different conditions: when the unattended feature matches the attended feature vs. when the two features are mismatched. In an fMRI study (Saenz et al., 2002) using this paradigm, cortical responses to the unattended stimuli were recorded in the V1, V2, V3, V3A and MT+ areas. They found that the fMRI responses in these areas were enhanced when the direction of the ignored stimuli matched the attended direction. In a single-unit recording study with similar a paradigm, Treue and Martinez-Trujillo (1999) demonstrated that neuronal responses in direction-selective cells of macaque cortical middle temporal (MT) area were greater when they attended to the preferred motion direction outside the receptive field than when they attended to the anti-preferred direction outside the receptive field.

Modulation effects of feature-based attention on motion perception have also been observed in psychophysical studies (Boynton, Ciaramitar & Arman, 2006; Tzvetanov, Womelsdorf, Niebergall & Treue, 2006). To study the effect of feature-based attention behaviorally, it is important to measure observers' performance on the unattended stimuli that are outside the focus of attention. However, it is almost impossible to measure directly the behavioral performance on an unattended stimulus. Hence, researchers have been trying to use some indirect methods to measure the global effect of feature-based attention. Boynton, Ciaramitar and Arman (2006) used the method of adaptation to infer the effect of feature-based attention. They presented two overlapping fields of dots moving in opposite directions in an aperture on the left side of the fixation point. Observers attended and performed a task on one of the fields on the left. An unattended filed of dots was presented on the right side, moving either in the same direction as the attended field, opposite to the attended field, or orthogonal. Motion aftereffects (MAEs) at the unattended location were measured under different attentional conditions. Since it is difficult to measure directly observers' behavioral performance on unattended stimuli, these authors tried to use the strength of the MAE at the unattended location to infer the strength of processing of the unattended stimuli. The underlying assumption is that a greater MAE at the unattended location would indicate stronger processing of the unattended stimuli. Thus, according to theories of feature-based attention, when the direction at the unattended location is the same as the attended direction, the processing of the unattended stimuli is enhanced, therefore, stronger MAE should be observed. This was indeed the result of their experiment: the strength of the MAE was stronger when the unattended field had the same direction as the attended field.

It has also been found that feature-based attention exerts an influence on center-surround interactive motion repulsion effect. Tzvetanov, Womelsdorf, Niebergall and Treue (2006) presented stimuli of two groups of dots moving transparently in orthogonal directions in the surround annulus, while one single field of dots was presented moving in a single direction in the center. Observers were asked to pay attention to one of the groups in the surround and the group in the center, and then perform a direction discrimination dual-task on both surround and center groups. The control condition was that, for the same stimuli as above, observers only performed a direction discrimination task in the center field. Compared to the control condition, a significant repulsion effect between the center field and attended surround direction was found in the test condition. Again, this result shows indirectly the effect of feature-based attention. Attention to a motion direction in the surround increased its influence on the center stimuli.

Of particular interest here, Saenz, Buracas & Boynton (2003) observed that the feature-based enhancement on motion perception was obtained only when there were competing stimuli. They employed random dot patterns (RDPs) in a dual-task paradigm. Two apertures of RDP stimuli were presented simultaneously on the left and right sides of a central fixation point. Each aperture contained two superimposed families of dots moving in opposite directions, upward and downward. Observers were asked to attend to one of the two families of dots on each side, and detect speed changes of the attended families. With this arrangement, the authors were able to compare two conditions with an identical physical stimuli display: one condition was when the attended motion direction in the left aperture was the same as the attended direction in the right aperture, and the other condition was when these two attended directions were opposite. If, as suggested by feature-based attention theories, attention to a feature enhances the processing of the same feature in other spatial distant stimuli, then dividing attention to multiple stimuli with common features should get facilitated compared with dividing attention to stimuli with opposing features. Therefore, observers' performance should be better when the two attended directions were the same than when they were different. The results were consistent with this prediction. Observers' judgments were significantly more accurate when attending to two families with the same motion directions. This suggested that feature-based attention does indeed improve the processing of stimuli that share the attended feature throughout the visual field. Interestingly, the enhancement was eliminated when only one family of dots was presented in each aperture. In other words, the feature-based attentional effect was manifested only when there were nearby competing distractors. According to the authors, the strengthening of the attentional effect in the presence of distractors was due to the effort to filter out competing distractors, meaning attention was engaged more strongly with distractors present.

However, in a different study, Lu and Itti (2005) measured threshold elevations for dual-task thresholds with respect to single-task thresholds using grating stimuli without competing distractors. They found that the threshold elevation was significantly higher for stimuli that shared the same task-relevant features than for stimuli that had different task-relevant features, demonstrating the global feature-based attentional effect on stimuli without nearby distractors. One of the differences between these two studies is that discrimination tasks were used in Lu and Itti’s (2005) study, whereas detection tasks were used in Saenz, Buracas & Boynton’s (2003) study. If the strength of feature-based attentional effect depends on how strongly attention is engaged on the task, then a more demanding attentional task will elicit stronger effect than a less demanding task. A discrimination task requires stronger attention engagement than a detection task does.

In our current study we observed an effect of feature-based attention on RDP stimuli without competing distractors, consistent with Lu & Itti‘s (2005) study. The stimuli were similar to those used by Saenz, Buracas and Boynton (2003). Discrimination tasks were used in two experiments. In these two experiments, the effects of feature-based attention on the perception of motion speed and motion direction were examined. Staircase procedures were applied to measure the threshold elevations on speed and direction discriminations.

2.2. Methods

Observers. Three observers participated in experiment 1A, and four participated in experiment 1B. All of them had normal or corrected-to-normal visual acuity. Observers were naïve as to the purpose of the experiments.

Stimuli. Psychophysics Toolbox extensions of Matlab were used to generate stimuli (Brainard, 1997; Pelli, 1997; Pelli and Zhang, 1991). Stimuli consisted of two intervals of random-dot patterns (RDP) in each trial of the experiment, displayed on a SONY TRINITRON CPD-G520P monitor; the viewing distance was 50 cm. Two RDP apertures were presented in each interval, one on each side (left and right) of the fixation mark, which was a cross with an arrow pointing to the left or right. The fixation mark was present at the center of the screen with a size of 1.5 deg in visual angle. Each RDP aperture contained one group of moving dots. The aperture that the arrow was pointing to was the attended aperture in the single-task condition, or the primary task aperture in the dual-task condition (see Figures 2.1 and 2.2). In the single-task condition, the attended aperture was always the left aperture or always the right aperture in a given block. The primary aperture in the dual-task condition was always the left aperture. Observers were asked to fixate at the central fixation mark throughout the experiment, and then performed two-interval forced-choice (2IFC) task(s). In the single-task condition, discrimination task was performed on only the attended aperture. In the dual-task condition, discrimination tasks were performed on both apertures.

In Experiment 1A, dots in both apertures were moving upward. In the non-task aperture (the unattended aperture in the single-task condition), dots moved with a speed of 1.55 deg/sec in both intervals. However, in each task aperture (attended aperture in the single-task condition, both apertures in the dual-task condition), dots in one of the intervals moved with a base speed, low (1.55 deg/sec) or high (3.87 deg/sec). Dots in the other interval moved with a speed that was incrementally different. The magnitude of the difference was determined by Quest staircases. In Experiment 1B, dots in both apertures were moving with a speed of 3.87 deg/sec. In the non-task aperture, dots moved always vertically upward. But in each task aperture, dots in one of the intervals moved in a principal direction, horizontally rightward or vertically upward. In the other interval, the direction was tilted from the principal direction. The amount of tilt was determined by Quest staircases.

Procedure. Quest staircases (Watson and Pelli, 1983) were used to measure discrimination thresholds. Thresholds were measured in both single-task and dual-task conditions. Single-task and dual-task experiments were conducted in separate blocks. Each trial of the experiments started with a fixation mark that lasted for 150 – 250 ms. The first interval of the stimuli was then presented for 500 ms, followed by a 100-ms inter-stimulus interval (ISI) and the 500-ms second interval (see Figures 2.1 and 2.2). The ratios between thresholds in the secondary task in the dual-task condition and thresholds of the single task were used to indicate how feature-based attention modulates observers' performance on the discrimination. At the beginning of each experiment (1A and 1B), observers ran a practice single-task session.

In Experiment 1A, observers performed speed discrimination task(s). The base speeds in the two apertures could be the same (both low base speeds) or different (one low and one high). Same-base-speed and different-base-speed conditions were mixed randomly in the same block. In the single-task condition, speed in the unattended aperture was fixed at 1.55 deg/sec. The base speed in the attended aperture was 1.55 degree/second in the same-base-speed condition, and 3.87 degree/second in the different-base-speed condition. Observers were asked to decide which interval of the attended aperture contained the faster motion. In the dual-task condition, the base speed in the primary task aperture (left aperture) was fixed at the low base speed (1.55 deg/sec). In the secondary aperture (right aperture), the base speed was either the same as (1.55 deg/sec) or different from (3.87 deg/sec) that in the left aperture (see Figure 2.1). Observers were told to perform speed discrimination tasks on both apertures, but that the task on the left aperture was primary. They were required to respond to the primary task first, and then respond to the secondary task. Both responses were made at the end of each trial. Observers performed the speed discrimination tasks by pressing one of the two keys using their left hands for the left aperture, and one of another two keys using their right hands for the right aperture.

In Experiment 1B, observers performed direction discrimination task(s). In the single-task condition, dots in the unattended aperture moved always in the upward direction. In the attended aperture, the principal direction could be upward (same-principal-direction condition) or rightward (different-principal-direction condition). Similarly, in the dual-task condition, the principal direction in the left aperture was always upward, but it could be upward (same-principal-direction condition) or rightward (different-principal-direction condition) in the right aperture (see Figure 2.2). Observers responded as to which interval(s) contained the tilted motion direction.

2.3. Results

Discrimination thresholds in both single-task and dual-task conditions were measured in both experiments. Threshold ratios between the dual-task threshold in the secondary aperture and single-task threshold were computed (Figure 2.3 and Figure 2.4):

$$R = \frac{\text{dual-task threshold in the secondary aperture}}{\text{single-task threshold}}$$

The central question that motivated Experiment 1A and 1B was to investigate the modulation effects of feature-based attention on the perception of motion speed and motion direction. Therefore, threshold ratios were subjected to one-sided repeated t-test with feature similarity (same- vs. different-based-speed in Experiment 1A; same- vs. different-principal-direction in Experiment 1B) as within subject variable, and alpha set to .05. In Experiment 1A, there was a trend toward an overall increase in threshold ratios in the different-base-speed condition. The increase was just short of significance (t (2) = 2.154, p = 0.08). The threshold ratios in the different-base-speed condition were significant larger than 1 (t (2) = 3.996, p = 0.029), whereas those in the same-base-speed condition were not (t (2) = 1.646, p = 0.121). In Experiment 1B, the repeated t-test revealed significant effect of feature similarity, t (3) = 5.747, p = 0.005. Ratios in the different-principal-direction condition were significantly larger than those in the same-principal-direction condition. Both the threshold ratios in the same-principal-direction condition and in the different-principal-direction condition were significant different from 1, t (3) = 2.580, p = 0.041, and t (3) = 4.634, p = 0.009, respectively.

The average discrimination thresholds across different sections of each individual observer were plotted in Figure 2.5 for Experiment 1A and Figure 2.6 for Experiment 1B. The threshold ratios shown in Figure 2.3 and Figure 2.4 were obtained from the thresholds presented in Figure 2.5 and Figure 2.6.

2.4. Discussion

Saenz, Buracas & Boynton (2003) employed RDP stimuli in a dual-task paradigm to study the behavioral effects of global feature-based attention. Observers could more accurately detect speed changes when they attended to two groups of dots moving in the same direction than in different directions. In their study, in order to perform the task, observers had to explicitly attend to two different features of the attended field of dots: the feature that defined which field of dots should be attended to (motion direction), and the task feature (motion speed). Although motion direction and motion speed of a moving object do not appear to be separable, at least phenomenologically, it is likely that feature-based attention manifests its effect differently for these two motion features. In their study, the effects of these two features were confounded. In the present study, we examined the isolated effect of feature-based attention on each of these two features, by asking observers to explicitly pay attention to only one of these two features. Thus, we designed two separate experiments and, in each experiment, one of the features was manipulated across different conditions, while the other feature remained constant.

The magnitudes of the feature-based attentional effects were different in the two experiments. Different threshold elevation patterns were observed when observers attended to the speed of the moving dots versus when they attended to the direction of motion. In the speed discrimination task, the threshold ratios in the same-base-speed condition were essentially equal to 1, i.e., there were insignificant threshold elevations. In other words, the dual-task thresholds in the same-base-speed condition were the same as the thresholds in the single-task condition. The threshold elevations in the different-base-speed condition were significantly larger than 1, but marginally significantly different from those in the same-base-speed condition. In the direction discrimination task, thresholds in both the same-principal-motion-direction and different-principal-motion-direction conditions were significantly larger than 1. Besides, the threshold elevation in the same-principal-direction condition is significantly smaller than that in the different-principal-direction. A feature-based attentional modulation effect was more pronounced for motion direction than for motion speed. This difference between the speed discrimination task and direction discrimination task may indicate that our visual system is more sensitive to speed changes than to direction changes. One may argue that speed changes are easier to detect, thus requiring less attention. For this reason, there is less room for an attentional effect in speed discrimination tasks than in direction discrimination tasks.

Another interesting finding in Saenz, Buraca and Boynton’s (2003) study was that the feature-based attentional enhancement was eliminated or reduced significantly in the absence of competing distractors, i.e., when the apertures with the RDP stimuli contained dots moving only in one direction, without a competing family of dots moving transparently in the opposite direction. Similarly, as suggested by many other studies (Moran & Desimone, 1985; Motter, 1993; Luck et al., 1997; Treue & Martinez Trujillo, 1999; Treue & Maunsell, 1999), the effect of attention was stronger in the presence of distractors. The strength of the attentional effect depends on how strongly attention is engaged in the task. When there are competing stimuli present, observers are forced to engage more effort on the task, so that they can filter out the effect of the distractors. Therefore, what is critical is not whether there are distractors or not, but whether attention is engaged to the task strongly enough. In contrast to Saenz, Buraca and Boynton's (2003) finding, Lu and Itti (2005) reported a feature-based attentional effect using grating stimuli without competing distractors.

The failure to observe a feature-based attentional effect in the absence of distractors in Saenz, Buraca and Boynton's (2003) study might be due to the fact that we are highly sensitive to speed changes and that attention was not strongly engaged in the speed change detection task. In addition to the difference in stimulus type, another difference between Saenz, Buraca and Boynton's (2003) study and Lu and Itti's (2005) study is that a discrimination task instead of a detection task was used in Lu and Itti's (2005) study. In the present study, we used similar RDP stimuli without competing distractors, as those used in Saenz, Buraca and Boynton's (2003) study. In order to engage observers' attention more strongly, we used a discrimination 2AFC task, instead of a detection task. A significant feature-based attentional effect was observed in the direction discrimination experiment, and a marginally significant effect was observed in the speed discrimination task as well. These results are consistent with the findings from Lu and Itti's (2003) study. We believe that we could have observed stronger attentional effects if we utilized competing stimuli as did Saenz, Buraca and Boynton's (2003).

Another manipulation that can be tried in future experiments is to compare performances with different nominal directions of motions and speeds. One could compare the strength of attentional effects in an experiment using motion directions along ±45-degree diagonals ("north-east" and "north-west" directions to those obtained in the present study with vertical and horizontal motion directions. Similarly, one could use different nominal speeds or speed ratios and conduct a parametric study to investigate how the attentional effect varies with variations in the two values of speed that were used in each conditions. These studies are not expected to produce qualitatively different results, other than parametric variations, and are not deemed to be strategic for our purposes.

3. Experiment 2: Feature-based attentional modulation in visual search

3.1. Introduction

One of the popular tools to investigate how attention influences visual information processing has been the visual search task. In particular, the visual search paradigm has been one of the major methods used to study how the visual system extracts and combines features. In the real world, as well as in the laboratory, a visual search task requires observers to locate a target among many distractors. The target usually differs from the distractors by features (color, shape, etc.). For instance, there are often occasion where one needs to look for his friend who is in a red shirt in a crowd. In such a case, the color feature red becomes a defining characteristic to base the search on. This example illustrates the important role played by features in the visual search task in everyday life. While the behavioral effects of feature-based attention were studied in different paradigms, feature-based attention may be most important and useful for visual search tasks.

Research on visual search has been focused for decades on whether search is parallel or serial (Treisman & Gelade, 1980; Wolfe, Cave, & Franzel, 1989; Cave & Wolfe, 1990; Treisman, Vieira, & Hayes, 1992; Wolfe, 1994; Wolfe, 1998; Thornton & Gilden, 2007). In general, single-feature search and conjunction search are two of the most common visual search tasks in the literature. A single-feature search task, commonly referred to as “feature search task”, in which the target differs from distractors on the basis of one feature dimension (e.g., searching for a horizontal oriented target among many vertical oriented distractors), is thought to involve a parallel processing. The reaction time (RT) and accuracy to search for the target remains essentially unchanged as the number of distractors increases in a feature search task. By contrast, a conjunction search task, in which the target differs from distractors on the basis of a combination of two or more feature dimensions (e.g., searching for a red-horizontal target among red-vertical and green-horizontal distractors), is thought to involve a serial processing. In this case, RT increases and accuracy decreases as the number of distractors increases. In addition to these two types of search tasks, there are some other types, such as digit-among-letters (Farell & Pelli, 1993; Moore & Egeth, 1998), or one symbol among other similar symbols, such as a T among L's (for a review, see Julesz, 1981).

Regardless whether visual search is parallel or serial, it has been well documented that visual search could be aided from feature-based attention. According to theories of feature-based attention, the processing of an attended feature is enhanced throughout the visual field, which makes searching for the object that possesses the attended feature easier and faster. Evidence supporting that feature-based attention could aid visual search performance comes from various sources of psychophysical studies (Egeth et al., 1984; Farell & Pelli, 1993; Shih & Sperling, 1996; Bacon & Egeth, 1997; Moore & Egeth, 1998; Mounts & Melara, 1999; Wolfe et al., 2004). In addition, during recent decades, many brain-imaging studies have also been conducted to investigate the neural mechanism of the top-down guidance from both spatial attention and feature-based attention in visual search (Bichot, Rossi & Desimone, 2005; Weidner et al., 2009; Egner et al., 2008). In addition, eye-movement studies have provided evidence on which features are used to guide visual search and how this is accomplished (Motter & Belky, 1998; Chen &

Zelinsky, 2006; Neider & Zelinsky, 2006; Shen & Paré, 2006; Rutishauser & Koch, 2007).

One of the earliest psychophysical findings that demonstrated feature-based attentional effects on visual search came from Egeth, Virzi and Garbart's study (1984). They reported that visual search can be limited to a subset of the entire display on the basis of a particular feature. They used a color-shape conjunction visual search task and explicitly encouraged observers to search for a target either in the subset of items that had the same color as the designated target or the subset of items that had the same shape as the designated target. The finding was that observers' search performance could benefit from limiting their searches to a subset based on the color or the shape, and the search times increased as a function of the number of items that shared the attended feature, but not as a function of the number of all items in the display. Similar results were found in other studies (Zohary & Hochstein, 1989; Kaptein et al., 1995; Bacon & Egeth, 1997). Performance in visual search can also benefit from feature-based attention implicitly. Studies on priming effects indicated that visual search performance was facilitated if the to be searched targets shared the same feature as the targets in the prior trials (Maljkovic and Nakayama, 1994, 1996; Wolfe, et al., 2003).

However, feature-based attention did not always improve visual search performance under all circumstance (Farell & Pelli, 1993; Shih & Sperling, 1996). Farell and Pelli's (1993) study found that feature-based attention did not have an effect on a digit-among-letters search task. In their study, the stimulus array consisted of one digit and several letter distractors, and the items could be of large or small size. In the beginning of each block, observers were told about the size of the digit target and they could search the target based on the size feature. Despite this explicit instruction, observers' performance did not benefit from paying attention to the size of the items.

Moore and Egeth (1998) conducted a series of experiments to uncover what were the underlying reasons that caused the mixed findings in the Egeth et al. (1984) study and the Farell & Pelli (1993) study. There are three primary differences between these two studies: Firstly, different kinds of tasks were used: a conjunction search task vs. a digit-among-letters search task. Secondly, the attended features were different. In the Egeth et al. (1984) study, participants were instructed to attend to the color or the shape of the items, whereas in the Farell & Pelli (1993) study, participants were instructed to attend to the size of the items. Finally, the stimuli were displayed in different ways and different dependent variables were measured. In the Egeth et al. (1984) study, the stimuli were displayed until response and reaction time was measured. On the other hand, in the Farell & Pelli (1993) study, the stimuli were displayed briefly and followed by a mask, and response accuracy was measured. According to the Moore and Egeth's (1998) experimental findings, it was the display type and dependent measure that caused the apparent conflicts in these two studies. The authors further inferred that feature-based attention did not provide facilitation effect for visual search under the data-limited condition, in which stimuli were shown for very limited time. In Moore and Egeth's (1998) study, the digit-among-letters visual search task was used in all the five experiments. In their study, they did not rule out the possibility that the cause of the conflict between the Egeth et al. (1984) study and the Farell & Pell (1993) study was not due to one single factor, but a combination of factors. In other words, it is possible that the effect of feature-based attention is minimal when a task of digit-among-letters is performed under data-limited condition. Even though it has been shown that feature-based attention did aid conjunction visual search when the stimuli were presented until response, it is still unclear whether feature-based attention would still provide the same facilitation effect to conjunction search if the stimuli are presented briefly. In more recent studies, researchers used different paradigms to examine the modulation effect on the performance of conjunction visual search task by attending to one of the feature dimensions. Olds and Fockler (2004) developed a feature preview paradigm, in which previews of one of the features of the items in the search array were shown prior to the actual search stimuli. Results were mixed in the two experiments in this study. A color preview did not have any effect on the visual search in their experiment 1 but did accelerate the search in the second experiment. And an orientation preview had no effect on the search in one experiment but decelerate the search in the other experiment. In a different study, using the same paradigm, Sobel, Pickard and Acklin (2009) manipulated the display size, the density of the search array, the saliency of the color feature, and the distractor ratios to further investigate this feature preview effect on conjunction search. They confirmed that color preview did help visual search but orientation preview did not. We found similar results in the current study, color valid cue speeded the conjunction search whereas orientation valid cue did not.

In the current study, one of our main goals was to further explore the effect of feature-based attention on a conjunction search task, especially when the search stimuli are shown for a limited time. We know that a conjunction visual search is a more difficult task than a digit-among-letters visual search task, and it would be even more difficult under the data-limited condition. In order to avoid a floor effect, we did not use masking in the current study. A color-orientation conjunction search task was used. The visual search performance could be compared when attention was directed to different features of the same search stimuli.

The other goal of the present study was to investigate how feature-based attention affects conjunction search task on a trial-by-trial basis, and the temporal dynamics of its effect. Most of the studies that demonstrated the effect of feature-based attention on visual search are on a block design basis (Egeth, Virzi, & Garbart, 1984; Bacon & Egeth, 1997), meaning a target is well-defined and fixed for an entire block, and observers are asked to attend to a particular target throughout the block. We know that visual search is usually faster when the target is the same throughout the block than when it is different from trial to trial (Maljkovic & Nakayama, 1994; Geyer, Müller, & Krummenacher, 2006; Kristjánsson, 2006; Sobel, Pickard, & Acklin, 2009). Feature-based attention may have a different effect on visual search in a block design than in a trial-by-trial design. Meanwhile, by using a pre-cue paradigm on a trial-by-trial design, we were able to investigate the temporal characteristics of the feature-based attentional effect on conjunction search. Wolfe et al., (2004) employed a similar paradigm to study the effect of attention on a trial-by-trial basis. However, in their study, an exact search target was cued with 100% validity in the beginning of each trial. By contrast, in the current study, an odd-man-out paradigm was used. Only one of the features of the target was cued with 80% validity in the beginning of each trial. Therefore, the main goals of the present study included:

(1) To study if feature-based attention has an effect on conjunction visual search task under the condition where stimuli are presented with limited time.

(2) To study how performance in color-orientation conjunctive search changes when observers attend to a pre-cued location, or color, or orientation on a trial-by-trial basis.

(3) To study the temporal characteristics of these feature-based attentional pre-cue effects.

3.2. Methods

Observers. Eight observers participated in each condition of the experiment. All of them had normal or corrected-to-normal visual acuity. Except for the author (XZ), all other observers were naïve as to the purpose of the experiments.

Stimuli. The search stimuli consisted of eleven elements, formed by combining horizontal/vertical (H/V) orientation with red/green (R/G) color, arranged on an imaginary, almost circular ellipse at 6° eccentricity around a central fixation point. The elements were roughly equidistant from each other. The viewing distance was 60 cm. The size of each element was 0.3 degree * 1.3 degree. Either one (target) or none of the elements differed from others (distractors). There were 4 possible combinations of target/distractors, randomly presented across target-present trials (equal to target-absent trials) in an odd-man-out paradigm: RV or GH target among RH and GV distractors; RH or GV target among RV and GH distracters (see Figure 3.1). Observers' task was to respond on target presence/absence.

Procedure. The flicker photometry method was used to determine the equiluminance values of red and green colors for each observer. Observers participated in a one-hour practice session, where they practiced on the conjunctive visual search task without cues. The search stimuli were identical to those in main experiment, except that during the first half hour, the search stimuli were presented until response; and in the second half hour, the search stimuli were presented for 300 ms as in the main experiment.

After the practice session, observers participated in the main experiment, which consisted of 360 trials for each cue-stimuli ISI value of each cue type. Each trial started with a fixation phase for 500-1000 ms, and followed by a brief cue lasting for 50 ms. A cue-stimulus ISI was interposed after the offset of the cue, and it varied from 0-700 ms. The search stimulus then appeared for 300 ms (see Figure 3.2). The designated cue could refer to location, color (sensory or symbolic), or orientation (see Figure 3.3). The same precue was used in the same block. Cues were either neutral or informative with 80% validity. Observers were asked to respond as soon as possible and as accurately as possible. An auditory feedback was provided at the end of each trial to signify whether the response was correct or incorrect with two different tones. Reaction time and accuracy were used as measures of performance.

3.3 Results

The reaction time and accuracy for each type of pre-cue were subjected to 2-way repeated measure ANOVA tests independently. To correct for the violation of sphericity in some of the data, the Greenhouse-Geisser statistics were used and reported here.

3.3.1 Reaction Time

Color Sensory Cue

Target Present

Figure 3.4 depicts the reaction time as a function of ISI and different cue validity conditions for target present and absent in the color sensory cue experiment. A 2-way repeated-measure ANOVA was conducted on ISI (six levels) and cue-validity (three levels) for trials in which a target was present. The factor cue-validity includes three levels: invalid, neutral and valid cue. The ANOVA revealed that the main effect of cue-validity was significant, F (1.02, 8.19) = 7.87, p = 0.022; but the main effect of ISI and the interaction effect were not, F (1.64, 13.1) = 0.68, p = 0.50, F (4.313, 34.48) = 1.35, p = 0.27, respectively. Pair-wise comparisons showed that search was faster when the cue was valid than when it was neutral (p = 0.01) or invalid (p = 0.024), but the difference of reaction time between invalid cue and neutral cue was only marginally significant (p=0.079).

Target Absent

Unlike when a target was present, there were only two different cue validity levels when the target was absent: color cue (red or green patch cue) vs. neutral cue (gray patch cue). A 2-way repeated-measure ANOVA was conducted on ISI (six levels) and cue-validity (two levels). The main effect of cue validity was significant, F (1, 8) = 6.87, p = 0.03. Search was faster when the cue was a color cue than when it was a neutral cue. The main effect of ISI and the interaction effect were insignificant, F (5, 40) = 0.62, p = 0.69, F (5, 40) = 0.54, p = 0.74.

Color Symbolic Cue

Target Present

Figure 3.5 shows the reaction time as a function of ISI and different cue validity conditions for the color semantic cue. A 2-way ANOVA revealed that the main effect of cue-validity and the interaction effect were not significant, F (1.09, 7.61) = 3.33, p = 0.106, F (2.92, 20.41) = 1.58, p = 0.23, respectively; but the main effect of ISI was significant, F (2.27, 15.88) = 6.08, p = 0.009. Paire-wise comparisons showed that search was slower when the ISI was 0 ms than when it was 100 ms (p = 0.003); 400 ms (p = 0.009) or 700 ms (p =0.013). Reaction time from ISI of 100 ms, 400 ms and 700 ms were not significantly different from each other.

Target Absent

Similar patterns were observed for reaction time when a target was absent. The main effect for cue validity and the interaction effect were not significant, F (1, 7) = 1.52, p = 0.26, F (3, 21) = 0.18, p = 0.91, respectively; but the main effect of ISI was significant, F (1, 7) = 20.36, p < 0.0005. Search was slower when ISI was 0 ms than when it was 100 ms and, in turn, was slower than when the ISI was 400 ms or 700 ms. Reaction time was not significantly different for ISI of 400 ms and 700 ms.

Location Cue

Target Present

Figure 3.6 depicts the reaction time as a function of ISI and different cue validity conditions for the location cue. A 2-way ANOVA revealed that the main effect of cue validity was significant, F (1.03, 7.23) = 6.44, p = 0.037, whereas the main effect of ISI and the interaction effect were insignificant, F (1.22, 8.57) = 3.12, p = 0.109; F (2.88, 20.17) = 0.85, p = 0.47. Paire-wise comparisons showed that reaction time was shorter for a valid cue than for a neutral cue (p = 0.047), which in turns was shorter than for invalid cue (p = 0.038).

Target Absent

When a target was absent, a 2-way ANOVA revealed that the main effect of cue validity was significant, F (1, 7) = 6.74, p = 0.04. Reaction time was shorter when the cue was a neutral cue than when it was a color cue. The main effect of ISI and the interaction effect were not significant, F (4, 28) = 2.70, p = 0.05; F (4, 28) = 0.37, p = 0.83, respectively.

Orientation Cue

Target Present

Figure 3.7 shows the reaction time as a function of ISI and different cue validity conditions for the orientation cue. A 2-way ANOVA revealed that the main effect of ISI was significant, F (2.29, 16.04) = 8.19, p = 0.003; but the main effect of cue validity and the interaction effect were not significant, F (1.97, 13.75) = 0.01, p = 0.99, F (2.05, 14.32) = 0.92, p = 0.42, respectively. Paire-wise comparisons showed that reaction time for ISI of 700 ms was significantly shorter than those for other ISI (0 ms: p = 0.007; 100 ms: p = 0.004; and 400 ms: p = 0.022). Reaction time for ISI of 0 ms, 100 ms and 400 ms were not significantly different from each other.

Target Absent

A 2-way ANOVA revealed that none of the effects was significant: main effect of cue validity (F (1, 7) = 1.72, p = 0.23), main effect of ISI (F (3, 21) = 1.84, p = 0.17), the interaction effect (F (3, 21) = 0.58, p = 0.63).

3.3.2 Accuracy

The results of accuracy for different cue types were also subjected to 2-way repeated measure ANOVA tests independently. The patterns were similar to those of reaction time. There is no accuracy and reaction time trade-off.

Color Sensory Cue

Target Present

Figure 3.8 presents the accuracy as a function of ISI and different cue validity conditions when the pre-cue was a color sensory cue. A 2-way ANOVA revealed that the main effect of cue validity was significant, F (1.03, 8.23) = 15.02, p = 0.004; but the main effect of ISI and the interaction effect were not significant, F (3.16, 25.26) = 1.46, p = 0.25, F (3.23, 25.84) = 1.66, p = 0.2, respectively. Pair-wise comparisons showed that observers responded more accurately when the cue was valid than when it was neutral (p = 0.003) and, in turn, they respond more accurately when it was neutral than when the cue was invalid (p = 0.007).

Target Absent

When a target was absent, none of the effects on accuracy was significant: the main effect of cue validity (F (1, 8) = 3.04, p = 0.12), the main effect of ISI (F (5, 40) = 1.61, p = 0.18), and the interaction effect (F (5, 40) = 0.83, p = 0.54).

Color Symbolic Cue

Target Present

The accuracy for color semantic cue is shown in Figure 3.9. A 2-way ANOVA revealed that the main effect of cue validity was significant, F (1.09, 7.61) = 9.48, p = 0.015. The main effect of ISI and the interaction effect were not significant, F (2.68, 18.76) = 2.44, p = 0.10; F (3.20, 22.34) = 2.59, p = 0.075, respectively. Pair-wise comparisons showed that accuracy was higher when the cue was valid than when it was neutral (p = 0.013 and this, in turn, was higher than when the cue was invalid (p = 0.027).

Target Absent

When a target was absent, none of the effects on accuracy was significant: the main effect of cue validity (F (1, 7) = 2.86, p = 0.14), the main effect of ISI (F (3, 21) = 2.48, p = 0.09), and the interaction effect (F (3, 21) = .73, p = 0.55).

Location Cue

Target Present

The accuracy for location cue is presented in Figure 3.10. A 2-way ANOVA revealed that the main effect of cue validity was significant, F (1.30, 9.07) = 12.77, p = 0.004. The main effect of ISI and the interaction effect were not significant, F (2.12, 14.87) = 1.02, p =0.39; F (2.50, 17.49) = 1.80, p = 0.19, respectively. Pair-wise comparisons showed that the accuracy was marginally significantly higher when the cue was valid than when it was neutral (p = 0.06) and this, in turn, was significantly higher than when the cue was invalid (p = 0.008).

Target Absent

A 2-way ANOVA revealed that none of the effects on accuracy was significant: the main effect of cue validity (F (1, 7) = .20, p = 0.67), the main effect of ISI (F (4, 28) = 1.36, p = 0.27), and the interaction effect (F (4, 28) = 1.24, p = 0.32).

Orientation Cue

Target Present

None of the effects on accuracy was significant: the main effect of cue validity (F (1.98, 13.89) = 0.45, p = 0.64), the main effect of ISI (F (1.81, 12.67) = 1.83, p = 0.20), and the interaction effect (F (2.80, 19. 62) = 1.17, p = 0.35).

Target Absent

Similarly, none of the effects were significant: the main effect of cue validity (F (1, 7) = 0.81, p = 0.40), the main effect of ISI (F (3, 21) = 0.40, p = 0.76), and the interaction effect (F (3, 21) = 0.11, p = 0.95).

3.4. Discussion

In the past decades, studies to investigate how attention or top-down control influences the visual search process have mainly used the paradigm of blocked designs (Egeth et al., 1984; Farell and Pelli, 1993; Moore and Egeth, 1998), in which subjects searched for exactly the same target in all the trials of a certain block. This paradigm does not allow one to study the temporal characteristics of the top-down control, or how an instant hint about the target would affect the search process. A paradigm of searching a target on a trial-by-trial basis would serve these purposes. In some resent studies that used the trial-by-trial paradigm (Wolf et al., 2004; Vickery, King and Jiang 2005), the exact target was used as the cue to provide top-down guidance prior to the visual search stimuli. In such a paradigm, the maximum top-down information about the target was provided to observers. This mimics some of the situations in real life. For instance, when one is searching for a red mug in a room, he knows which exact mug he is looking for; therefore he knows all the characteristics about his target prior to the search task. However, in some circumstances, we do not necessarily know what exact target we are looking for. Instead, we only know some partial information about the target. For instance, when a driver is sent to pick up a guest from the airport, the only information he may have about this guest is the color of the guest’s business suit. At the airport, the driver will search based on this limited information. Thus, a relevant question is what kinds of partial pre-knowledge are helpful for a visual search task? How much earlier should the pre-knowledge be presented in order for it to assist in a visual search task? These are the questions that we investigated in the current study. A trial-by-trial basis odd-man-out paradigm with different kinds of cues was used.

The pre-cue effects from different kinds of cues: color, location vs. orientation

Although the pre-cue in the current study was not valid all the time (it had 80% validity), an efficient search strategy is still to search the subset that contained the cued feature first. The pre-cue was expected to guide the search by helping observers to decide which subset to search first. Therefore, better performance should be observed for valid cue condition than invalid cue condition.

Our results showed that color (both sensory and semantic) and location precues improved search performance. Valid cues led to better performance (shorter RT and/or higher accuracy) while misleading invalid cues resulted in performance cost (longer RT and/or lower accuracy). These results are consistent with studies that used blocked design and other paradigms (e.g., Posner et al., 1980; Shih & Sperling, 1996; Cheal & Gregory, 1997; Moore & Egeth, 1998; Brawn & Snowden, 1999). Observers were able to utilize the color and location pre-cue to limit their search to a subset of the search items. In addition, the current findings also suggest that observers could update the search subset quickly on a trial-by-trial basis by using the color or location pre-cue presented at the beginning of each trial.

By contrast, visual search performance did not benefit from an orientation pre-cue. There was no difference on both RT and accuracy among the valid, neutral and invalid cue conditions. The orientation pre-cue did not seem to help observers select a subset efficiently. Due to the brief presentation duration of the stimuli, in order to limit the search to the most relevant subset, a segmentation process must be accomplished quickly.

In the current study, segmentation may be easier to accomplish based on color or location than on orientation. These findings demonstrated that during visual search, not all kinds of partial information about the target would be equally beneficial for the task. Other studies have also shown that, among different kinds of features, color has advantage over other features, such as size, orientation and motion (Moore & Egeth, 1998; Olds & Fockler, 2004; and Sobel, Pickard & Acklin, 2009). For instance, studies that used a preview paradigm found that observers' performances were improved after a preview of the color of the search items; however a preview of the orientation did not provide assistance to the visual search (Olds & Fockler, 2004; and Sobel, Pickard & Acklin, 2009). A further question would be why certain features (e.g. color) have an advantage over other features (e.g. orientation) in guiding visual search? This may likely depend on the distinguishability of the two values of the specific feature dimension used in the experiment. For instance, although horizontal and vertical are the two most distinguishing values within the orientation feature dimension, they may not be as distinguishable as the red and green color.

In the present study, we also investigated how a color sensory cue and a color semantic cue affect the performance of a conjunctive search differently. In the study by Wolfe, et al. (2004), in which the exact identity of the target was cued on each trial, they reported that pictorial cues were more effective than semantic cues. Observers were faster with the guidance of pictorial cues than semantic cues. Using random polygons and real-world stimuli, Vickery, King and Jiang (2005) also showed that observers were faster in search speed when the cue was a pictorial cue then when it was a semantic cue. In the current study, a color semantic cue was not as helpful as a color sensory cue. The cue validity effects were observed on both the reaction time measure and the accuracy measure for color sensory cues whereas, for color semantic cues, the cue validity effect was observed only on the accuracy measure, but not the reaction time measure.

Time course of the pre-cueing effect

Studies that used the cueing paradigm have shown that spatial and feature-based attention exhibited different temporal characteristics. Spatial exogenous attention exerts its effect in a very early stage, starting within 100 ms, while it takes about 200-300 ms for endogenous spatial attention to be effective (Posner, Snyder & Davidson, 1980; Cheal & Lyon, 1991). Feature-based attention is even slower than endogenous spatial attention (Hayden & Gallant, 2005; Liu, Stevens & Carrasco 2006). For instance, Liu, Stevens & Carrasco (2006) found that feature-based attention took longer than 300 ms to exert its effect.

In studies to investigate the temporal characteristics of the cueing effect on visual search tasks, Wolfe et al. (2004) reported that both an exact pictorial cue and a word cue led to faster RT than an uninformative cue did when the cue was shown only 50 ms ahead of the stimuli, and the effect reached maximum when it was 200 and 400 ms ahead. In the Vickery, King and Jiang (2005) study, they also showed that it took 200 ms for an exact target cue to facilitate observers' search performance. However, they did not investigate cue lead times that were less than 200 ms.

Interestingly, in the current study, the effects from color and location pre-cues did not vary as ISI changed. The magnitude of the effects at different ISI did not differ significantly for color sensory or location cues. Both color sensory and location cues exhibited their effects on directing visual search immediately after the cue was presented. Only for the color semantic cue, in trials where a target was present, the interaction effect on accuracy between cue validity and ISI was marginally significant. The results showed a tendency that the difference on accuracy between the neutral cue and the invalid cue conditions varied along with ISI. The accuracy did not differ from each other for the neural and the invalid cue conditions if the cue was presented immediately before the search stimuli; however, the accuracy dropped greatly for the invalid cue condition when the cue was presented 100 to 700 ms ahead of the stimuli. These results may indicate that, compared to a color sensory cue or a location cue, it takes longer for a color semantic cue to affect the visual search performance. Similarly, Wolfe et al. (2004) also reported that it took longer for a word cue than for a pictorial cue to exert its full effect on assist visual search task. In addition, for color semantic cue, the cue validity effect was due to a performance cost from an invalid cue instead of performance facilitation from a valid cue.

Limited display duration

Studies have shown that attending to a feature could aid conjunctive search when the stimuli were presented until response (Egeth, Virzi & Garbart, 1984; Bacon & Egeth, 1997; Wolfe, et al. 2004). Here, we showed that feature-based attention could also provide assistance to visual search when the stimuli were presented for very brief times.

The accuracy values in the current study are relatively low, especially when the cue is invalid. This is mainly because of the short presentation duration of the stimuli.

4. Experiment 3: Feature-based attentional modulation on prior entry

4.1 Introduction

Some researchers in the field of attention believe that there exists a prior-entry effect of attention on perception. The fundamental hypothesis of *prior-entry* effect states that attention can accelerate sensory processing, thereby causing attended objects to be perceived earlier than unattended objects. Titchener (1908, p.251) summarized in one of his seven laws of attention that "The object of attention comes to consciousness more quickly than the objects which we are not attending to". This effect of attention has been investigated for more than a century. However, there is still no agreement among researchers on whether there indeed exists a prior-entry effect. To better understand how attention affects the temporal resolution of perception, and to provide one more piece of evidence to the prior-entry hypothesis, we used some of the new developed methods to investigate this phenomenon from a new point of view.

The hypothesis of prior-entry effect was mostly examined in the multisensory domain, especially for the tactile, auditory and visual modalities. Typically, temporal order judgment (TOJ) task was used to test the existence of prior-entry effect. In a multisensory TOJ paradigm, two stimuli of different modalities (e.g. a sound and a flash) are presented to observers. One stimulus precedes the other by various stimulus onset asynchronies (SOA). Observers are required to judge which modality's stimulus comes first (e.g. visual stimulus first vs. auditory stimulus first). The point of subjective simultaneity (PSS) is then measured to indicate how much time one stimulus has to precede the other in order for them to be perceived as simultaneous. Generally, for a tactile-visual pair of stimuli, a visual stimulus has to lead a tactile stimulus in order for them to be perceived as simultaneous (Spence, Shore & Klein, 2001). For a visual-auditory pair, a visual stimulus usually has to lead the auditory stimulus to be perceived as simultaneous (e.g., Zampin, Shore & Spence, 2003; van Eijk et al., 2008).

To study prior-entry effect, attention is manipulated to see how it affects the performance of the TOJ task. Observers are instructed to direct their attention to one of the modalities or divide their attention to both modalities. PSS are measured under different attentional conditions. In theory, a shift of PSS under different attentional conditions will suggest an effect of prior-entry (Shore, Spence & Klein, 2001). Some earlier studies found an approximately 50 ms prior-entry effect for auditory-tactile pairs, and an effect of approximately 30 ms for auditory-visual pairs (S.A. Stone, 1926; Stember et.al., 1971). However, there were also earlier studies that did not find significant multisensory prior-entry effects of attention (Frey & Wilberg, 1975). Although findings from early studies are mixed, the evidence supporting the existence of prior-entry effect face a serious criticism, which comes from a potential confounding effect of response bias. In these early studies, the typical TOJ task was used. Observers were instructed to attend to one of the two modalities, and they were asked to report “which modality’s stimulus was presented first”. The inherent problem in this instruction is that observers may simply report the modality to which they were asked to attend. Therefore, evidence obtained from TOJ experiments using this paradigm is not convincing.

In order to reduce this confounding effect and provide more convincing evidence for the existence of prior-entry effect, two new methods were introduced recently (Shore, Spence & Klein, 2001; Schneider & Bavelier, 2003). Shore, Spence and Klein (2001) implemented an orthogonal judgment method in a TOJ task, in which observers attended to one of the two modalities and performed a spatial discrimination task (i.e. left vs. right first). In other words, the attended dimension and the response dimension are orthogonal to each other in this design. The authors argued that responses to “left” or “right” position should not be preferred by attending to either “visual” or “tactile” modality, whereas response to “visual” or “tactile” might be. Thereby, response biases should be smaller in an orthogonal design than in a nonorthogonal design used in early studies. Shore, Spence and Klein (2001) used a probability manipulation method to direct observers’ attention to the most frequent stimulus modality, and observers were instructed to report whether the left or right stimulus was presented first. A significant shift of PSS was found. Visual stimuli had to lead tactile stimuli by approximately 155 ms when observers attended to the tactile modality, as opposed to approximately 22 ms when they attended to the visual modality. The orthogonal TOJ design was also combined with an electrophysiological method to examine the modulation effect of attention on the timing of neural processing. Vibell et al. (2007) looked at the effect of attention on an orthogonal TOJ task using event related potentials (ERPs). They found that directing attention to different modalities resulted in shifts of peak latencies of early visual ERP components. P1 and N1 peaked significantly earlier when attention was directed to vision than to touch. This study was the first to show electrophysiological evidence supporting the hypothesis of multisensory prior-entry.

Even though findings from orthogonal designs are more convincing than those from non-orthogonal designs, a second-order response bias can still survive in an orthogonal design. In other words, observers can still have the tendency to report the spatial position of the stimuli presented in the attended modality. Therefore, to eliminate all kinds of response bias, Zampini, Shore and Spence (2005) used another type of perceptual judgment task, simultaneity judgment (SJ), to further investigate the prior-entry effect between auditory and visual modalities without bias. In a simultaneity judgment paradigm, observers report whether two stimuli appeared simultaneously or successively. Responses should depend only on the interval between the two stimuli but not their order; there is no reason for observers to prefer one stimulus over the other, no matter under what attentional condition. Therefore, judgments from the SJ task reflect more accurately the sensory effects other than the change of response criterion. If attention has a sensory acceleration effect on perception, PSS shifts should be observed directly from the SJ task (Schneider & Bavelier, 2003; Zampini, Shore & Spence, 2005). Researchers believe that studies with the SJ task would provide even more convincing evidence on the hypothesis of prior-entry. In Zampini, Shore and Spence’s (2005) study, they observed that visual stimuli had to lead auditory stimuli by 46 ms to reach PSS when observers attended to the auditory modality, in comparison with 32 ms when attended to the visual modality. The difference of PSS is significant, which suggested clearly an effect of multisensory prior-entry.

Prior-entry effects have also been studied within the visual modality. A few studies have been conducted to explore if prior-entry effects can be elicited by spatial attention

(Stelmach & Herdman, 1991; Hikosaka, Miyauchi & Shimojo, 1993; Shore, Spence & Klein, 2001; Schneider & Bavelier, 2003). If spatial attention can speed up visual sensory processing, then objects in the attended location would be perceived prior to those in the unattended location. Shore, Spence and Klein (2001) implemented an orthogonal cueing design to study how peripheral and central attentional cuing affects the performance in the TOJ task. A peripheral flash or a central arrow cue was presented prior to the TOJ stimuli to orient attention either to the left or right of the fixation mark. Instead of reporting directly the location of the first stimulus, observers were asked to indicate whether a vertical or horizontal line was presented first. Prior-entry effects were observed from both endogenous and exogenous spatial attention cueing. The prior-entry effect was approximately 61 ms for exogenous orienting and 17 ms for endogenous orienting, and objects in the unattended location have to lead objects in the attended location in order for them to be perceived as being presented simultaneously. Schneider and Bavelier (2003) replicated the same effects using the TOJ task. In the same study, Schneider and Bavelier demonstrated a significant but smaller prior-entry effect from an exogenous cue using the SJ task. However prior-entry effect from an endogenous cue in their SJ paradigm was observed only when the cue lead time (the time interval between the cue and the stimuli) was 600 ms but not when it was 0, 100, 300, 1000, or 1500 ms. In both studies, prior-entry effect from exogenous spatial attention is larger than that from endogenous spatial attention.

Studies from different methods have provided strong evidence for the existence of prior-entry effects in the multisensory domain and within the visual modality, although evidence from endogenous spatial attention is still equivocal. In the current study, we aim to explore the prior-entry effect within the visual modality from another point of view. We investigate whether there exists a prior-entry effect based on feature-based attention. Feature-based attention has been demonstrated to have similar behavior consequences as spatial attention (Saenz, Buracas & Boynton, 2003; Boynton, Ciaramitar & Arman, 2006). For example, both modes of attention facilitate human behavioral performance. Processing of objects in the attended location or with the attended feature is enhanced (Posner, Snyder & Davidson, 1980; Eriksen & James, 1986; Saenz, Buracas & Boynton, 2003). The speed of detecting targets increases if the targets are located at the attended location, or if the targets share the same attended features on consecutive trials (Maljkovic & Nakayama, 1994). However, spatial attention can be both bottom-up (exogenous) or top-down (endogenous), whereas feature-based attention is thought to be mainly top-down (endogenous) (Hayden & Gallant, 2005).

To investigate if feature-based attention has similar influence on the temporal processing of perception as spatial attention does, we examine the existence of a feature-based prior-entry effect. The two new methods, orthogonal TOJ and SJ tasks, are used in the following two experiments. In experiment 3A and 3B, we tried to replicate the prior-entry effect of spatial attention and explored the prior-entry effect of feature-based attention using the orthogonal TOJ design similar to Shore, Spence and Klein's (2001). Observers were asked to make responses based on the orientation (in experiment 3A) or the location (in experiment 3B) of the bars presented, whereas the attentional cue is either a spatial cue (in experiment 3A) or a color feature cue (in experiment 3A and 3B). Therefore, the response dimension is always orthogonal to the cueing dimensions. As discussed above, even though the orthogonal TOJ design can minimize the first-order response bias, observers can still engage a second-order response bias. Therefore, in experiment 3C, to examine further the existence of feature-based prior-entry effects, a SJ task was used in an effort to eliminate all kinds of response bias.

4.2 Experiment 3A – TOJ task (no attentional task on cue)

4.2.1. Methods

Observers. Four observers participated in Experiment 3A. All of them had normal or corrected-to-normal visual acuity. All observers were naïve as to the purpose of the experiments.

Stimuli. The display (see Figure 4.1) consisted of two boxes that remained on the screen throughout the block, one on each side (left and right) of a central fixation dot. The viewing distance was 60 cm. The entire display subtended 2.8 degree * 13 degree in visual angle. The fixation dot was 4.2 degrees away from the inner edge of each box. In each trial of the experiments, there was one oriented bar presented in each box. The bars were 0.2 degree * 1.5 degree of visual angle. One of them was tilted to the northeast and the other was to the northwest. Each bar was randomly assigned to be red or green. The color and orientation combinations of the bars were counter balanced to produce equal numbers of each combination.

Procedure. The basic procedure was similar in experiment 3A, 3B and 3C; there were some variations in each experiment. In general, each trial of the experiments started with a fixation phase, followed by a cue phase, and finally a stimulus phase. The fixation phase, which consisted of only the fixation dot and the boxes, lasted for 500-750 ms. During the cue phase, the cue lead time (CLT, the time from the onset of the cue to the onset of the first stimuli), the cue duration, and observers’ tasks on the cue were varied in different subsections of the experiment 3. In experiment 3A, the CLT was 110 ms, with the cue presented for 50 ms and a short cue-stimuli interval lasting 60 ms. Two kinds of cues were used, feature and spatial cues. For feature cuing (see Figure 4.1 (a)), the central fixation dot changed to a color patch (red, green, or gray for neutral cue), and then changed back to a dot. For spatial cuing (see Figure 4.1 (b)), the frame line surrounding one of the boxes (or both boxes for neutral cues) became thicker (8 pixels), and then returned to its original size (2 pixels).

The last phase of each trial was the stimulus phase. The first stimulus (the northwest bar or the northeast bar) was presented in the left or right box, followed by the second stimulus (the northeast bar or the northwest bar) in the other box after a variable stimulus onset asynchrony (SOA: 15, 45, 90, 135, 240 ms). Subsequently, both bars stayed on the screen until observers responded. Observers were instructed to make an unspeeded temporal order judgment (TOJ) on which bar came first, the northwest one or the northeast one, by pressing two different keys. There were 32 trials for each SOA of each type of cues.

A flicker photometry method was used to measure the equiluminance values for red and green patches for each observer at the beginning of each experiment. Observers then participated in a practice session with SOA of 30 and 90 ms between the two stimuli. During the practice session, an auditory feedback was provided at the end of each trial to signify whether the response was correct or incorrect with two different tones.

4.2.2 Results

The average proportion of “northwest first” responses across observers was plotted as a function of SOA in Figure 4.2. In the spatial cue experiment, the cue dimension was location whereas the task dimension was orientation. In order to show if there is prior-entry effect present, it is necessary to correlate each type of location cue to an orientation cue, for data display purpose, to directly associate observers’ responses to the cue. Similarly, in the feature cue experiment, each type of color cue was correlated to an orientation cue. Therefore, the proportions of responses were presented in terms of three different orientation cue conditions (northwest-cue, neutral-cue and northeast-cue) in Figure 4.2.

For spatial cue, with respect to the neutral-cue condition, responses in the northwest-cue and northeast-cue conditions shift to the left and right horizontally, respectively, as shown in Figure 4.2(b). In other words, observers were more likely to report that the northwest-oriented bar was presented first when the spatial cue was associated with a northwest cue, and less likely when it was associated with a northeast cue. However, this pattern was absent for a feature cue, as shown in Figure 4.2(a). Responses under the three cue conditions using feature cue were essentially the same.

Logit models were fitted to data of each cue condition for each observer using maximum likelihood estimation. Points of Subjective Simultaneity (PSS) were then estimated from the models. Average PSS across observers was shown in Figure 4.3. A one-way ANOVA test indicated that, for spatial cue, there were significant differences on PSS under different cue conditions, $F(2, 9) = 7.56$, $p = 0.012$. Tukey’s post hoc test revealed that there was a significant difference between the PSS of the northwest-cue condition and that of the northeast-cue condition (-74 ms vs. 79 ms), $p < 0.05$. The average PSS of the neutral condition was 16 ms, which was not significantly different from those of the other two cue conditions ($p > 0.05$ for both comparing to the PSS of the northwest-cue and the northeast-cue conditions). The effect of cue condition was not significant for feature cue from a one-way ANOVA test, $F(2, 9) = 0.22$, $p = 0.80$.

4.2.3 Discussion

In this experiment, we aimed to replicate the prior-entry effect from exogenous spatial attention and to test if a color feature cue would elicit a similar effect on the TOJ task. As shown in Figure 4.2 and 4.3, a shift of PSS was observed from the exogenous spatial cue, which suggested the presence of a prior-entry effect. The magnitude of the effect can be measured by half of the difference of PSS between northwest-cue and northeast-cue conditions. It is 77 ms (-75 ms for northwest-cue and +79 ms for northeast-cue) for a spatial cue. The magnitude of this effect is consistent with findings from other previous studies. Shore, Spence and Klein (2001) using the same cue lead time (60 ms) as in the current study, found a 74 ms shift of PSS in a TOJ task. Stelmach and Herdman (1991) reported a slightly smaller effect (50ms) with a cue lead time of 250 ms. But Hikosaka, Miyauchi, and Shimojo (1993b) found even smaller magnitudes using onset cue lead times of 50, 150, 400, and 1600 ms.

A shift of PSS was not observed in the feature cue experiment (Figures 4.2(a) & 4.3(a)). An exogenous spatial cue can capture observers’ attention automatically and strongly

(Eriksen & Hoffman, 1972; Posner & Cohen, 1984). It is very difficult for observers to ignore an abrupt-onset spatial cue. However, this is not the case for the feature cue. In this experiment, observers were asked to look at the center color patch cue passively, and then perform the TOJ task on the periphery; it is very likely that observers may have simply ignored the cue. After the experiment, the observers reported that they felt the spatial cue disturbing, but not the feature cue. Therefore, the absence of the prior-entry effect for the feature cue may be possibly due to the fact that attention was not engaged to the feature. Furthermore, the time course of feature-based attention is different from that of spatial attention. The effects of feature-based attention usually develop more slowly than those of spatial attention (Liu, Stevens & Carrasco, 2006). Therefore, the cue lead time of 60 ms in this experiment may have been too short for feature-based attention to exert its effects. In our next experiment, we introduced an attentional task on the cue with a range of longer cue lead times.

4.3 Experiment 3B – TOJ task (with attentional task on cue)

4.3.1 Methods

Observers. Eight observers participated in the long CLT condition; seven participated in the medium CLT condition; and six participated in the short CLT condition. All of them had normal or corrected-to-normal visual acuity. All observers were naïve as to the purpose of the experiments.

Stimuli and Procedure. The stimuli display was similar to that in experiment 3A. To engage observers' attention on the feature cues, attentional tasks on the cues were included in Experiment 3B (see Figure 4.4(a) and Figure 4.4(b)). Both red and green cues were presented in each trial. Observers were instructed to attend to the red or green cue in separate blocks. Different cue lead time (CLT) between the cue and the first stimulus was used: 1200 ms (long CLT) as shown in Figure 4.4(b), 700 ms (medium CLT) as shown in Figure 4.4(b) and 250 ms (short CLT) as shown in Figure 4.4(a). For short CLT, the central cue consisted of four color patches, two reddish and two greenish. Observers performed a same-or-different-saturation task on the attended color. In other words, they were asked to discriminate whether the two patches of the attended color had the same saturation or not. The two patches had the same saturation in half of the trials, and different saturation in the other half. The two patches of the unattended color could also have the same or different saturation, independently of the relationship between the patches of the attended color. The duration of the color cues was 150 ms, and a 100 ms cue-stimulus interval followed. For medium and long CLT, only two color patches, one reddish and one greenish, were presented. The cues lasted for 600 ms in the medium CLT condition and 1000 ms in the long CLT condition. At the last 150 ms of the cue duration, a color saturation change event occurred on the attended color in half of the trials. Observers were asked to discriminate whether there was a color saturation change even on the attended color. There could also be a saturation change event on the unattended color, independently of the occurrence of an event on the attended color. A short cue-stimulus interval (100 ms for medium CLT and 200 ms for long CLT) followed the offset of the cues.

During the stimulus phase, the first stimulus (the northwest bar or the northeast bar) was presented in the left or right box, followed by the second stimulus (the northeast bar or the northwest bar) in the other box after a variable stimulus onset asynchrony (SOA: 15, 45, and 240 ms). Observers were instructed to make an unspeeded temporal order judgment (TOJ) on which bar came first, the left one or the right one, by pressing two different keys.

The 80% color saturation threshold for each observer was measured at the beginning of Experiment 3B. Observers participated in a practice session with SOA of 30 and 90 ms between the two stimuli. Auditory feedback was provided during the practice session.

4.3.2 Results

The average proportion of “red first” responses across observers is plotted as a function of SOA for the three different CLT conditions in Figure 4.5. Even though the task was to report whether the stimulus on the left or on the right was presented first, we converted a response of location to a corresponding response of color, for data display purpose. In other words, the response was converted to an appropriated color response, as if observers were asked to report whether the red or greed stimulus was presented first. The purpose of this transformation is to see clearly the effect of prior-entry.

For all three CLT conditions, there was a left horizontal shift of responses for the attend-to-red condition relative to the attend-to-green condition. Observers were more likely to report that the red bar was presented first when attending to the red color, and less likely when attending to the green color. Logit models were fitted to the data of each cue condition for each observer using maximum likelihood estimation. PSS were then estimated from the models. Average PSS across observers are shown in Figure 4.6. One-tailed paired t-test revealed significant differences on PSS between different attention conditions for Long CLT (t (7) =2.33, p=0.026), and for medium CLT (t (6) =2.52, p=0.023). The difference on PSS for the short CLT condition was marginally significant (t (5) =1.55, p=0.09).

4.3.3 Discussion

Within the visual modality, the prior-entry effect has been tested for both exogenous and endogenous spatial attention (Stelmach & Herdman, 1991; Spence, Shore & Klein, 2001; Schneider & Bavelier, 2003). The effect was generally smaller from endogenous spatial cues than from exogenous spatial cues. Shore, Spence & Klein (2001) demonstrated a shift of PSS of 30 ms from endogenous spatial cues, smaller than the magnitude from exogenous spatial cues in the same study (74 ms). Schneider and Bavelier (2003) also reported smaller effects across different cue lead times. Some studies even found null results from endogenous attention (Jaskowski, 1993).

In order to observe prior-entry effects, it is crucial to ensure attention was effectively controlled (Schneider & Bavelier, 2003). In most previous studies, spatial attention was directed to a location by either using an abrupt onset cue for exogenous attention or a foveal cue (e.g. a central arrow) for endogenous attention. However, there was no performance measurement on how effectively attention was manipulated. A central cue (e.g. an arrow) was commonly used and has been demonstrated to be an effective cue to direct endogenous attention, and in most of the studies using this type of cue, the cue was relevant to the task, such as providing validity information about the target location. But in studies that investigated prior-entry effects of endogenous spatial attention, the cue was not directly relevant to the task. It did not provide additional information about which stimulus would be presented first. Therefore, it is possible that the irrelevant central cue was not sufficient in engaging endogenous attention. A larger prior-entry effect may be demonstrated with a more efficient way of engaging endogenous attention. In our current study, we controlled observers' attention by having an attentional task on the cued feature. Although we did not investigate the effect of endogenous spatial attention, the findings from feature-based attention are an interesting comparison to those from endogenous spatial attention. Furthermore, feature-based attention is thought to involve mainly an endogenous top-down processing, therefore findings from the current experiment also provided future understanding on prior-entry effects from endogenous type of attention in general.

As shown in Figures 4.5 and 4.6, a different pattern of results was observed in this experiment than in the feature cue condition of experiment 3A. A significant left shift of PSS was observed when attending to red color versus when attending to green color. The average PSS were – 15 ms and + 15 ms for the attend-to-red and attend-to-green conditions, respectively. That is, when attention was directed to red color, the green bar needed to be physically presented about 15 ms prior to the red bar for the two bars to be perceived as simultaneous, and vice versa. The magnitude of the effect (15 ms) is relatively small, but compatible to that from endogenous spatial attention (Shore, Spence & Klein, 2001; Schneider & Bavelier, 2003). Observers' performances on the cue task were at least 70% correct. Therefore observers did pay attention to the cued feature. Using this method to ensure an efficient engagement of attention, our study offers additional evidence that prior-entry effects from endogenous attention are indeed smaller than that from exogenous attention in general.

Although an orthogonal TOJ paradigm was used in the current experiment, the effect could also be interpreted equally well by the explanation of secondary response bias (Shore, Spence & Klein, 2001; Schneider & Bavelier, 2003). As demonstrated in Shore, Spence and Klein's (2001) study, secondary response bias still survived in an orthogonal TOJ paradigm. In order to eliminate response bias completely, and to further examine if the effect observed here from feature-based attention was indeed an attentional prior-entry effect, or simply a reflection of response bias, we used a SJ task with a similar setup in the next experiment.

4.4 Experiment 3C – SJ task (with attentional task on cue)

4.4.1 Methods

Observers. Seven observers participated in Experiment 3C. All of them had normal or corrected-to-normal visual acuity. All observers were naïve as to the purpose of the experiments.

Stimuli and Procedure. The stimuli display was exactly the same as in experiment 3B. Observers were asked to make simultaneity judgment instead of temporal order judgment. That is, they were instructed to determine whether the two stimuli (lines) were presented simultaneously or consecutively, regardless of the order. One CLT (700 ms) conditions was studied. The second stimulus followed the first stimulus after various SOAs values (0, 30, 45, 60 and 90 ms). A practice session with SOAs of 0 and 130 ms was given to observers. Auditory feedback was provided during the practice session.

4.4.2 Results

The proportions of “simultaneous” responses are shown as a function of SOA in Figure 4.7. Proportions presented in the figure were averages across observers. Observers’ responses under the two different attention conditions were essentially the same. Gaussian models were fitted to the data of each attentional condition for each observer. PSS were then estimated from the models. One-tailed paired t-test showed no significant difference on the PSS between the two attentional conditions.

4.4.3 Discussion

Studies using simultaneity judgment task have demonstrated the existence of prior-entry effect across modalities. Zampini, Shore and Spence (2005) found a significant prior-entry effect for visual-auditory pair of stimuli (a 14 ms shift of PSS). When attention was directed to audition, visual stimulus had to lead auditory stimulus by about 46 ms for the two stimuli to be perceived as simultaneous. However, when attention was directed to vision, the PSS was smaller (32 ms). Prior-entry effect from exogenous spatial attention within the visual modality has also been demonstrated using an SJ task. Stelmach and Herdman (1991) reported a shift of PSS of 23 ms. In Schneider & Bavelier's (2003) Experiment 1, they also found significant shifts of PSS for exogenous spatial attention, and the magnitudes of the effects depended on the cue lead time between the cue and the stimuli.

However, as far as we know, only one study has used an SJ task to investigate the effect of endogenous type of attention. In Schneider & Bavelier's (2003) Experiment 2 & 3, a central arrow cue and a gaze-directed cue was used to direct attention endogenously in an SJ task. They found that significant shifts of PSS were present only at a cue lead time of 600 ms for a central arrow cue, and at cue lead times of 300 and 1500 ms for gaze-directed cue. In the current study, we used an SJ task to test the prior-entry effect endogenously but with feature-based attention. No shift of PSS was observed, and the PSS for both attentional conditions were nearly at 0 ms.

The lack of shift in PSS from an SJ task does not support the existence of prior-entry effect from feature-based attention. The discrepancy of the results of the TOJ and SJ tasks may suggest that the sensory acceleration observed in the TOJ task was due to response bias, rather than prior-entry effect. However, it could also be that the prior-entry effect manifests itself for a different CLT window for feature-based attention. It may as well be that the prior-entry effect from feature-based attention is small, and the SJ task is not as sensitive as the TOJ task to detect such effect. In addition to the data reported here, we also tried SOAs of ± 15 ms in one of the pilot studies on the SJ task. However, without forcing observers to choose which stimulus was presented first, the proportion of “simultaneity” responses for SOA ± 15 ms was essentially the same as for SOA of 0 ms. In other words, observers tended to give “simultaneity” responses whenever they did not surely perceive the successive presentation of the two stimuli. The decision criteria used in the SJ task is very different from those in the TOJ task. Studies that contained a “simultaneous” response option have shown large individual differences on the decision criteria. In two of the earlier studies that combined a “simultaneous” response option in addition to a regular TOJ option, one demonstrated a clear prior-entry effect (Stelmach and Herdman, 1991), whereas the other did not (Jaskowski, 1993). And one of the major differences between these two studies was that in Stelmach and Herdman ‘s (1991) study, there were only less than 5% of the trials where observers chose the “simultaneous” option. But in Jaskowski’s (1993) study, observers chose this option most of the time when the SOA was close to zero. The results of simultaneity judgment task seem to largely depend on the decision criteria of the observers. It may be a good method to rule out response bias, but it may not be a robust method to show the prior-entry effect.

It will be interesting in future research to investigate further this effect with a different task. A plausible method might be to use a detection task instead of a judgment task with a similar cueing paradigm as in the current study. The task could be to detect the presence of a shape. Reaction time could be measured under two conditions: when the target shape is of the attended color, versus when it is of the unattended color. It would support the claim of prior-entry effect if reaction time to the target of the attended color is faster than that to the target of the unattended color.

Another interesting observation from the current study is that, when the two stimuli were physically presented simultaneously, observers gave simultaneous responses less than 70% of the time. It would be interesting to see when they perceived the two stimuli were presented sequentially, which stimulus was perceived first. Unfortunately, we did not envision using these data, hence we did not record them. Therefore, an interesting future study may be to have two judgment questions, with the SJ task preceding the TOJ task.

5. General Discussion and Future Work

It has been documented that feature-based attention can modulate many aspects of our visual perception. Particularly, motion perception and visual search are the two most frequently investigated processes that are influenced by feature-based attention. However, some specific aspects of these modulation effects have not been fully investigated. In the current thesis, we examined further some aspects of the attentional modulation on motion perception and visual search. In addition, we also explored a question that has not been investigated for feature-based attention yet, namely, how feature-based attention modulates the temporal processing of visual stimuli.

Motion perception

Motion perception is the general term that refers to both speed perception and direction perception. Studies have shown that the speed discrimination thresholds are affected by motion speed (De Bruyn & Orban, 1988; Lappin, Tadin, Nyquist & Corn, 2009). The direction discrimination thresholds also depend on the motion direction (Hohnsbein & Mateeff, 1998; Matthews & Qian, 1999). In most previous studies that investigated how feature-based attention affects motion perception, the distinction between the attentional effects on speed perception and on direction perception was rarely made. In the current thesis, results in experiment 1A and 1B demonstrated that feature-based attention affected speed discrimination and direction discrimination differently. Larger feature-based attentional effects were observed for direction discrimination than for speed discrimination.

There are two possible reasons why differences on the magnitude of the attentional effects were observed between direction and speed discrimination. One reason may be that we human are more sensitive to speed changes than direction changes. This is supported by the finding that for speed discrimination, the dual-task thresholds in the same-base-speed condition were the same as the thresholds in the single-task condition. That is, we are very sensitive to speed change, such that it took less extra effort to attend to an additional aperture that had the same motion speed, as opposed to attending to only one aperture. On the other hand, for direction discrimination, the dual-task thresholds in the same-principal-direction condition were significantly larger than the thresholds in the single-task condition. The second possible reason may have to do with the distinguish-ability between the two values within each feature dimension. For direction discrimination, the two different principal directions were upward and rightward motion, which are most distinguishable from each other within the direction dimension. However, for speed discrimination, the two base speeds (1.55 degree/sec vs. 3.87 degree/sec) might not be as distinguishable.

Visual Search

In experiment 2, by combining the cueing paradigm in a trial-by-trial odd-man-out conjunctive search task, we were able to study how attending to different kinds of features (color sensory, color semantic, location and orientation) influenced the search performance. The results showed that not all kinds of pre-cued features were helpful in guiding conjunctive search. Consistent with other visual search studies, color pre-cue was more helpful than orientation pre-cue. However, the reason that caused this difference is yet unknown. Color feature may have intrinsic advantage over other features, such as, size or orientation, such that segmentation processing based on color feature is easier to accomplish. It could also be due to how distinguishable were the values used for the color dimension and the orientation dimension.

Although feature-based attention has similar behavioral consequence on perception as spatial attention does, the temporal characteristics of feature-based attention seems to be very different from spatial attention. Studies that used motion paradigm to investigate the time course of feature-based attention generally found that feature-based attention exhibits its effect at a relatively later stage (around 300 ms) than spatial attention does (around 150 ms) (Hayden & Gallant, 2005; Liu, Stevens & Carrasco 2006). However, in the current study, as well in some other visual search studies (Wolfe et al., 2004; Vickery, King and Jiang, 2005), feature-based attention seemed to exhibit its effect very early. For instance, the attentional effect was observed as early as 0 ms ISI between the cue and the search stimuli. Also, in Wolfe et al. (2004) study, the effect was observed when the cue was shown only 50 ms ahead of the stimuli. Therefore, the temporal characteristic of feature-based attention effect may likely depend on the specific stimuli and tasks. An inhibition of return phenomenon is usually observed for spatial attention in many different paradigms, whereas no similar phenomenon was observed for feature-based attention in previous motion paradigm studies (Liu, Stevens & Carrasco 2006), nor in the current visual search paradigm study. Thus, this may confirm again that feature-based attention is indeed a purely goal-driven process.

The common observations from Experiment 1 and 2 are that first of all, we human beings are more sensitive to some features (e.g. color and speed) than the others (e.g. orientation and direction). Second of all, a follow-up question from both studies is whether the effect of feature-based attention on a particular feature dimension is an all-or-none effect as long as the two feature values are distinguishable from each other, or its magnitude depends on how distinguishable the two feature values are. For instance, in the direction discrimination experiment, if the two principal directions were “upward” and “+45 degrees”, which are not as distinguishable as upward and rightward motion, would the magnitude of the attentional effect be the same as observed in the current study, or would it be smaller? Future studies would be necessary to uncover this question.

Prior-entry effect

In experiment 3, a series of three experiments were conducted to explore if there exists a prior-entry effect based on feature-based attention. To the best of our knowledge, our study was the first to test the prior-entry hypothesis on feature-based attention. Studies on spatial prior-entry effect have found that the effect from endogenous spatial attention was generally smaller than that from exogenous spatial attention. As shown in many studies, feature-based attention is thought to be mainly top-down, which is an endogenous kind of attention. Therefore, if there is a prior-entry effect based on feature-based attention, we would expect it to be relatively small.

In studies that investigated the spatial visual prior-entry effect, a cue was usually used to direct observes’ spatial attention. However, in those studies, observers had only one task, which was either the temporal order judgment (TOJ) or simultaneity judgment (SJ) task. The disadvantage of this paradigm is that the cue was disassociated with the TOJ or SJ task, especially for endogenous attentional cues. In order to overcome this disadvantage and to ensure the engagement of feature-based attention, an additional task on the cue was used in experiments 3B and 3C. A relatively small prior-entry effect was observed in experiment 3B with the TOJ task, however a similar effect was not observed in experiment 3C with the SJ task. Some may think that the results from the SJ task are more convincing, because of the potential response-bias confounding effect in the TOJ task. However, the SJ task is not as sensitive as the TOJ task. If the prior-entry effect based on feature-based attention effect was relatively small, the SJ task may not be able to detect such effect. Given that both TOJ and SJ tasks have some disadvantages, new paradigms or technique are needed to further examine this prior-entry hypothesis. A potential good method to investigate the prior-entry effect is the event related potentials (ERP) technique due to its high temporal resolution. Evidence that supports the existence of a multisensory prior-entry effect has been shown using the ERP technique (Vibell et al., 2007), whereas similar studies have not been conducted yet on spatial prior-entry or feature-based prior-entry effects.

Future Work

Several interesting follow-up questions can be investigated in the future. The first one is to explore how the magnitude of the feature-based attentional effects varies as the distinguish-ability between the two values within each feature dimension changes. A series of experiments can be conducted to investigate this question. For example, in

Experiment 1 in the current thesis, the base speeds of 1.55 degrees/sec and 3.87 degrees/sec were used in the speed discrimination task. It would be interesting to see how the attentional effects change as the difference between the two base speeds increases. Similarly, the two principal directions used were upward and rightward in the direction discrimination task, resulting in a maximal difference. The magnitude of the feature-based attentional effects may change as the difference of the principal directions decreases. The same question could be examined in the visual search paradigm. As shown in Experiment 2, the color visual cue seems to be more helpful than the orientation visual cue. However, it is unclear what the underlying mechanism is that causes this difference between color and orientation cues. To further investigate whether it is due to the fact that the distinguish-ability between red and green is larger than that between horizontal and vertical, the same experiment could be repeated with a pair of colors that are less distinguish-able, such as red and pink.

In Experiment 2, visual search task performance was improved from a visual cue that provided partial information about the target, and the magnitude of the improvement remained the same for the values of ISI tested in the experiments. Additional experiments with a wider range of ISI values could reveal the time course of the cueing effects. A further question to be examined would be whether the way in which the partial information is presented to observers affects the cueing effects. In the current thesis, the partial information was provided through a visual cue; it would be interesting to investigate how the effects would be different if the partial information was provided through an auditory cue, as well as the time course of the auditory cueing effects.

Further studies are required to provide stronger evidence for the existence of prior-entry effects based on feature-based attention. For psychophysical experiments, both TOJ and SJ paradigms use discrimination tasks and primarily percentage of response as a measure; a paradigm with emphasis on reaction time may be more robust to detect prior-entry effects. A potential experiment would be to measure reaction time in both the task on the cue and the primary prior-entry task, using similar settings as in Experiment 3. In other words, observers would be asked to first detect a color saturation change on the cue, and then respond to the object that appears first. They can be instructed to respond as quickly and as accurately as possible on both tasks. If there exists a prior-entry effect elicited by feature-based attention, we expect to observe the following effect: when the cue is a red color cue, reaction time to a red object that appears first would be shorter than that to a greed object. To eliminate potential response bias, reaction times will be analyzed only for trials in which observers respond correctly. Another powerful method to detect the prior-entry effect may be by using the event related potentials (ERP) technique. Therefore, an interesting future experiment would be to repeat Experiment 3 while observers' ERP responses are being monitored.

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FIGURE CAPTIONS

Figure 2.1. Schematic diagrams of stimuli in the dual-task condition of Experiment 1A. The direction of the white arrows represents the motion direction of the dots, and the length of the arrows indicates the magnitude of the speed. Observers' tasks were speed discriminations. (a) An example of the same-base-speed condition: the base speeds were 1.55 deg/sec on both apertures; correct responses were interval 2 in the left aperture and interval 2 in the right aperture. (b) An example of the different-base-speed condition: the base speeds were 1.55 deg/sec in the left aperture and 3.87 deg/sec in the right aperture; correct responses were interval 2 in the left aperture and interval 1 in the right aperture.

Figure 2.2. Schematic diagrams of stimuli in the dual-task condition of Experiment 1B. (a) An example of the same-principal-direction condition: the principal directions were upward on both apertures; correct responses were interval 2 in the left and interval 1 in the right. (b) An example of the different-principal-direction condition: the principal direction was upward in the left aperture and rightward in the right aperture; correct responses were interval 2 in the left aperture and interval 2 in the right aperture.

Figure 2.3. Results of Experiment 1A. Threshold ratios for individual observers are shown. Blue bars specify the threshold ratios for the same-base-speed condition (Rsame); green bars represent the threshold ratios for the different-base-speed condition (Rdiff).

Figure 2.4. Results of Experiment 1B. Threshold ratios for individual observers are shown. Blue bars specify the threshold ratios for the same-principal-direction condition (Rsame); green bars represent the threshold ratios for the different-principal-direction condition (Rdiff). Error bars represent S.E.M (standard error of the mean).

Figure 2.5. Individual speed discrimination thresholds in Experiment 1A. Error bars represent S.E.M (standard error of the mean).

Figure 2.6. Individual direction discrimination thresholds in Experiment 1B. Error bars represent S.E.M (standard error of the mean).

Figure 3.4. Four possible combinations of target/distractors in target-present trials in Experiment 2.

Figure 3.5. Schematic diagram for the sequence of events in each trial. This is an example of color cue. In this example, the “green color cue” is a valid cue; the “write color cue” is a neutral cue; and the “red color cue” is an invalid cue.

Figure 3.6. Three other cue types in Experiment 2. The informative cues are on the left and right columns, whereas the neutral cues are in the middle column.

Figure 3.4. Average reaction time for color sensory cue. The five different curves represent the following five conditions: (1) NT_Neutral: when the target was absent and

the cue was a gray color cue (neutral cue); (2) NT_Color: when the target was absent and the cue was a color (red or green) cue; (3) YT_Invalid: when the target was present and the cue was an invalid cue; (4) YT_Neutral: when the target was present and the cue was a neutral cue, (5) YT_Valid: when the target was present and the cue was a valid cue.

Figure 3.5. Average reaction time for color semantic cue. The five different curves represent the following five conditions: (1) NT_Neutral: when the target was absent and the cue was a gray color cue (neutral cue); (2) NT_Color: when the target was absent and the cue was a color (red or green) cue; (3) YT_Invalid: when the target was present and the cue was an invalid cue; (4) YT_Neutral: when the target was present and the cue was a neutral cue, (5) YT_Valid: when the target was present and the cue was a valid cue.

Figure 3.6. Average reaction time for location cue. The five different curves represent the following five conditions: (1) NT_Neutral: when the target was absent and the cue was a gray color cue (neutral cue); (2) NT_Color: when the target was absent and the cue was a color (red or green) cue; (3) YT_Invalid: when the target was present and the cue was an invalid cue; (4) YT_Neutral: when the target was present and the cue was a neutral cue, (5) YT_Valid: when the target was present and the cue was a valid cue.

Figure 3.7. Average reaction time for orientation cue. The five different curves represent the following five conditions: (1) NT_Neutral: when the target was absent and the cue was a gray color cue (neutral cue); (2) NT_Color: when the target was absent and the cue was a color (red or green) cue; (3) YT_Invalid: when the target was present and the cue

was an invalid cue; (4) YT_Neutral: when the target was present and the cue was a neutral cue, (5) YT_Valid: when the target was present and the cue was a valid cue.

Figure 3.8. Average accuracy for color sensory cue. The five different curves represent the following five conditions: (1) NT_Neutral: when the target was absent and the cue was a gray color cue (neutral cue); (2) NT_Color: when the target was absent and the cue was a color (red or green) cue; (3) YT_Invalid: when the target was present and the cue was an invalid cue; (4) YT_Neutral: when the target was present and the cue was a neutral cue, (5) YT_Valid: when the target was present and the cue was a valid cue.

Figure 3.9. Average accuracy for color semantic cue. The five different curves represent the following five conditions: (1) NT_Neutral: when the target was absent and the cue was a gray color cue (neutral cue); (2) NT_Color: when the target was absent and the cue was a color (red or green) cue; (3) YT_Invalid: when the target was present and the cue was an invalid cue; (4) YT_Neutral: when the target was present and the cue was a neutral cue, (5) YT_Valid: when the target was present and the cue was a valid cue.

Figure 3.10. Average accuracy for location cue. The five different curves represent the following five conditions: (1) NT_Neutral: when the target was absent and the cue was a gray color cue (neutral cue); (2) NT_Color: when the target was absent and the cue was a color (red or green) cue; (3) YT_Invalid: when the target was present and the cue was an invalid cue; (4) YT_Neutral: when the target was present and the cue was a neutral cue, (5) YT_Valid: when the target was present and the cue was a valid cue.

Figure 3.11. Average accuracy for orientation cue. The five different curves represent the following five conditions: (1) NT_Neutral: when the target was absent and the cue was a gray color cue; (2) NT_Color: when the target was absent and the cue was a color (red or green) cue; (3) YT_Invalid: when the target was present and the cue was an invalid cue; (4) YT_Neutral: when the target was present and the cue was a neutral cue, (5) YT_Valid: when the target was present and the cue was a valid cue.

Figure 4.1. Schematic diagrams for trials in experiment 3A. (a) Feature cue: the cue color could be red (as the example here), green or gray (neutral cue); trials with the three types of cues were randomly mixed in the same block with equal probability. (b) Spatial cue: the cue could be presented on left (as the example indicated), right or both boxes; similarly to part (a), a mixed design with equal probability of the three types of cues was used.

Figure 4.2. Proportion of "northwest first" responses as a function of SOA between the two stimuli. Positive SOAs represent trials in which the NorthWest oriented bar is presented first; Negative SOAs are for trials in which the NorthEast oriented bar is presented first.

Figure 4.3. PSS data for each cue conditions: (a) for feature cue experiment; (b) for spatial cue experiment.

Figure 4.4. Schematic diagrams for trials in experiment 3C and 3D. The red patch(es) and green patch(es) were presented randomly above or below the fixation mark. Observers attended to either one of the colors in separate blocks. (a) In the short CLT condition, the cue consisted of four color patches. Observers were to judge whether the two patches of the attended color had the same saturation. (b) In the medium and long CLT condition, the cue consisted of only two patches, and observers were to detect a saturation change event on the attended color. The cue duration was 600 ms in the medium CLT condition and 1000 ms in the long CLT condition; the cue-stimuli intervals were 100 ms and 200 ms, respectively.

Figure 4.5. Proportion of "red first" responses as a function of SOA between the two stimuli. Positive SOAs represent trials in which the Red bar is presented first; Negative SOAs are for trials in which the Green bar is presented first.

Figure 4.6. PSS data when attending to different color features for the three different CLT conditions.

Figure 4.7. Simultaneity data when attending to different color features.

FIGURES

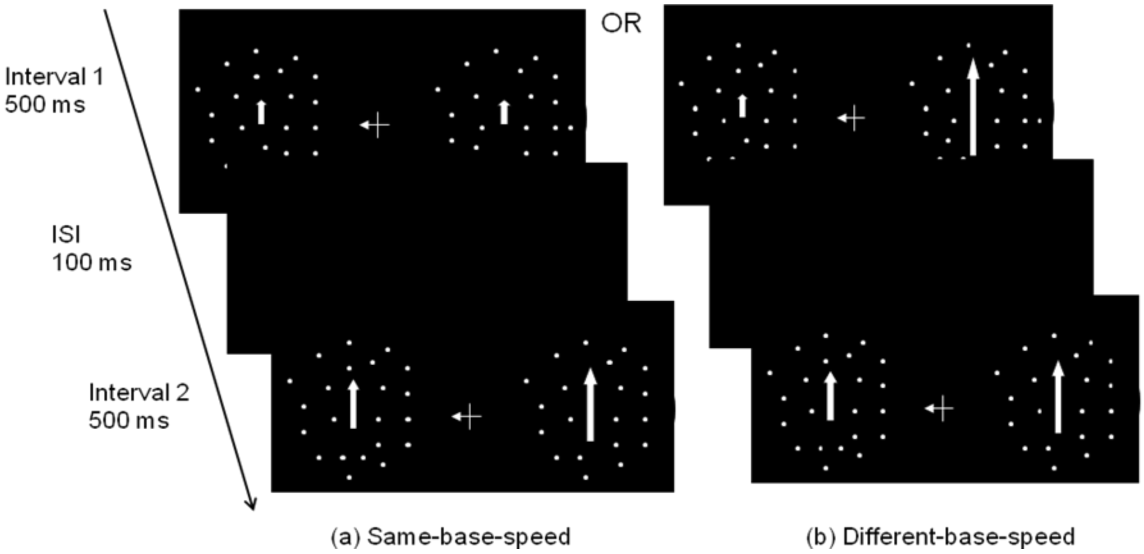


Figure 2.1

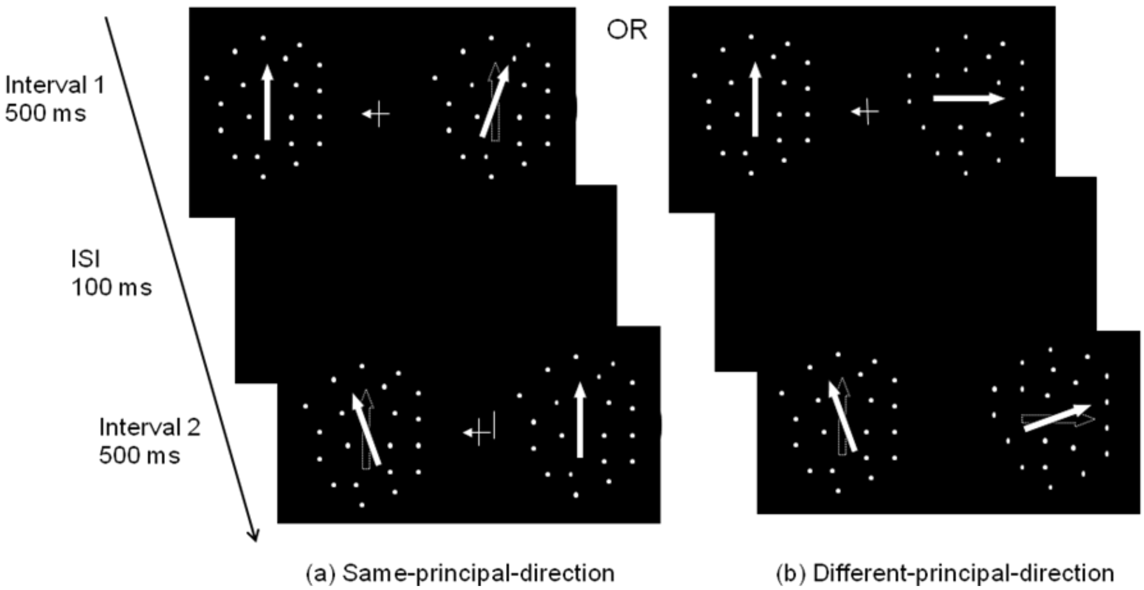
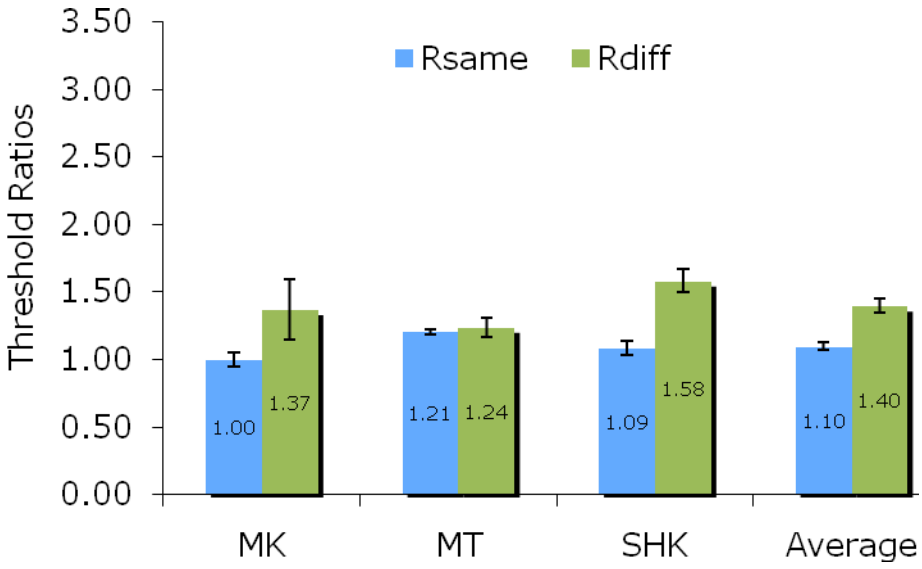


Figure 2.2



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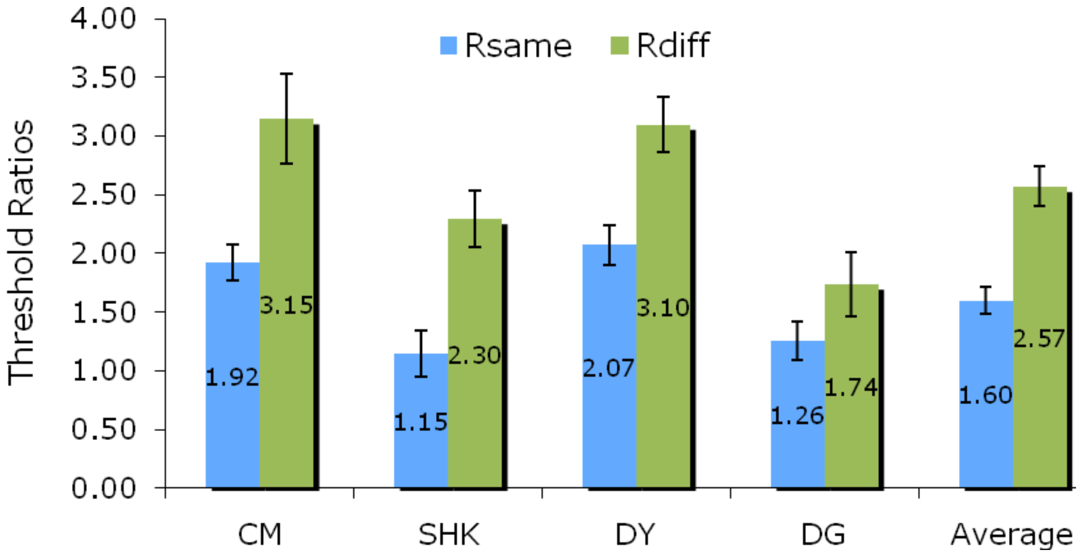

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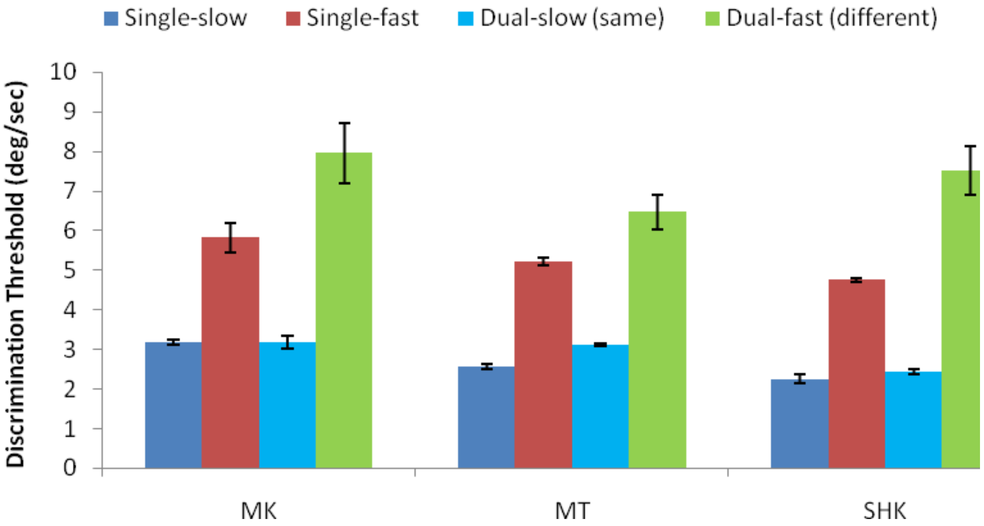
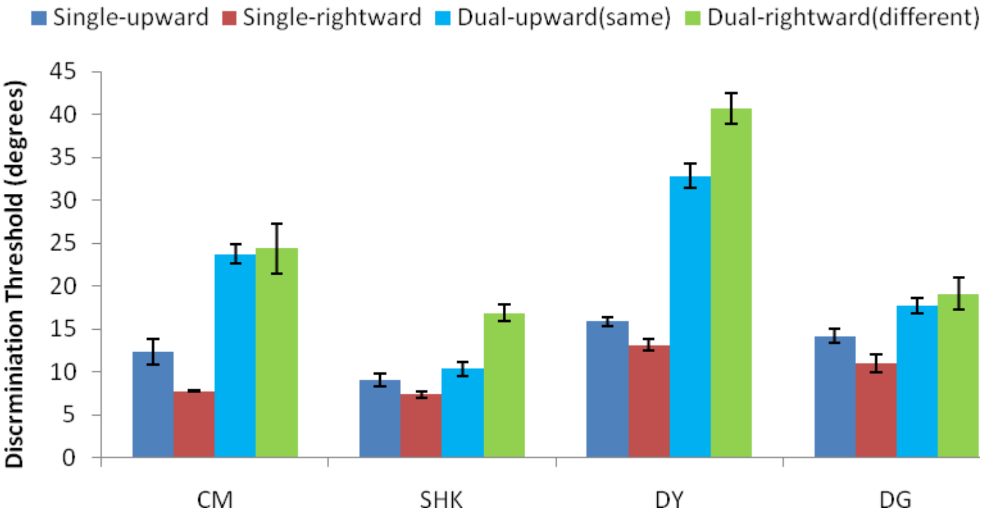


Figure 2.5



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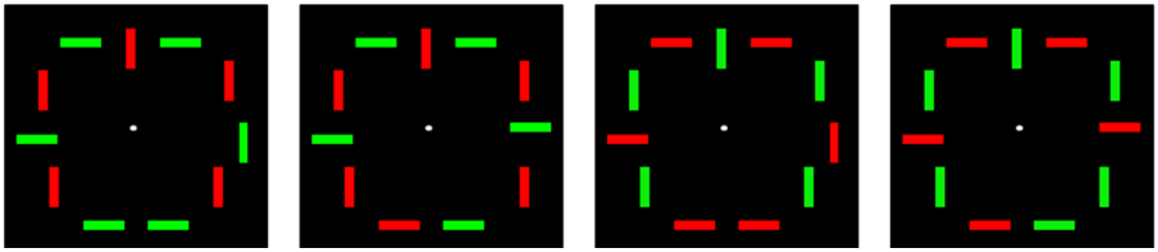


Figure 3. 7

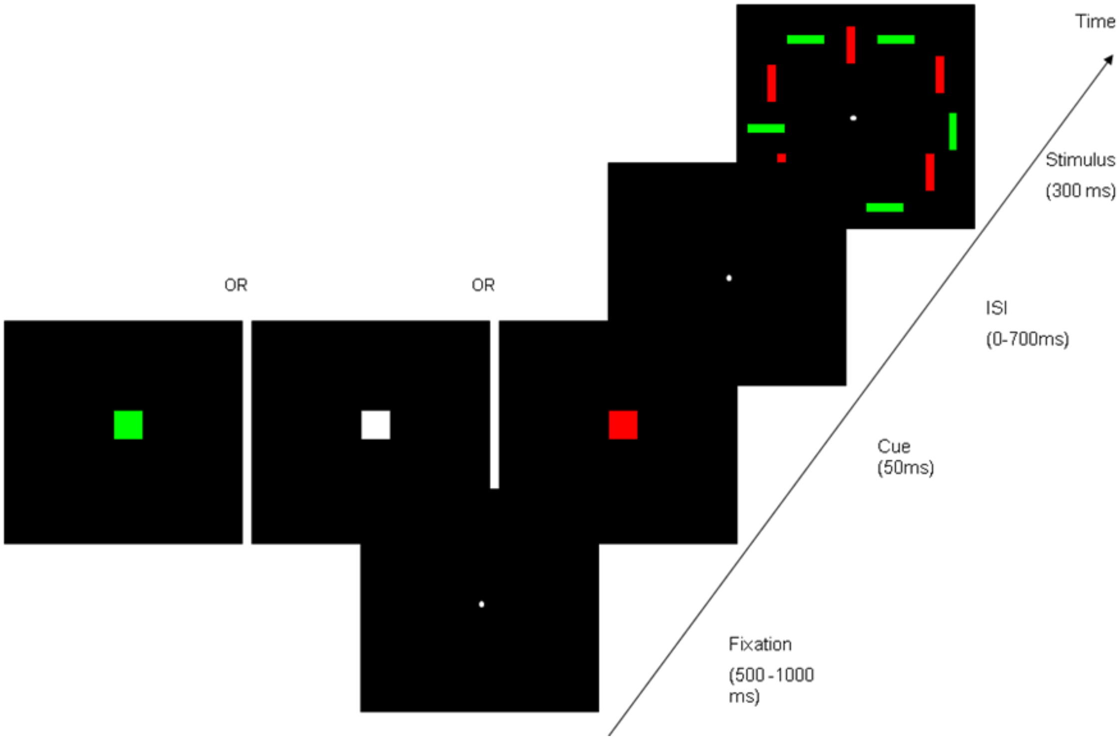


Figure 3. 8

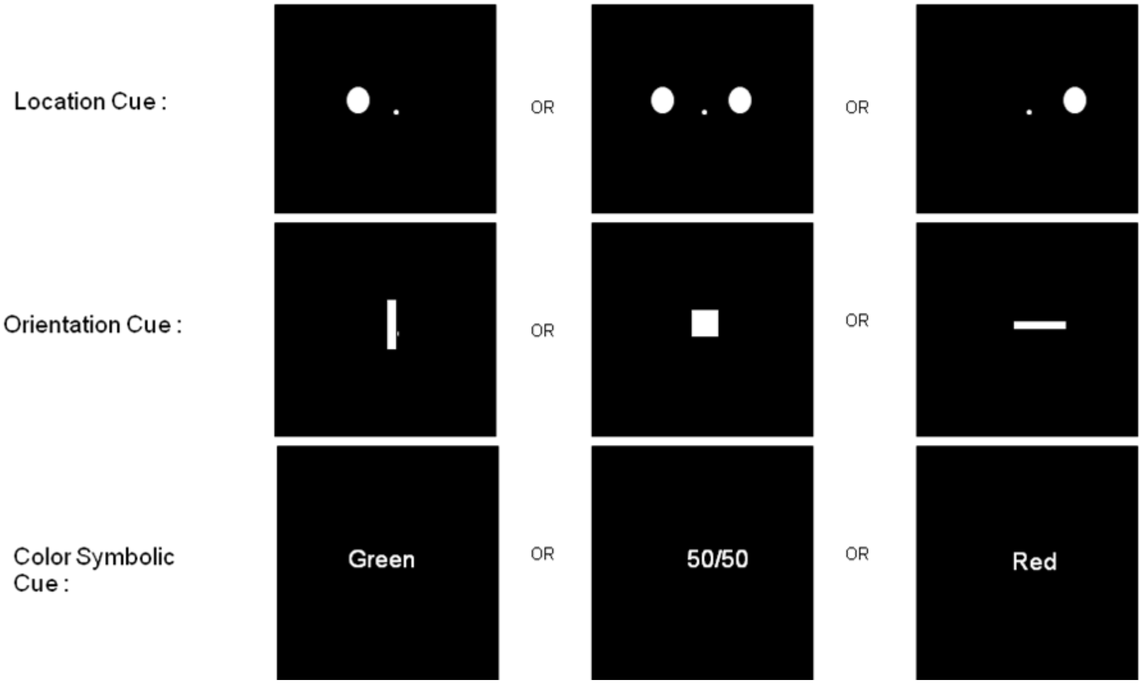

Location Cue :
OR
OR
Orientation Cue :
OR
OR
Color Symbolic Cue :
Green
OR
50/50
OR
Red

Figure 3. 9

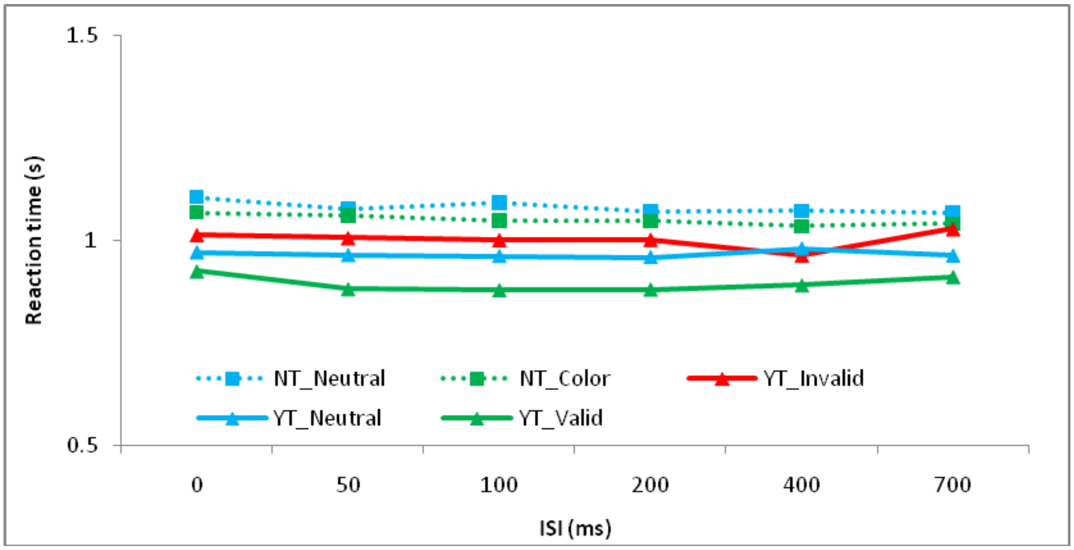


Figure 3.4.

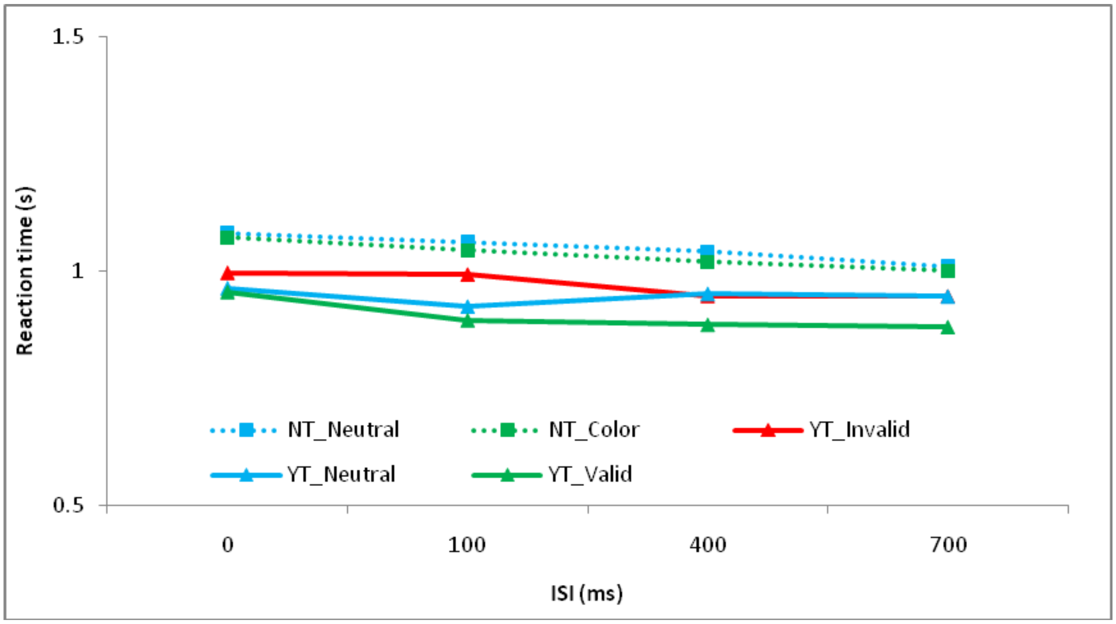
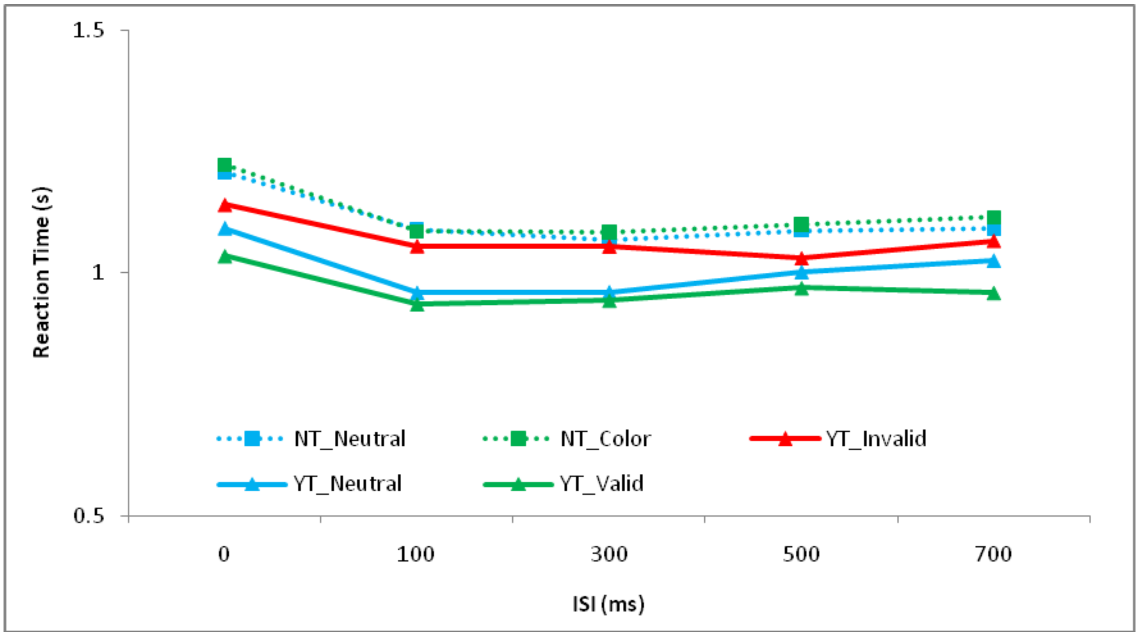


Figure 3.5



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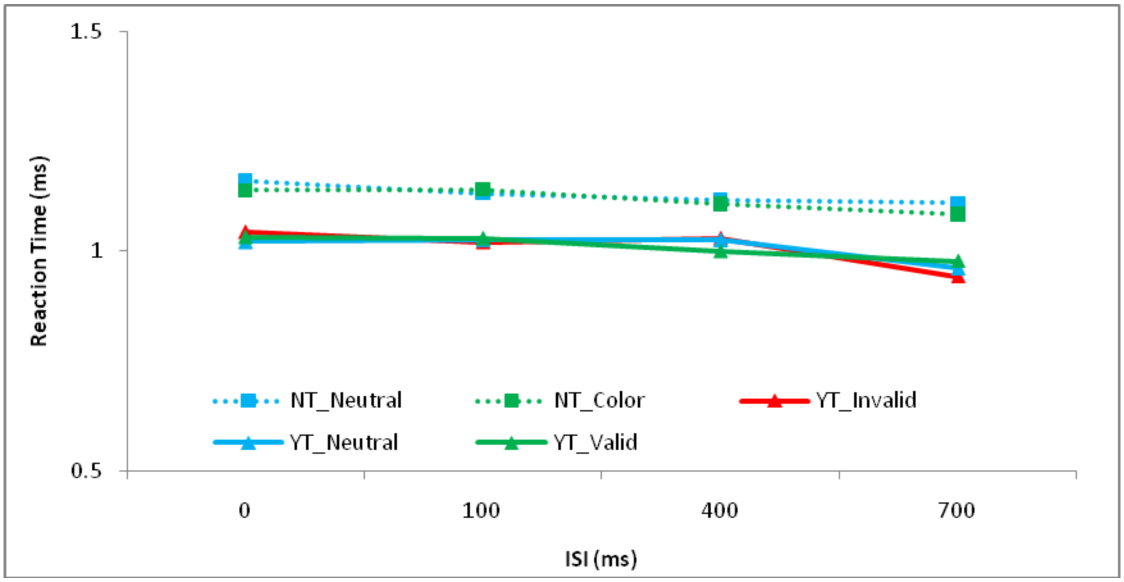

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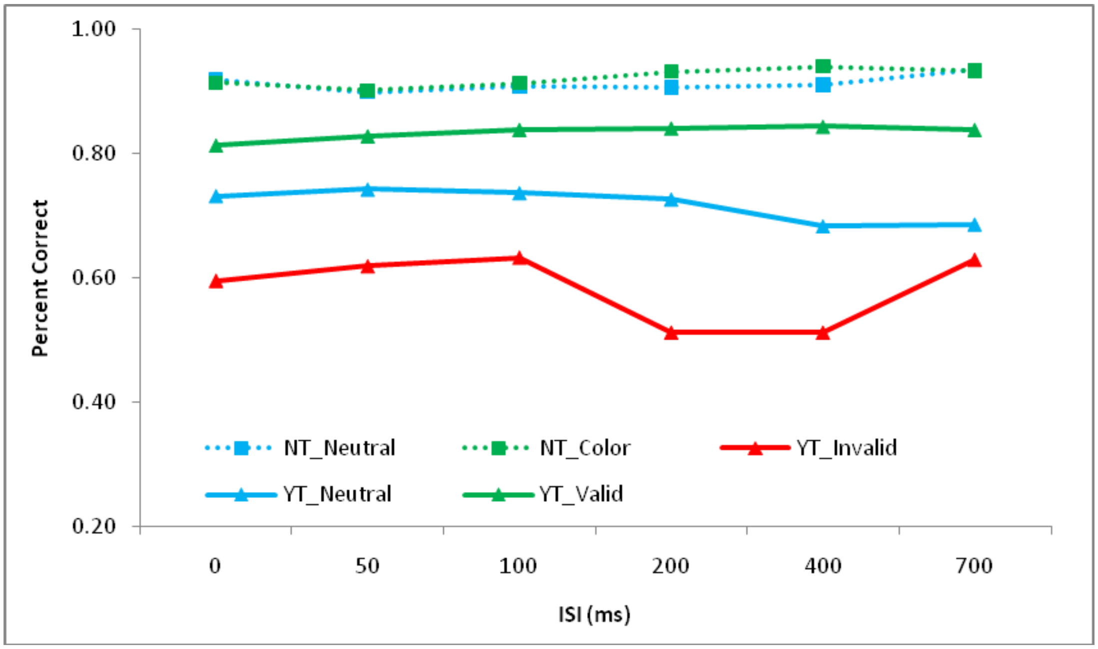
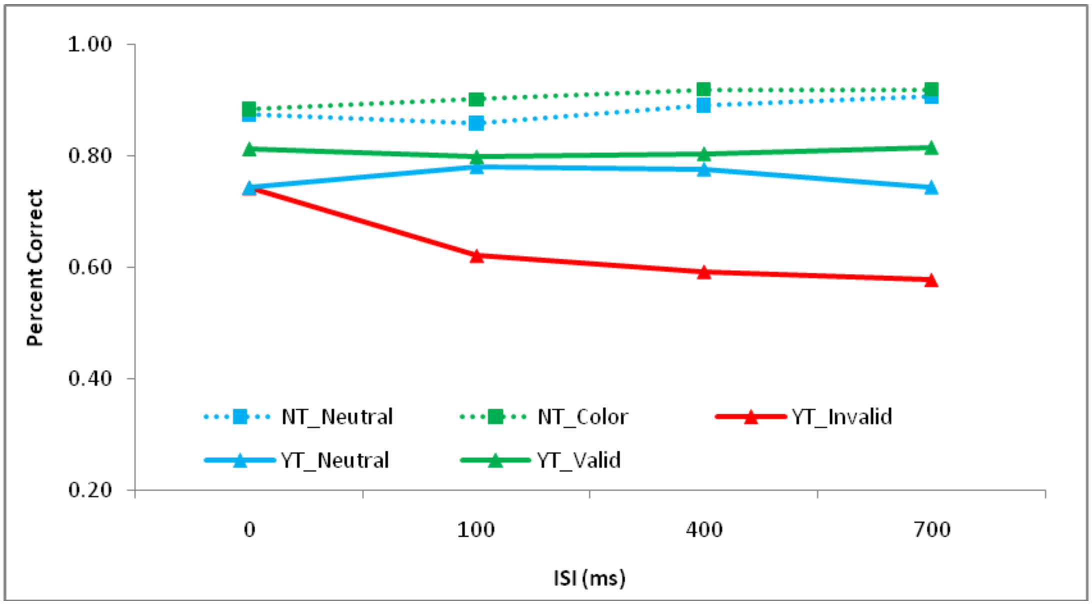


Figure 3.8



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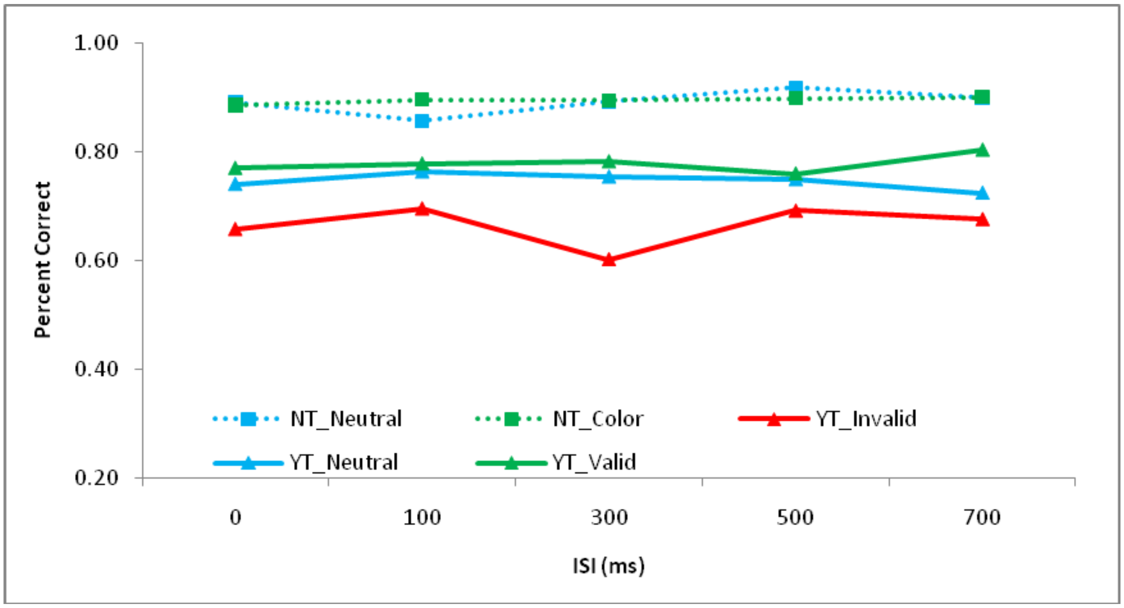

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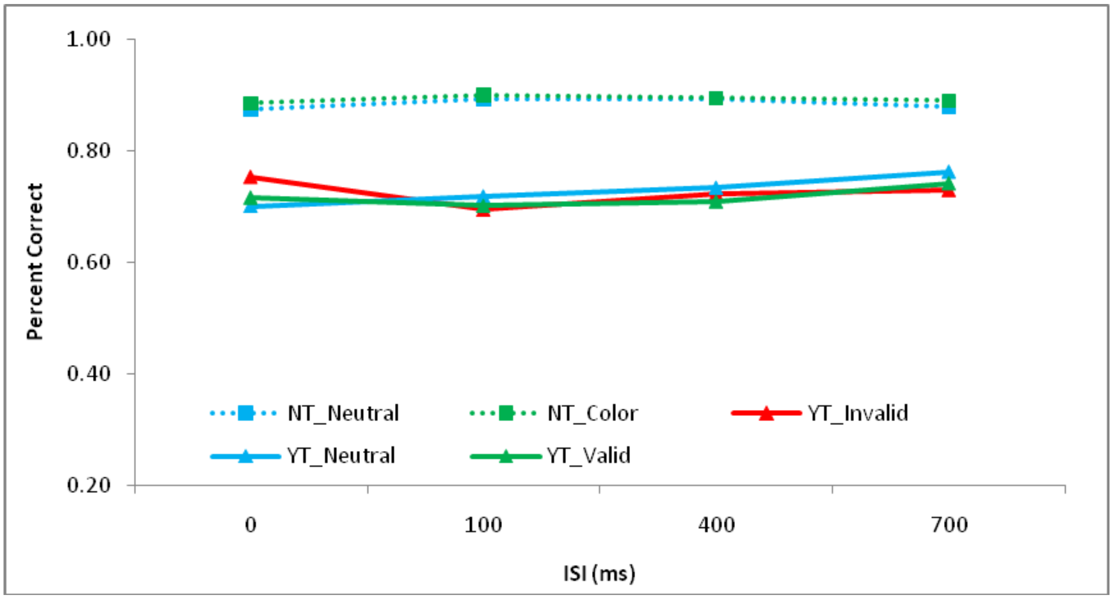
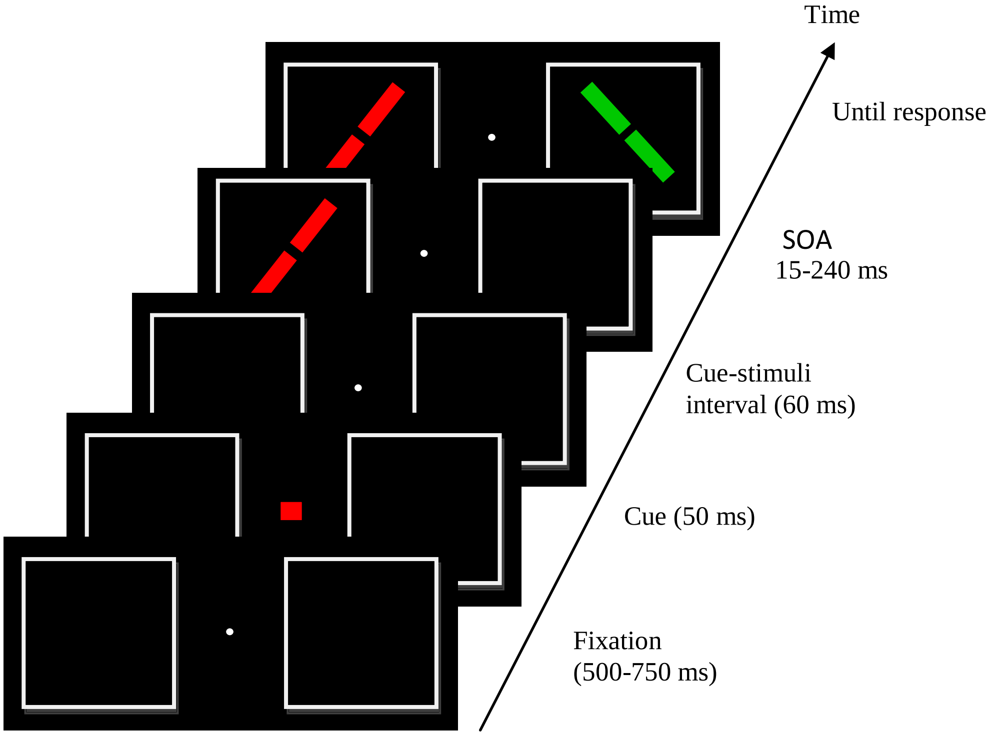
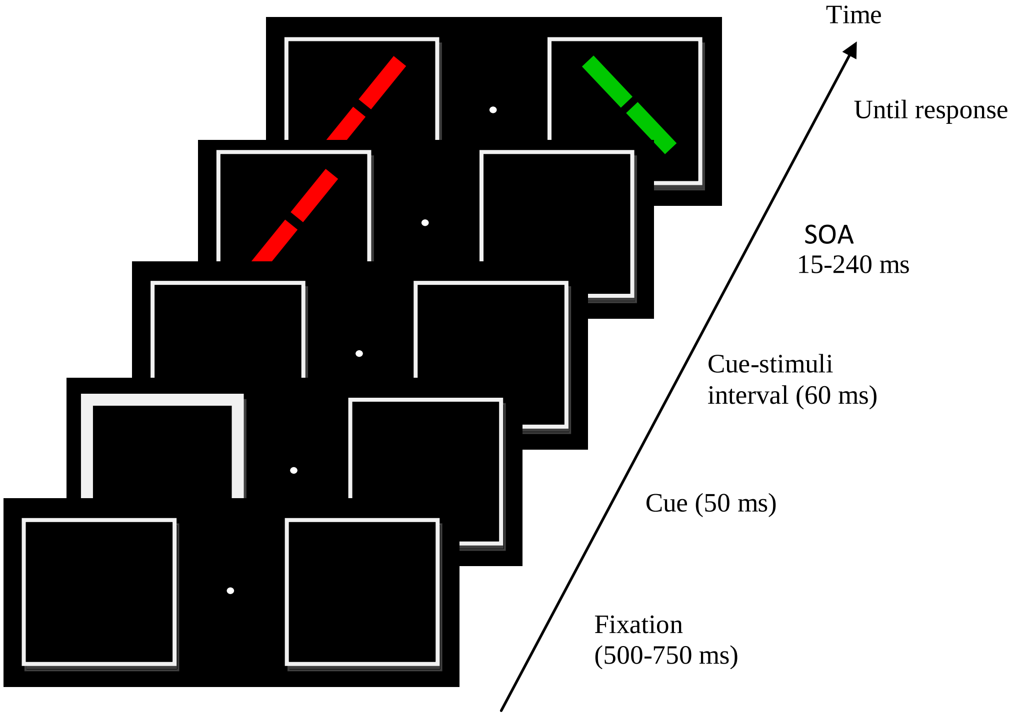


Figure 3.11

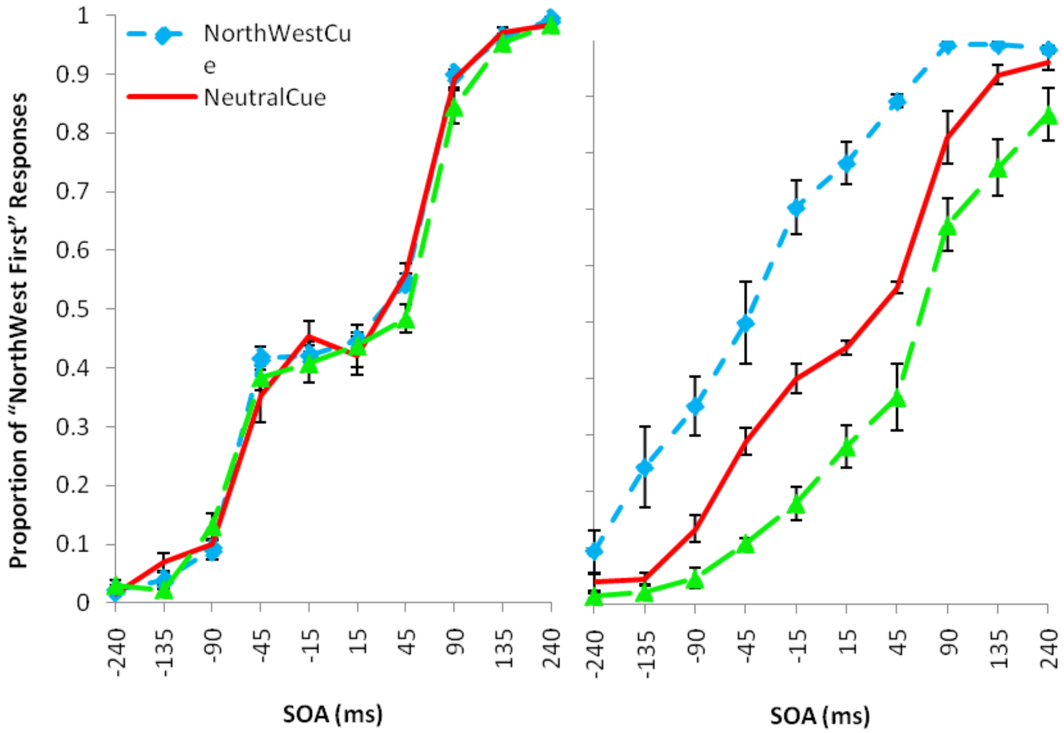

Time
Until response
SOA
15-240 ms
Cue-stimuli
interval (60 ms)
Cue (50 ms)
Fixation
(500-750 ms)

(a)


Time
Until response
SOA
15-240 ms
Cue-stimuli
interval (60 ms)
Cue (50 ms)
Fixation
(500-750 ms)

(b)

Figure 4.1



(a) Feature Cue

(b) Spatial Cue

Figure 4.2

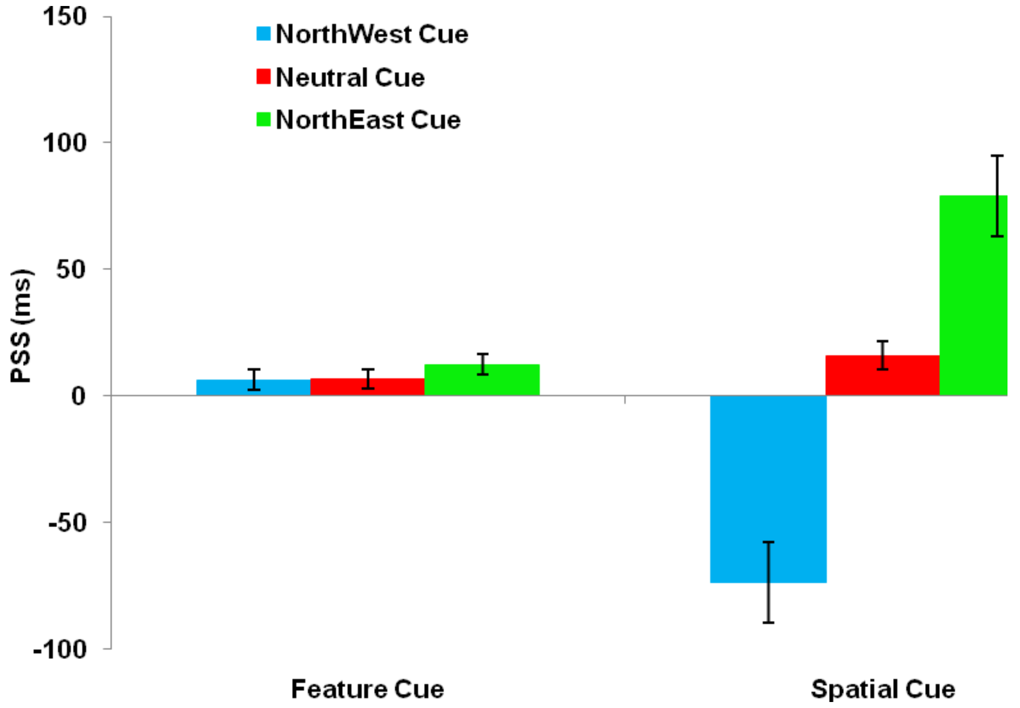

150
100
50
0
-50
-100
PSS (ms)
NorthWest Cue
Neutral Cue
NorthEast Cue
Feature Cue
Spatial Cue

Figure 4.3

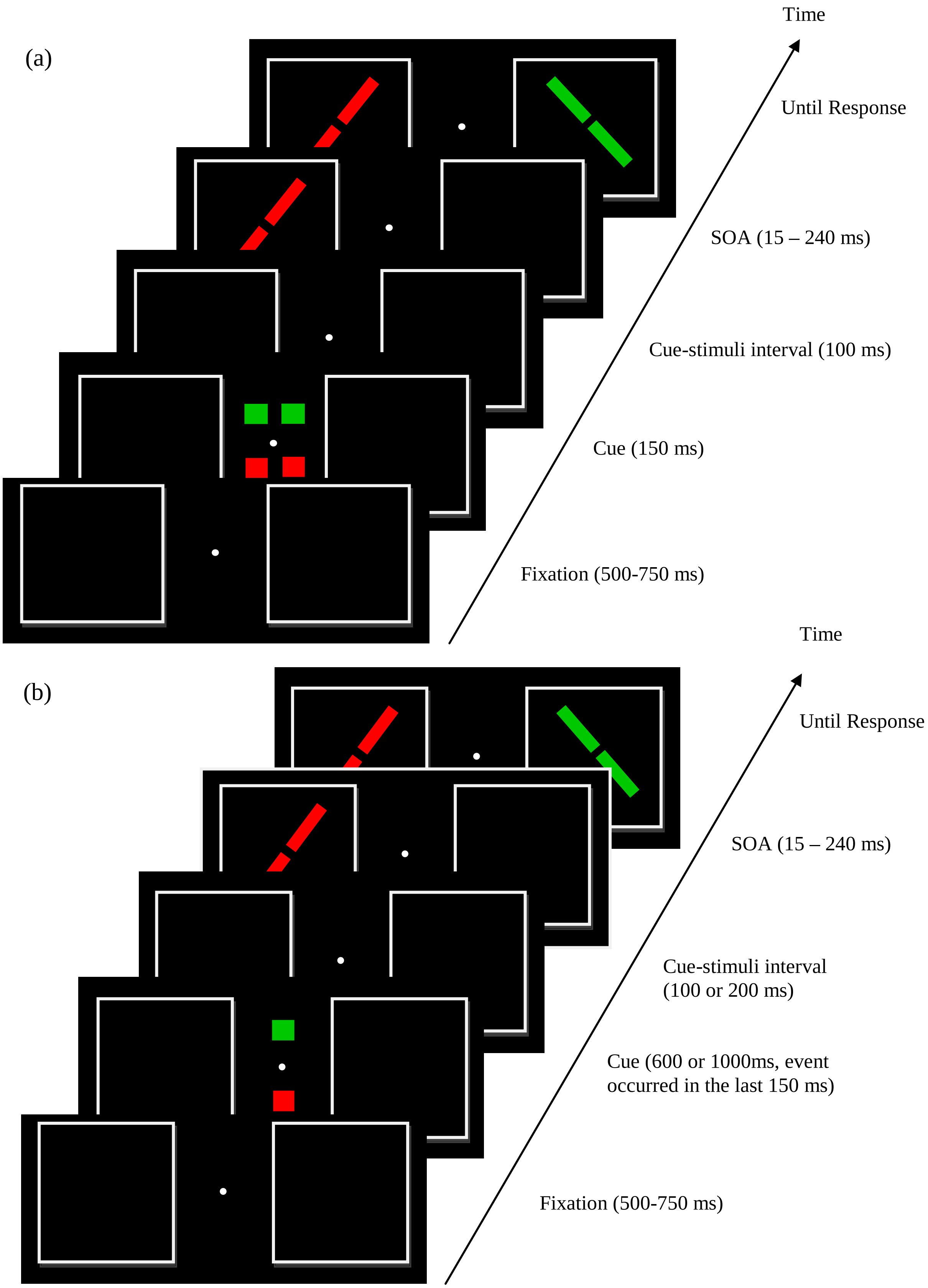
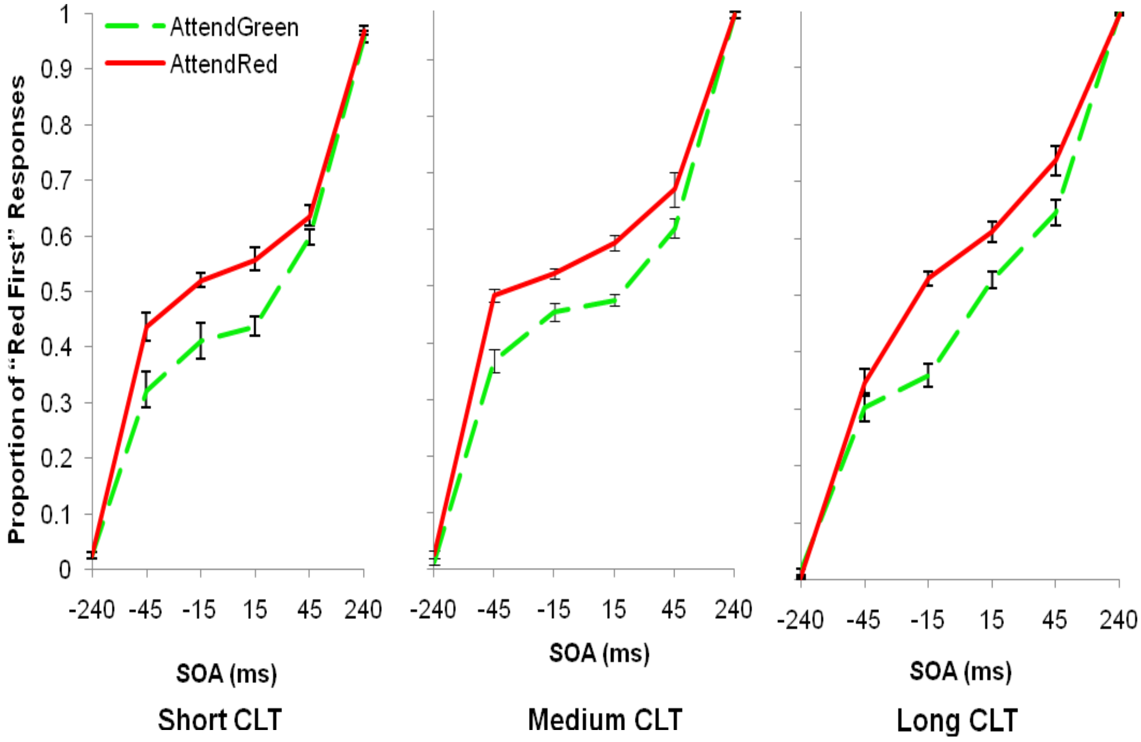

(a)
Time
Until Response
SOA (15 – 240 ms)
Cue-stimuli interval (100 ms)
Cue (150 ms)
Fixation (500-750 ms)
(b)
Time
Until Response
SOA (15 – 240 ms)
Cue-stimuli interval
(100 or 200 ms)
Cue (600 or 1000ms, event
occurred in the last 150 ms)
Fixation (500-750 ms)

Figure 4.4



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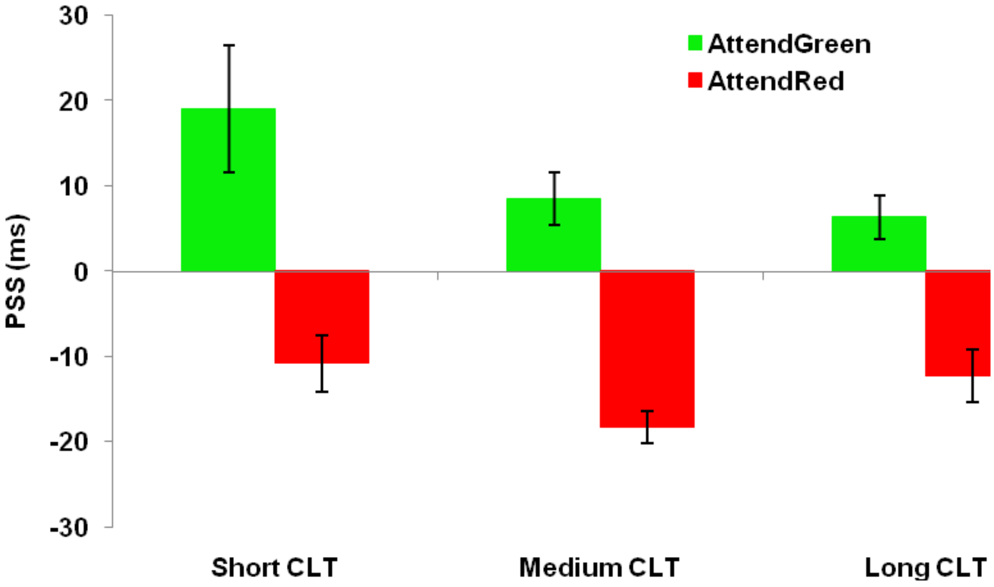

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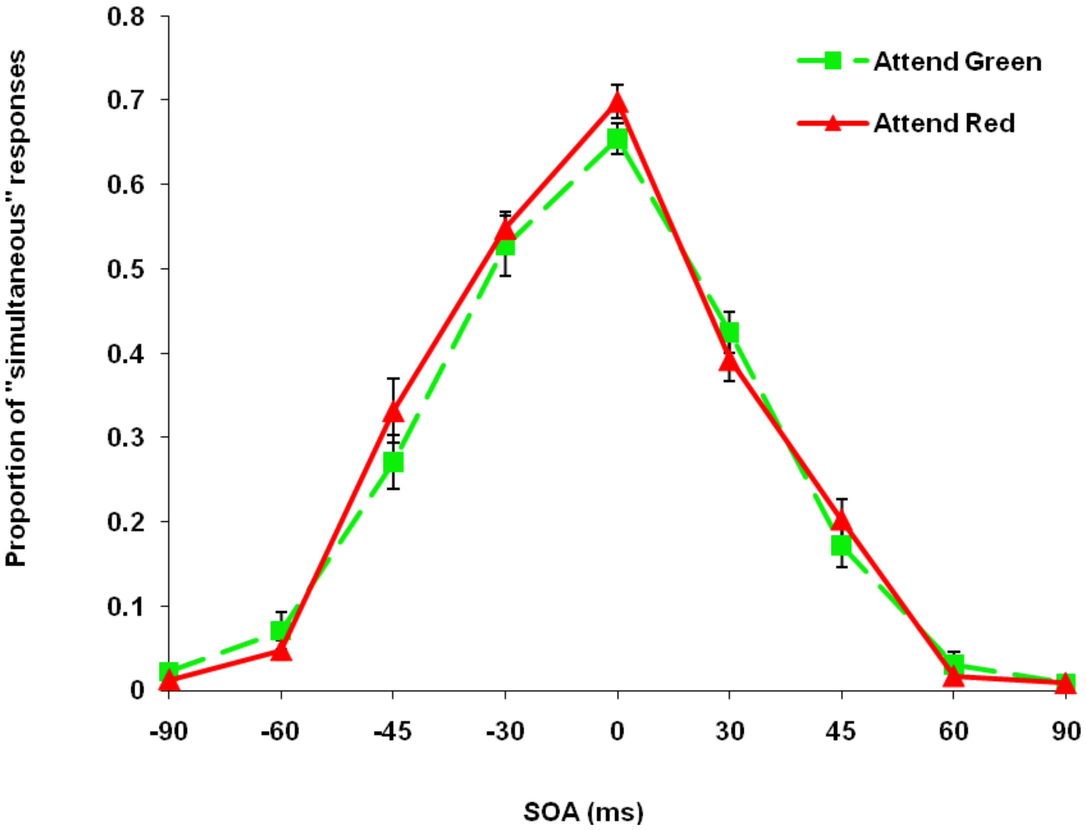
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Proportion of "simultaneous" responses
-90
-60
-45
-30
0
30
45
60
90
SOA (ms)
Attend Green
Attend Red

Figure 4.7

Curriculum Vita

Xiaohua Zhuang

EDUCATION

July 2003	Peking University, Beijing, China
	B.S. in Psychology, and B.A. in Economics
January 2010	Rutgers University, New Brunswick, NJ, USA
	Ph.D. in Psychology

PUBLICATION AND CONFERENCE PRESENTATION

Chai, Y.-C., Papathomas, T.V., & Zhuang, X. (2010). Dominance of Sharp over Blurred Image Features in Interocular Grouping during "Patchwork" Binocular Rivalry. Vision Sciences Society 10th Annual Meeting, Naples, Florida (submitted).

Zhuang, X., & Papathomas T.V. (2009). Prior entry for feature-based attention: Are objects of the attended color perceived earlier? *Journal of Vision*, 9(8), 144a.

Chai, Y.-C., Papathomas, T.V.., Zhuang, X., & Alais, D. (2009). Binocular rivalry between a sharp image and a low-pass filtered version of itself: Low-pass dominance increases with eccentricity. *Journal of Vision*, 9(8), 303a.

Wang, L., MacCann, C., Zhuang, X., Liu, O. L., & Roberts, R. (2009). Assessing Teamwork and Collaboration in High School Students: A Multi-method Approach. *Canadian Journal of School Psychology*, 24, 108-124.

Zhuang, X., & Papathomas T.V. (2008). Feature- and location-based attention in color/orientation conjunctive visual search. *Journal of Vision*, 8(6), 1079a

Zhuang, X., Papathomas T.V., & Vidnyánszky, Z. (2006). Position-invariant motion contrast effects are mediated by attention. *Journal of Vision*, 6(6): 952a

Papathomas T.V., Vidnyánszky, Z., & Zhuang, X. (2004).From 2D to 3D and back: Perception of rotated 2D pictorial scenes depends on the 3D surfaces they depict. Vision Sciences Society 4th Annual Meeting, Sarasota, Florida.