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注意力分配在空間上和物體上之機制差異

Distinct Mechanisms of Location-Based and Object-Based Visual Attention

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Distinct Mechanisms of Location-Based and Object-Based Visual Attention

Wei-Lun Chou

Abstract

Visual attention studies have suggested two bases of selection—location-based and object-based. Location-based attention denotes that locations in the visual field are selected; object-based attention denotes that objects are selected. Location- and object-based attention are not mutually exclusive; they can influence the allocation of attention simultaneously. Over the last two decades, many studies have focused on the boundary conditions of each basis of selection; however, little is known about the underlying mechanisms of each. This thesis describes a series of five studies examining the mechanisms of location-based and object-based attention.

Section I includes three studies manipulating visibility of stimuli with respect to *location* (chapter 2), *object* (chapter 3), and *target* (chapter 4) and distinct functions (action/object recognition), brain pathways (dorsal/ventral pathway), and underlying mechanisms (signal enhancement/noise exclusion) of location-based and object-based attention are differentiated accordingly. Section II includes two studies manipulating high-level factors—working memory (chapter 5) and expectations (chapter 6)—and demonstrated the high-level cognitive factors also affect location-based attention and object-based attention differently.

Taken together, results from these five studies show that location-based and object-based attention (1) are influenced by consciousness in different ways, (2) have different underlying mechanisms, (3) involve different kinds of working memory, and (4) rely on different aspects of cue validity. These findings challenge and shed new insights into current theories of attention. The consciousness-dependent hypothesis and the optimization hypothesis are proposed to explain the novel findings reported in this thesis.

Keywords: double-rectangle paradigm, subliminal spatial cue, object awareness, signal enhancement, noise exclusion, working memory, cue validity

注意力分配在空間上與物體上之機制差異

周蔚倫

摘要

研究證據支持視覺注意力可以運作在空間上或物體上，分別被稱為空間為基礎注意力以及物體為基礎注意力，兩者同時影響視覺注意力的分配。近二十年來，相關研究著重在探討空間為基礎注意力以及物體為基礎注意力的特性，然而對於兩者的內在機制以及兩者的關係著墨較少。本論文旨在對空間為基礎注意力以及物體為基礎注意力的內在機制做系統性的探討和比較。

論文第一個部份包含三個研究，分別操弄位置(第二章)、物體(第三章)以及目標物(第四章)的可見度，系列研究結果展現空間為基礎注意力和物體為基礎注意力在功能上及內在機制上的差異。論文第二個部份操弄工作記憶(第五章)以及線索有效性(第六章)，進一步在這兩個涉及較高階認知功能的向度上展現空間為基礎注意力和物體為基礎注意力的差異。

整合論文中的五個研究，空間為基礎注意力和物體為基礎注意力在不同面向中展現本質上的差異：一、操弄意識對兩者造成不同的影響， 二、兩者由不同的內在機制達成，三、涉及不同種類的工作記憶，以及，四、展現各自獨立的線索有效性。這些結果挑戰了現存的重要視覺注意力理論並且提供了新的思考方向。論文中並提出具體可檢驗的假說來解釋論文中新穎的實徵證據。

關鍵詞：雙矩型派典、閾下空間線索、物體意識、訊號增強、雜訊排除、工作記憶、線索有效性。

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Chapter 1

Introduction: Distinct Mechanisms of Location-Based and Object-Based Attention

The complex visual world comprises an overwhelming amount of information. Because of limited capacity of our cognitive system, only a fraction of this information is selected for further processing; hence, our visual system comprises mechanisms of *selective attention* that can prioritize processing of particular information. For example, when we focus on an object (or the location occupied by the object), we become conscious of the object; otherwise, it fades from our consciousness. This daily-life observation is supported by empirical evidence of inattentional blindness (Mack & Rock, 1998) and change blindness (Simons & Levin, 1997). In addition to bringing information to awareness, attention facilitates processing speed, discriminability, and spatial resolution (Carrasco & McElree, 2001; Posner, 1980; Yeshurun & Carrasco, 1998) by filtering out irrelevant noise (Lu & Dosher, 2000) or sensitizing to relevant signal (Carrasco, Penpeci-Talgar, & Eckstein, 2000).

Two bases of attentional selection

Attention allocation was conventionally described in metaphors such as an "internal spotlight," a "zoom lens," or a "gradient structure." According to the spotlight metaphor (Posner, 1980), attention acts like a beam to illuminate a region in the visual field; stimuli falling inside the attentional beam are facilitated. Eriksen and Yeh (1985) further suggested that the region of the visual field selected by attention can vary in size just like a zoom lens. Stimuli falling within the attentional beam are facilitated. The gradient model (Downing & Pinker, 1985) further suggests that enhanced processing of the selected region falls off gradually with distance. All these models imply that attention operates in a location-based manner, called location-based attention.

Since the early 1970s, in an effort to manipulate participants' attention, many studies have used a location marker, for example, a spatial cue, prior to target display to indicate the possible location of an upcoming target. This method has been named the cueing paradigm. Researchers compare performance in the cue-present with the cue-absent conditions or in valid with invalid conditions to infer the effect of location-based attention. Eriksen and Hoffman (1972) showed that a location cue reduces target identification time of the cue-present trials relative to that of the cue-absent trials. This was one of the first indications that a pre-cue can facilitate target processing at the cued location.

In contrast to location-based attention, however, growing evidence over the past two decades has shown that attention operates not only in a location-based but also in an object-based manner; that is, attention can select grouped parts across different locations (i.e., an object) and then highlight the processing of information belonging to the selected object (Baylis & Driver, 1993; Brawn & Snowden, 2000; Chou & Yeh, 2005; Duncan, 1984; Watson & Kramer, 1999).

Duncan (1984) applied a divided-attention paradigm to provide one of the first pieces of evidence of object-based attention. He found that participants identified two attributes belonging to a single object more accurately than two attributes belonging to two objects (see also Baylis & Driver, 1993; Kramer, Weber, & Watson, 1997; Marino & Scholl, 2005; Watson & Kramer, 1999; Vecera, 1994).

By modifying Posner's cueing paradigm, Brawn and Snowden (2000) cued one of two spatially overlapping objects by enhancing one object's luminance. They found that participants detected targets faster at the cued object than at an uncued object (see also Chou & Yeh, 2005; Egly, Driver, & Rafal, 1994). In addition to the divided attention paradigm and the object cueing paradigm, the notion of object-based attention is also supported by a larger interference effect in a flanker task when distractors (i.e., incompatible flankers) and target were located at the same object than at different objects under a focused attention situation (e.g., Kramer & Jacobson, 1991; Richard, Lee, & Vecera, 2008; but see Shomstein & Yantis, 2002).

Later studies have indicated that object-based attention is influenced by multiple cues of object-hood (Marino & Scholl, 2005). Object-based attention operates on single-region objects (Egly et al., 1994; Watson & Kramer, 1999), illusory objects (Moore, Yantis, & Vaughan, 1998), and grouped elements (Matsukura & Vecera, 2006; Moore et al, 1998).

The relationship between location-based and object-based attention

Many studies have shown that both location-based and object-based attention can simultaneously influence attention deployment, suggesting that location-based and object-based attention are not mutually exclusive. Egly and colleagues (1994) used a cueing paradigm with a double-rectangle display to demonstrate the coexistence of location-based and object-based attention. They presented two outlined rectangles, with one end of one rectangle brightened as a cue to indicate the possible location of a target. The target was a small solid square, shown subsequently within one end of a rectangle. Location-based attention was indicated by the *spatial-cueing* effect: Reaction times (RTs) were shorter when the target appeared at the cued location than at uncued locations. Object-based attention was indicated by the *same-object advantage*: RTs were shorter when the target appeared at the uncued end of the *cued* rectangle than at the *uncued* rectangle, with an equal cue-to-target distance between the two. Consistent with Egly et al., a series of studies using various stimuli and tasks have demonstrated the spatial-cueing effect and the same-object advantage (Abrams & Law, 2000; Avrahami, 1999; Lamy & Tsal, 2000; Moore et al., 1998; Shomstein & Yantis, 2004). The double-rectangle method is a simple and elegant way to probe and compare location-based and object-based attention in a single task.

Different accounts have been published explaining the same-object advantage in the double-rectangle method. Different accounts assume different relationships between location-based and object-based attention. The spreading hypothesis (Richard et al., 2008) states that when attention is cued to a location within an object, attention will automatically spread from the cued location to the whole object. Consequently, any cue that can successfully direct attention to a specific location within an object should also cause attention to spread throughout the entire cued object (we tested this assumption in chapter 2). Such spread of attention allows better visual performance relative to a target within the cued object than the uncued object. Since attentional modulation is triggered by a location cue and spreads to the whole object, the same-object advantage should be an instance of location-based attention; that is, the underlying mechanism of object-based attention is the same as that of location-based attention (we tested this assumption in chapter 4).

On the other hand, Shomstein and Yantis (2002) proposed the *prioritization hypothesis* to explain the same-object advantage. This hypothesis suggests that object-based attention reflects a specific attentional prioritization strategy regarding locations within the attended object, rather than modulation of early sensory enhancement extending from location-based attention (we tested this assumption in chapter 4). Accordingly, the prioritization hypothesis does not take a specific position regarding the similarity of mechanisms between location- and object-based attention. At best, it predicts different mechanisms for the *exogenous* spatial-cueing effect and the strategic object-based scanning strategy.

Consistent with this trend, behavioral studies have demonstrated the dissociation of location- and object-based attention; for example, different types of working memory are involved (Chou & Yeh, 2008; Matsukura & Vecera, 2009), and they have different time courses (List & Robertson, 2007; Shomstein & Yantis, 2004). In addition, physiological studies have shown that different brain areas are responsible for location-based and object-based attention (Fink, Dolan, Halligan, Marshall, & Frith, 1997; He, Humphreys, Fan, Chen, & Han, 2008; He, Fan, Zhou, & Chen, 2004; Wager, Jonides, & Reading, 2004). For example, tasks that trigger location-based attention activate anterior brain areas, whereas tasks that are relevant to object-based attention involve posterior brain areas (He et al., 2008). These studies demonstrating differences between location-based and object-based attention hint at the possibility that they may be two qualitatively different forms of attention.

The unified account of location-based and object-based attention

Although several studies have found differences between location-based attention and object-based attention, a unified account of location-based and object-based attention (see Mozer & Vecera, 2005, for a review) is still a widely held belief (e.g., Davis & Driver, 1997; Kasai & Kondo, 1997; Richard et al., 2008). Rather than viewing location-based attention and object-based attention as two qualitatively different forms of attention, the unified account claims that object-based attention is a consequence of the spread from *location*-based attention (Richard et al., 2008) or a grouped array of attended *locations* (Vecera, 1994).

Reexamining the unified account of location-based and object-based attention

Although some evidence has been presented of differences between location-based and object-based attention, evidence strongly supporting the notion that location-based and object-based attention are two qualitatively different forms of attention is lacking (see Mozer & Vecera, 2005, for a review). This thesis thus seeks to examine the qualitatively different underlying mechanisms of location-based and object-based attention.

In section I, we manipulated the participants' awareness of location information (chapter 2) and object information (chapter 3), and the visibility of target stimuli (chapter 4). The findings suggest distinct functions (action/object recognition), brain pathways (dorsal/ventral pathway), and underlying mechanisms (signal enhancement/noise exclusion) of location-based and object-based attention, respectively.

In section II, by manipulating two higher-level factors—working memory (chapter 5) and cue validity (chapter 6)—we demonstrated that location-based attention and object-based attention also showed discrepancies in higher-level cognitive aspects. The findings of our study challenge current theories of object-based attention and reveal new insights into them.

Chapter 2

Subliminal Spatial Cues Capture Attention and Strengthen Between-Object Link

Chou, W. L., & Yeh, S. L. (submitted).

Abstract

According to the spreading hypothesis of object-based attention (e.g., Richard et al., 2008), a subliminal cue that can successfully capture attention to a location within an object should also cause attention to spread throughout the whole cued object and lead to the same-object advantage. Instead, we propose that a subliminal cue strengthens the between-object link, which is coded primarily within the dorsal pathway that governs the visual guidance of action. By adopting the two-rectangle method (Egly et al., 1994) and using an effective subliminal cue to compare with the classic suprathreshold cue, we found a different result pattern with suprathreshold cues than with subliminal cues. The suprathreshold cue replicated the conventional location and object effects, whereas a subliminal cue led to a different-object advantage with a facilitatory location effect and a same-object advantage with an inhibitory location effect. These results support our consciousness-dependent hypothesis but not the spreading hypothesis.

Introduction

To recognize an object in a multi-object scene, our brain needs to calculate the relation of properties—shape, color, configuration, and so on—*within* objects. For example, a pail with a curvature on the side can be a mug, but if the curvature is on the top of the pail, it is more likely to be a bucket (Biederman, 1987). Visual attention can facilitate processing of properties belonging to the same object, that is, *object-based attention* (Duncan, 1984; Egly et al., 1994), and this kind of object-based attention may be achieved by strengthening the *within-object link* that is critical for object recognition. However, to act in a multi-object environment, our brain needs to calculate the relation of properties—orientation, size, and distance—*between* objects. For example, to hit a baseball, it is critical to know the moment-by-moment distance between the ball and the bat. In this case, it is likely that attention helps action execution by strengthening the *between-object link* (Davis, 2001; Humphreys, 1998) that is important for visually guided action.

Indeed, two visual pathways have been identified for the two main functions of vision: object recognition and action (Goodale & Milner, 1992). The ventral pathway—from visual primary cortex (V1) to temporal cortex—is mainly involved in object recognition, whereas the dorsal pathway—from V1 to frontal-parietal cortex—is mainly involved in the visual guidance of action (Goodale, Milner, Jakobson, & Carey, 1991; Kluver & Bucy, 1938). The double-dissociation demonstrated by neuropsychological patients provides evidence for the two-pathway theory. On one hand, patients with lesion areas in the ventral pathway lose *conscious* vision for object recognition but not the *unconscious* vision to act (Goodale & Milner, 2004). For example, Patient DF cannot report the orientation of a pencil, but she can posture her hand correctly as she reaches out to grasp it (Goodale et al., 1991). On the other hand, patients with lesions in the dorsal pathway have intact *object recognition* but impaired *visually guided* action. These optic ataxia patients are able to report the orientation of a slot cut in a disk, but they cannot reach out and pass their hand through it (Perenin & Vighetto, 1988). Contrary to Patient DF, the optic ataxia patients have conscious vision for object recognition but they cannot use this vision to guide their action. This double-dissociation of *conscious* and *unconscious* vision revealed by neuropsychological patients with damage in ventral and dorsal pathways, respectively, hints at the possibility that manipulating normal participants' consciousness of the stimuli can dissociate the two pathways and show their difference in affecting performance. This is the goal of the current study.

In a seminal paper, Egly and colleagues (1994) used a cueing paradigm with a double-rectangle display to demonstrate the existence of within-object link. They presented two outlined rectangles, with one end of one rectangle brightened as a cue to indicate the possible location of a target. The target was a small solid square, shown subsequently within one end of a rectangle. Within-object link was indicated by the *same-object advantage*: RTs were shorter when the target appeared at the uncued end of the *cued* than at the *uncued* rectangle, with an equal cue-to-target distance between the two. As with Egly et al., a series of studies showing this same-object advantage have used suprathreshold stimuli that supposedly trigger conscious vision in the ventral pathway (e.g., Abrams & Law, 2000; Lamy & Tsal, 2000; Moore et al., 1998). We hypothesize that if *subliminal* stimuli are used, *different-object advantage*—that is, faster response to a target within an uncued object than within a cued object—should be obtained instead because unconscious vision involved in the dorsal pathway is primarily for action, and action requires a between-object link.

In contrast to this consciousness-dependent hypothesis, the influential spreading hypothesis of object-based attention would make an opposite prediction (Richard et al., 2008). The spreading hypothesis states that when attention is cued to a location within an object, attention will spread automatically from the cued location to the whole object. Consequently, a subliminal cue that can successfully capture attention to a specific location within an object should also cause attention to spread throughout the whole cued object. In sum, regardless of the participant's awareness of the cue, a conventional *same-object advantage* is expected.

To test these two hypotheses, we designed four experiments orthogonally by crossing the cue type (subliminal/suprathreshold) with the cue-to-target stimuli-onset-asymmetry (SOA; 100 ms/1000 ms). A subliminal cue was followed by suprathreshold cue in each pair of experiments. The experiments were structured as follows:

1. Experiment 1: subliminal cue, 100-ms SOA.
2. Experiment 2: suprathreshold cue, 100-ms SOA.
3. Experiment 3: subliminal cue, 1000-ms SOA.
4. Experiment 4: suprathreshold cue, 1000-ms SOA.

Manipulation of SOA allows us to examine the object effects induced by the spatial cue across different time courses. Past studies using suprathreshold cues have shown that one's attention is attracted first to the cued location but then is inhibited from going there again, as indicated by an early facilitation (faster RT) followed by late inhibition (slower RT) at the cued location (for a review, see Klein, 2000). Bennett and Pratt (2001) examined the spatial distribution of the late-inhibition component and found facilitation in the quadrant *opposite* to the cued (inhibited) location. Assuming that attention relocates to the opposite quadrant in the long-SOA condition, the uncued object in the current study becomes “attended-object,” and a reversed object effect should be obtained. Indeed, with suprathrehold cues, results opposite to that obtained in the short SOAs were found instead (Jordan & Tipper, 1999).

A recent study by Mulckhuyse, Talsma, and Theeuwes (2007) has shown the same bi-phasic mode of early facilitation and late inhibition with a subliminal spatial cue. Thus, we hypothesize that opposite object effects should be obtained for a long-SOA condition compared with a short-SOA condition for the subliminal cue as well. That is, with subliminal cues, we should expect to find a different-object advantage for a short SOA and a same-object advantage for a long SOA. In contrast, the spreading hypothesis predicts conventional object effects—same-object advantage for a short SOA (Egly et al., 1994) and different-object advantage for a long SOA (Jordan & Tipper, 1999)—as long as a subliminal cue attracts attention to its location.

General Method

Participants

Seventy-seven paid volunteers participated in this study (*N* = 29, 20, 17, and 11 in Experiments 1 to 4, respectively). All participants had normal or corrected-to-normal vision and were naïve as to the purpose of the experiment.

Stimuli, Apparatus, and Design

The stimuli were presented on a VGA monitor with the resolution of 640 ×

480 pixels in a 256-color mode. A visual C++ computer program was run on an IBM-compatible computer to present the stimuli and collect the RT data. Participants sat in a dimly lit chamber with a viewing distance of 57 cm. Head position was maintained with a chin rest.

Figure 1 illustrates the stimuli and sequence of events for a target-present trial (83% of total trials) in each experiment. The displays were comprised of a pair of adjacent rectangles, oriented either vertically or horizontally. The fixation cross was a red plus sign (1° × 1°). Each rectangle (2° × 8°, with a stroke width 0.2°) was centered 3° from fixation. The cue, masks (1° × 1° solid grey squares), and the target (a solid black disk with 0.3° in diameter) were all centered 4.24° from fixation.

A spatial pre-cue was presented at one end of a rectangle, with one of the three cue-target relationships:

1. *Valid*: The target appeared at the cued location.
2. *Invalid same-object (IS)*: The target appeared at the uncued location within the cued object.
3. *Invalid different-object (ID)*: The target appeared at the near end of the uncued object.

The distance between the cue and the target were equal in the IS and ID conditions, making any RT difference between IS and ID conditions not attributable to location. There were four blocks of 58 trials each, including 16 valid, 16 IS, 16 ID, and 10 catch trials, presented in random order.

Procedure

Each trial began with a fixation display containing the fixation cross and two rectangles, with its duration jittered from 300 to 800 ms to reduce anticipation. In Experiment 1, following the fixation display, the cue display was presented for 16 ms and was then replaced by an 84 ms mask display, making the cue-to-target SOA 100 ms. Then the target (or, in the catch trials, nothing) was presented and remained visible until the participants either responded or, if there was no response, for 1000 ms. The next trial began after a 1000-ms intertrial interval, during which the screen was blank.

The subliminal cue was a small patch appearing at one end of the two rectangles in the cue display. The cue was presented 16 ms earlier than the other patches shown in the other three ends, giving the impression that all four patches appear simultaneously. The participants were asked to fixate at the central cross throughout each trial, and their task was to press the space bar on a computer keyboard as rapidly as possible whenever they detected the target. A 500-ms feedback beep was presented if the participant made a response to a catch trial that contained no target. Before the experimental trials, the participant was given 20 practice trials that were randomly selected from the experimental conditions.

After conducting the target-detection task, participants were asked to perform a cue-report task, which assessed whether participants were indeed unable to perceive the cue. Sixty-four trials (16 trials × 4 possible cue locations) with identical procedure to the trials in the target-detection task were conducted. Participants were asked to ignore the target but to indicate which of the patches was presented earlier than the other three patches by pressing a one of four designated keys on a computer keyboard. Each trial ended when a response was given and no feedback was provided. After this objective measure, the participants were asked directly about whether they had seen any patches occur before the others during the whole experiment. This open question served as a subjective measure of the awareness of the cue.

Instead of the subliminal cue used in Experiment 1, a suprathreshold cue was provided in Experiment 2. In Experiment 2, following the fixation display, the cue display was presented for 100 ms and then replaced by the target display. Instead of the short cue-to-target SOAs (100 ms) in the first two experiments, the SOAs were 1000 ms in Experiments 3 and 4. In Experiment 3, the cue display was presented for 16 ms and replaced by a 984-ms mask display. In Experiment 4, the cue display was presented for 100 ms and then replaced by a 900-ms fixation display.

Results

Cue-Report Task

All participants in Experiments 1 and 3 reported that they were unable to perceive the cue, which was collaborated by the objective measure. The mean detection accuracy of the four-alternative-forced-choice cue report tasks were not significantly above chance level (27% and 25%, respectively; *ps* > .30). All participants in Experiments 2 and 4 were fully aware of the cue.

Target-Detection Task

Figure 2 shows the mean correct RTs collapsed across rectangle orientation in all experiments, since orientation did not affect the RTs, nor did it interact with validity (*p*s > .05). The collapsed data were submitted to a one-way repeated measures Analysis of Variance (ANOVA) with the factor of validity (valid, IS, ID). The main effects of validity were significant in all four experiments [F (2, 28) = 4.00, $p < .05$; F (2, 19) = 17.76, $p < .001$; F (2, 16) = 4.33, $p < .05$; F (2, 10) = 17.86, $p < .001$ for Experiments 1 to 4, respectively]. There were no differences in error rates across conditions in each experiment, indicating no speed-accuracy trade-off.

In Experiment 1 (subliminal cue; 100-ms SOA), planned comparisons (two-tailed, paired t test) showed faster RTs for valid than for IS trials ($p < .05$), replicating the finding that a subliminal cue can capture participants' attention (e.g., Mulckhuyse et al., 2007). More importantly, the subliminal spatial cue led to the *different*-object advantage: Participants responded faster when the target appeared at the uncued object (ID) than at the cued object (IS) ($p < .05$).

In Experiment 2 (suprathreshold cue; 100-ms SOA), the RTs of valid trials were shorter than those of IS trials ($p < .05$), and the RTs of IS trials were shorter than were those of ID trials ($p < .01$). Experiment 2 replicated the typical patterns from a suprathreshold cue with a short SOA—location-based facilitation and same-object advantage. Comparing Experiments 1 and 2 reveal reversed object effects with subliminal and suprathreshold cues: *different*-object advantage for subliminal cues and *same*-object advantage for suprathreshold cues.

In Experiment 3 (subliminal cue; 1000-ms SOA), the RTs of valid trials were longer than those of IS trials ($p < .05$), indicating a late inhibition component of the subliminal cue with long SOA and also replicating the findings of Mulckhuyse et al. (2007). More importantly, participants responded faster when the target appeared at the cued object (IS) than at the uncued one (ID) ($p < .05$). That is, the subliminal spatial cue in a long-SOA condition led to location-based *inhibition* accompanied with object-based *facilitation*.

In Experiment 4 (suprathreshold cue; 1000-ms SOA), the RTs of valid trials were longer than those of IS trials ($p < .001$), which were longer than those of ID trials ($p < .05$). Namely, Experiment 4 found both location- and object-based *inhibition* and replicated the findings of Jordan and Tipper (1999). By comparing Experiments 3 and 4, we confirm that the subliminal cue and the suprathreshold cue led to reversed object effects also in a long-SOA condition.

Discussion

Our results show that a subliminal cue caused different-object advantage for short SOA (Experiment 1) and same-object advantage for long SOA (Experiment 3). These results are opposite to the object effects obtained with a suprathreshold cues used in Experiments 2 and 4 in which conventional object effects were replicated: same-object advantage for short SOA (e.g., Abrams & Law, 2000; Egly et al., 1994; Lamy & Tsal, 2000; Moore et al., 1998) and different-object advantage for long SOA (e.g., Jordan & Tipper, 1999; List & Robertson, 2007). The critical difference predicted by the spreading hypothesis and the consciousness-dependent hypothesis lies in the results with the use of subliminal cue (Experiments 1 and 3); we have demonstrated that the subliminal cue we used indeed did not reach consciousness, as confirmed by both subjective and objective measures of participants' awareness of the cue. Furthermore, the subliminal cue we used was effective in capturing attention to its location, as indicated by *faster* responses to targets shown at the cued location with short SOA and *slower* responses with long SOA, replicating early facilitation and late inhibition with a subliminal cue proven by Mulckhuyse et al. (2007). The fact that the suprathreshold and subliminal cues led to opposite object effects supports our consciousness-dependent hypothesis but not the spreading hypothesis.

The results of early facilitation with short SOA that leads to same-object advantage for suprathreshold cues and different-object advantage for subliminal cues can be explained as follows: The suprathreshold cue triggers the ventral pathway that is mainly responsible for *conscious* object recognition. Object recognition heavily relies on within-object link—thus, properties within the same object should be strengthened altogether—leading to the same-object advantage. The subliminal cue, however, triggers the dorsal pathway that is mainly responsible for visually guided action. Action heavily relies on between-object link—and, thus, properties between different objects should be strengthened instead—leading to the different-object advantage. The reversed result patterns triggered by the late inhibition with long SOA follow the same reasoning. Therefore, this study provides evidence of dissociating unconscious vision (dorsal) and conscious vision (ventral) pathways with neuropsychologically intact observers. Unlike previous studies supporting object-based attention that all used suprathreshold stimuli (e.g., Baylis & Driver, 1993; Brawn & Snowden, 2000; Duncan, 1984; Egly et al., 1994), the current study demonstrates opposite results from suprathreshold and subliminal cues by manipulating participants' consciousness regarding the cue.

Note that the task our participants performed was to detect a target within one end of two objects, which is considered a type of "vision-for-perception" task. Thus, it is reasonable that previous studies using suprathreshold cues found same-object advantage because the within-object link was emphasized in such perception tasks that supposedly are processed in the ventral pathway. When an action (i.e., pointing) that triggered the dorsal pathway was required, the same-object advantage was disrupted (Linnell, Humphreys, McIntyre, Laitinen, & Wing, 2005). Why would the same perception task with a subliminal spatial cue in the current study prove to be processed in the dorsal pathway that enhances between-object link? It is possible that unconscious spatial cues can bypass the constraint of task demands, making the dorsal pathway dominate the ventral pathway. The subliminal cue indexes a given location, then sent along the dorsal pathway, which is also known to process location information (Ungerleider & Haxby, 1994) without being masked by the influence of within-object links.

Davis, Welch, Holmes, and Shepherd (2001) used a divided-attention task wherein participants were asked to compare two target features within an object or across objects, and they also found a different-object advantage: a faster response when the two features belonged to different objects than to the same object. They argue that different-object advantage was obtained due to processes in the magnocellular pathway. Their assertion bears some similarities to our hypothesis because it has been suggested that the ventral and dorsal pathways are the cortical extensions of separate subcortical parvocellular and magnocellular pathways (Livingstone & Hubel, 1987). However, there is now considerable evidence showing that although the dorsal pathway is largely—though not entirely—dependent on magnocellular inputs, the ventral pathway receives major contributions from both magnocellular and parvocellular inputs (Merigan & Maunsell, 1993). Our study also differs from that of Davis et al. (2001). They manipulated the stimulus presentation that favors one pathway over the other and found same-object advantage in one case (e.g., only high-spatial frequency information available that favors the ventral pathway) and different-object advantage in the other (e.g., presenting the objects and target features simultaneously that favors the magnocellular pathway). However, we obtained both the same- and different-object advantage using the same stimulus displays. In our procedure, the objects were presented for 300 ms to 800 ms before the cue was shown, and the cue-to-target SOA was 100 ms or 1000 ms. Davis et al. (2001) suggest that it is the time interval between the objects and the target features (delayed 2400 ms or simultaneous) that determines whether a same- or a different-object advantage is observed. Although it is difficult to compare the cuing task and the divided-attention task, the object preview time in our procedures and the cue-to-target SOAs were long enough for the parvocellular pathway to operate. It is possible that the 16-ms subliminal cue triggers the magnocellular pathway, which is sensitive to transient changes; however, what we emphasize here is that the conscious status is critical for modulating the object effects.

Learning exactly how conscious and unconscious visual processes function will enrich our understanding of human visual processing that, on one hand, leads to object recognition and, on the other hand, to visually guided action. In practice, subliminal information can be useful in commercial and clinical settings to provide unconscious suggestions for undefended receptive advertisements and in behavioral modification (Greenwal, Spangenberg, Pratkanis, & Eskenazy, 1991; Karremans, Stroebe, & Claus, 2006; Merikle & Skanes, 1992). Further, our findings suggest that conscious state and timing are both critical factors that must be considered, not only for future studies but also for application purposes.

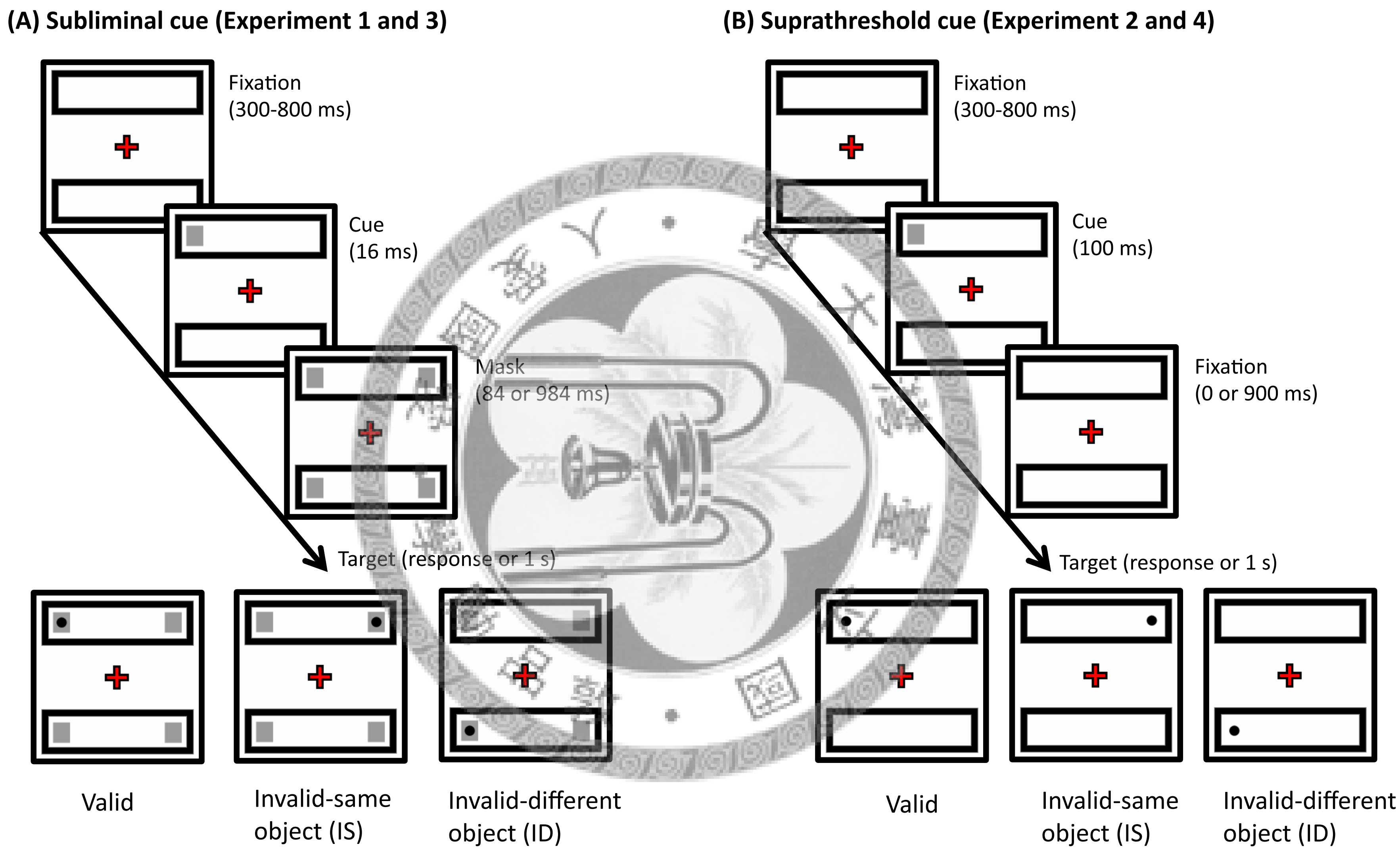


Figure 1. Example displays for each of the four experiments (Chapter 2). The rectangles were oriented either horizontally or vertically. The cue was a small patch appearing at one end of the two rectangles. The task was to detect the target (a black disk).

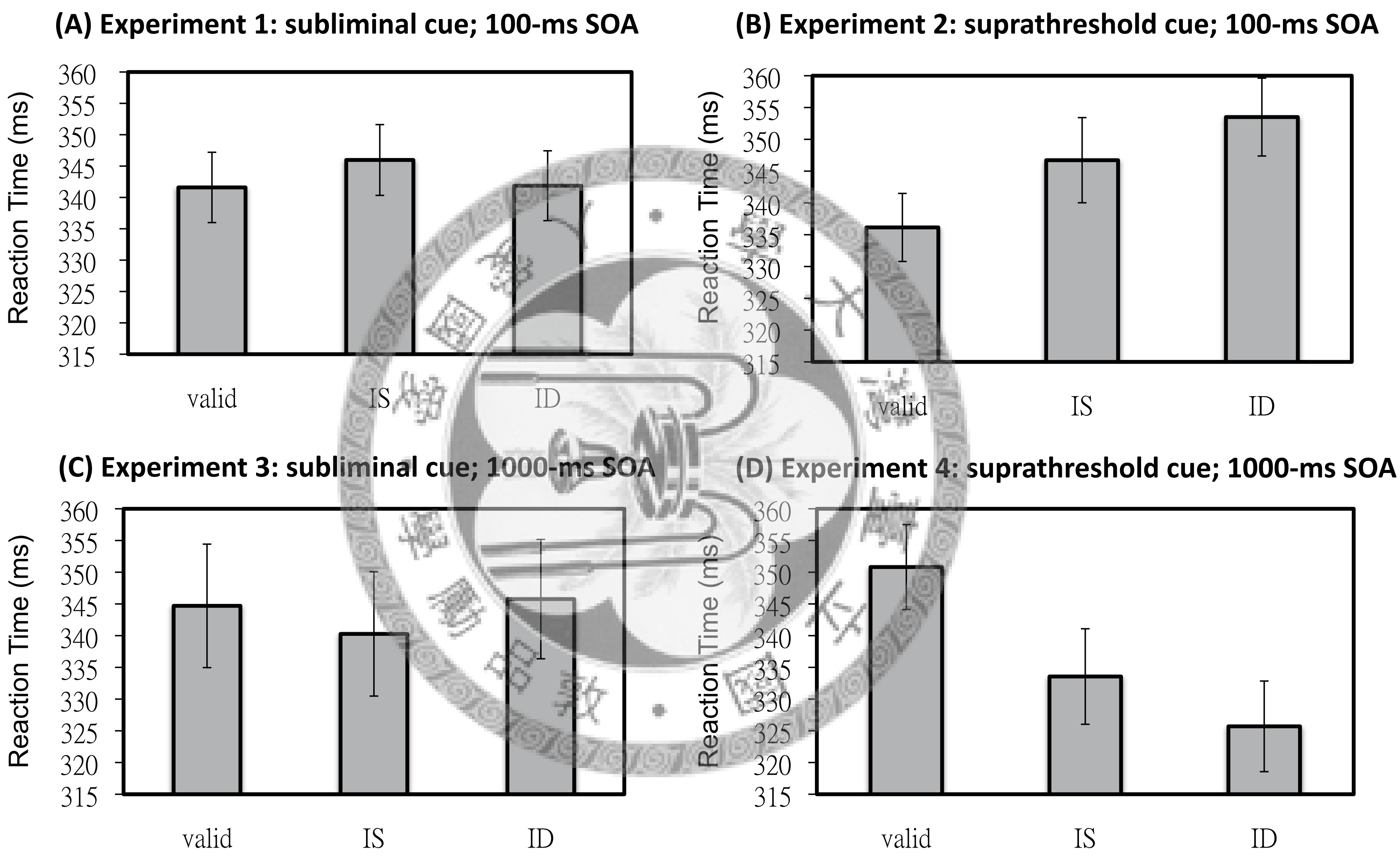


Figure 2. Mean correct reaction times (RTs) in each of the four experiments (Chapter 2). Error bars represent one standard error of the mean. IS: invalid-same object; ID: invalid-different object.

Chapter 3

Object-Based Attention Occurs Regardless of Object Awareness

Chou, W. L., & Yeh, S. L. (submitted).

Abstract

This study investigated whether object-based attention is modulated by participants' awareness of objects. We used the two-rectangle method (Egly et al., 1994) to probe object-based attention, and adopted the continuous flash suppression technique (Fang & He, 2005; Tsuchiya & Koch, 2005) to control for the visibility of the two rectangles. Our results show that object-based attention, as indexed by the same-object advantage—faster response to a target within a cued object than within a non-cued object—was obtained regardless of participants' awareness of the objects. This study provides the first evidence of object-based attention under unconscious conditions by showing that the selection unit of attention can be at an object level even when these objects are invisible—a level higher than the previous evidence for a subliminally cued location. We suggest that object-based attentional guidance plays a fundamental role of binding features in both conscious and unconscious mind.

Introduction

When we attend to an object, we become conscious of it; when we shift attention away from the object, it fades from our consciousness. This daily-life observation leads to the suggestion that attention is the gate to consciousness, which is supported by empirical evidence; for example, inattentional blindness (Mack & Rock, 1998) and change blindness (Simons & Levin, 1997). Recently, however, new evidence hints at the possibility that attention and consciousness might be two independent processes (see Koch & Tsuchiya, 2006, for a review). For example, under the condition of near absence of attention, observers can still be aware of whether the visual display contains an animal (Li, VanRullen, Koch, & Perona, 2002). Conversely, semantic information of a masked stimulus can be processed with focused attention but without consciousness (Ortells, Vellido, Daza, & Noguera, 2006). However, the critical evidence for a true double-dissociation of attention and consciousness—conscious perception without attention (defined as selection/filtering)—still awaits further unequivocal evidence to disentangle one position from the other. Nevertheless, it becomes clear from burgeoning studies conducted under this debate that attention and consciousness are not the same thing: Attention can move freely under unconscious conditions, as indicated by recent findings of attentional capture by a subliminal cue to its location (Jiang, Costello, Fang, Huang, & He, 2006; Mulckhuyse et al., 2007; Bahrami, Lavie, & Rees, 2007).

The fact that attention can operate unconsciously goes along with the influential feature integration theory, wherein various features belonging to the same location are processed in parallel and combined *only* when attention moves there (Treisman & Gelade, 1980); from then on, the spatial-temporal information of that location is compared to the stored representation to retrieve the information about the object (Treisman, 1996). Thereby, attention improves processing at a given location and combines whatever is there. According to this view, attention serves as the first step of detailed processing at one location due to limited capacity available, and thus one cannot know what was there beforehand. Along this line of reasoning, what remains unknown is whether attention can further operate on the whole object—that is, object-based attention—even when the objects remain invisible. Ecologically, the ability to make speedy correct fight-or-flight responses is important for survival. To an animal, the decision to fight or flee depends on whether it sees prey or an enemy. To recognize objects immediately, spatial information is important but insufficient; processing of properties belonging to the same object is also critical. Because many objects are out of our consciousness in the over-complex visual world, we hypothesize that not only location-based attention but also object-based attention can be influenced by unconscious information to advantage surviving.

In contrast to our hypothesis, however, Ariga, Yokosawa, and Ogawa (2007) argue that awareness of objects is necessary for object-based attention. They adopted the two-rectangle method (Egly et al., 1994) that contained two rectangles with one end of one rectangle flashing a small circle as a cue to indicate the possible location of a target. The target was shown subsequently within one end of a rectangle. Object-based attention was indicated by the *same-object advantage*: RTs were shorter when the target appeared at the uncued end of the cued than at the uncued rectangle, with an equal cue-to-target distance between the two. Ariga et al. (2007) used objects that were defined by perceptual completion—that is, illusory objects—and found that the same-object advantage was *not* obtained in the condition when observers were unaware of the illusory objects. Only when observers were aware of the objects was object-based attention found.

We noticed that in Ariga et al.'s (2007) study, awareness was manipulated by changing the object preview time; therefore, in their unconscious-object condition (Experiment 2), the objects and the target were presented simultaneously; that is, there was no object preview time. At least two studies from different groups imply that such a design may not be favorable for obtaining the same-object advantage: First, Davis and Holmes (2005) argue that the same-object advantage reflects strong within-object feature binding by mechanisms in the parvocellular to ventral-stream pathway that is responsible for object recognition. According to Davis and Holmes, the simultaneous presentation of the target and objects in Ariga et al. will weaken the contribution of this pathway because of the transient signals of the two; this would reduce or even eliminate the same-object advantage. Second, Shomstein and Behrmann (2008) showed that varying the object preview time changes the magnitude of the same-object advantage; the same-object advantage is observed only if there is ample object preview time to establish the object representation.

Based on these differing studies, we further hypothesize that it is *preview time* but not *awareness* that determines object-based attention: Given sufficient object preview time to successfully establish object representation, even invisible objects can lead to object-based attention. Despite a prevalent assumption that a long processing time unavoidably leads to the involvement of awareness and methodological difficulties in teasing apart the influences of processing time and awareness, it has been shown that the two can be dissociated in separate processing streams for implicit and explicit visual perception (Lo & Yeh, 2008).

To provide a long-enough object preview time, we used the newly developed paradigm called *continuous flash suppression* (CFS) (Fang & He, 2005; Tsuchiya & Koch, 2005). In this paradigm, constantly changing high-contrast patterns are flashed to one eye that provide strong interocular suppression signals to a static stimulus presented to the other eye. Critically, the suppression of the static stimulus can last for quite some time (see Lin & He, 2009, for a review). Unlike other paradigms used for manipulating awareness (e.g., masking or crowding) wherein awareness is manipulated by changing visual stimulation (e.g., either masked or not), CFS has the merit of keeping visual stimulation invariant and surmounting the limitations of binocular rivalry (e.g., relatively short suppression duration and uncontrolled variation of one percept to another) in studying consciousness.

By adopting the CFS technique in the current study, visual objects can be shown to observers with a relatively long preview time (1,900 ms). Moreover, unlike Ariga et al. (2007) wherein awareness was manipulated by changing object preview time, we designed a situation that made almost half of the participants aware and the other half unaware of the objects to provide a fair comparison—that is, the same stimuli and procedure—between the two groups of different awareness states.

Method

Participants

Twenty-six National Taiwan University undergraduate students were paid to participate in this study. All participants had normal or corrected-to-normal vision and were naïve as to the purpose of the experiment.

Apparatus, Stimuli, and Design

The stimuli were presented on a VGA monitor with the resolution of 640 × 480 pixels in a 256-color mode. A visual C++ computer program was run on an IBM-compatible computer to present the stimuli and collect RT data. Participants sat in a dimly lit chamber with a viewing distance of 57 cm. Head position was maintained with a chin rest.

Two different images—both surrounded by a frame (15.7° × 15.7° visual angle, with a thickness of 0.2°) composed of random dots—were projected onto each eye through a four-mirror stereoscope (see Figure 3 for an illustrated depiction). Figure 4 illustrates the stimuli and sequence of events for a trial that contained objects (the *object trial*). Dominant-eye images comprised 10.5° × 10.5° Mondrian patches, constructed from random-size small patches (one side length from 0.01° to 1.07°) with a randomly chosen color (RGB values from 0 to 255). Non-dominant-eye images comprised two horizontal light grey rectangles. Each rectangle (2° × 8°, with a stroke width 0.2°) was centered 3° from fixation. The contrast of the rectangles was raised gradually from 0% to 50% within 300 ms and was then kept constant at 50% contrast until the end of the trial. Fixation, cue, and target were presented binocularly at the corresponding locations of both eyes. The fixation was a red plus sign (1° × 1°). The cue and the target were identical (a 1° × 1° solid black patch) and all were centered 4.24° from fixation.

The spatial pre-cue was presented at one end of a rectangle, with one of the three cue-target relationships:

1. *Valid*: The target appeared at the cued location.
2. *Invalid same-object (IS)*: The target appeared at the uncued location within the cued object.

3. *Invalid different-object (ID)*: The target appeared at the near end of the uncued object.

The distance between the cue and the target were equal in the IS and ID conditions, making any RT difference between IS and ID conditions not attributable to location. There were 12 object trials, including 4 valid, 4 IS, and 4 ID trials, which were mixed with 22 no-object trials (foils). All trials were presented in a random order.

The stimuli and procedure of the no-object trials were identical to those of the object trials except there were no rectangles. Despite the absence of rectangles in the no-object trials, we still used the same denotations (valid, IS, ID) based on the imagery rectangles. The proportions of valid, IS, ID, and catch trials of the no-object trials were 70%, 10%, 10%, and 10%, respectively.

Structure of the Experiment

Figure 5 depicts the structure of the experiment. First, a dominant eye measurement was conducted: Participants used their thumb and index finger of their right hand to make a circle and view an object on the wall binocularly through this circle, closing the left or right eye alternatively to determine which eye could still see the object through the circle even when the other eye was closed. The eye that could still see the object was treated as the dominant eye. The dynamic Mondrians (the masks) were then presented to the dominant eye to provide stronger suppression to the critical stimuli that was presented to the other, non-dominant eye. In the beginning of the CFS procedure, the participants were asked to fuse the dichoptic images through a four-mirror stereoscope. After a perfect fusion, the experimenter started the target-detection task with the practice stage, which contained 20 no-object trials that were randomly selected from the training stage. After the practice stage and a short break, the training stage (34 no-object trials) and the critical stage (12 object trials mixed with 22 no-object trials) were conducted in sequence without break.

After conducting the target-detection task under the CFS procedure, participants were asked to perform the object-report tasks to assess their state of awareness of the rectangles. First, an open question was served as a subjective measurement: "Did you see any figures besides the cue, target, fixation, and Mondrians during the whole experiment?" Then a five-alternative-forced-choice (5-AFC) task followed to serve as an objective measurement: Multiple-choice questions contained five illustrations (two horizontal rectangles, two vertical rectangles, four squares, eight horizontal lines, and eight vertical lines), and the participants were asked to indicate the one they had seen during the experiment. Finally, the participants rated the confidence level (5-point scale, 1 denoting "not confident at all" and 5 denoting "very confident") about their choice in the 5-AFC task.

Procedure of the CFS Trial

Figure 4 illustrates the stimuli and sequence of events for an object trial. The images projected to the dominant eye were 10-Hz dynamic Mondrians. The fixation, cue, and target were presented to both eyes, and the rectangles were presented only to the non-dominant eye. Each trial began with a fixation display containing the fixation cross and two rectangles (or, in no-object trials, nothing) with 1,600-ms duration. Following the fixation display, the cue display was presented for 100 ms and then replaced by a 200-ms fixation display, making the cue-to-target SOA 300 ms and the object preview time 1,900 ms. Then the target (or, in the catch trials, nothing) was presented and remained visible until the participants responded; if there was no response, 1,000 ms. The next trial began after a 1,000-ms intertrial interval, during which the screen was blank.

The participants were asked to fixate on the central cross throughout each trial, and their task was to press the space bar on a computer keyboard as rapidly as possible whenever they detected the target. A 500-ms feedback beep was presented if the participant made a response to a catch trial that contained no target.

Results

Object-Report Tasks

For the subjective measurement, 16 participants reported that they were unable to perceive any figures aside from the cue, target, fixation, and Mondrians during the entire experiment; the other 10 participants reported seeing the rectangles. For the objective measurement (the 5-AFC task), 14 participants—include the 10 participants who reported seeing the rectangles in the subjective measurement—responded correctly (the average of 5-point confidence rating was 4.71, with a range from 3 to 5). The other 12 participants made an incorrect response (the average of 5-point confidence rating was 1.33, with a range from 1 to 3). Only participants who were unaware of the rectangles by *both* subjective and objective measurements were sorted to the “unaware group” in the further analysis, making 12 and 14 participants in “unaware group” and “aware group,” respectively. Figure 6 shows the summary of results in the two groups.

Target-Detection Task

The mean correct RTs of object trials were submitted to a two-way repeated measures ANOVA with the factor of awareness state (aware, unaware) and validity (valid, IS, ID). The main effect of validity was significant [F (2, 23) = 7.17, p < .005]. However, the main effect of awareness state was far from statistical significant [F (2, 23) = 0.49, p = .62]. There were no differences in error rates across conditions, indicating no speed-accuracy tradeoff.

Planned comparisons (two-tailed, paired t test) showed faster RTs for valid than for IS trials in both the aware and unaware groups (ps < .05), replicating the finding that a spatial cue can capture participants’ attention to the cued location (Egly et al., 1994). More importantly, the spatial cue led to the same-object advantage regardless of participants’ awareness of the objects: Faster RTs were found when the target appeared at the cued object (IS) than at the uncued object (ID) in both groups (ps < .05). The magnitudes of the same-object advantage in both aware and unaware group—24 and 44 ms, respectively—are well within the range of such effects reported in the literature (e.g., Moore et al., 1998; Shomstein & Behrmann, 2008).

The data from the no-object trials were also submitted to two-way repeated measures ANOVA with the factor of awareness state (aware, unaware) and validity (valid, IS, ID). The main effect of validity was significant [F (2, 23) = 8.27, p

< .005]. The main effect of awareness state was far from statistical significant [F (2, 23) = 0.39, p = .73]. There were no differences in error rates across conditions, indicating no speed-accuracy tradeoff. Planned comparisons showed faster RTs for valid than for IS trials in both aware and unaware groups (ps < .05), proving that the spatial cue in this study could capture participants' attention to the cued location. More importantly, data from the no-object trials did not show any significant difference between the IS and ID conditions in both groups (ps > .6).

Discussion

By adopting the CFS technique with the two-rectangle method, we found significant same-object advantage, regardless of whether the participants were aware or unaware of the objects. We have confirmed the consciousness state of the aware and unaware groups by both subjective and objective measures. Furthermore, the same-object advantage obtained was indeed caused by the objects and cannot be attributed to other confounding factors—for example, expectation, hemifield of target, and other strategies—because when we analyzed results from the no-object trials, there were no differences in performance between the IS and ID conditions in both groups. To our knowledge, almost all evidence supporting object-based attention is obtained from studies using suprathreshold objects (e.g., Baylis & Driver, 1993; Duncan, 1984; Egly et al., 1994). The fact that both aware and unaware groups led to similar same-object advantage in the current study provides evidence for object-based attention under the unconscious state—just as observed under the conscious state. In other words, consciousness of the object is not required for object-based attention, and the consciously and unconsciously perceived object may trigger the same attentional processing.

Showing that object-based attention can occur even when the observers are unaware of the objects is inconsistent with the results of Ariga et al.'s (2007) Experiment 2 because they did not obtain the same-object advantage when their observers were unaware to the objects. The fact that Ariga et al. used illusory objects, presented the cue before the objects, and provided no object preview time may have weakened the strength of object representation, thereby weakening the ability of the attentional guidance by unconsciously processed objects. In contrast, our use of real-contour object, presenting the objects before the cue, and providing 1,900 ms object preview time may have strengthened the object representation; thus, selection based on an unconscious object is possible. Indeed, Shomstein and Behrmann (2008) confirm that the strength of object representation plays a critical role in object-based attention.

The current results support our hypothesis that object-based attention can be obtained as long as sufficient object preview time is provided for establishing robust object representation. The reason that the same-object advantage was not obtained in Experiment 2 of Ariga et al. (2007) but was obtained in their Experiment 1 may not be due to the unaware versus aware state, but rather to the 0 ms vs. 400 ms object preview times used in that study. In our study, by adopting the CFS paradigm—an excellent tool that permits independent manipulation of processing time and awareness—we could provide a sufficient object preview time (1,900 ms) in both aware and unaware groups. The reliable finding of the same-object advantage from both the aware and unaware groups in the current study suggests that sufficient object processing time, but not the consciousness state, is critical for the same-object advantage (e.g., Davis & Holmes, 2005; Shomstein & Behrmann, 2008).

In addition to the methodological concern, along the mainstream of recent debate as to the issue whether attention and consciousness are independent (Koch & Tsuchiya, 2006) or whether attention is necessary for consciousness (Mack & Rock, 1998; Simons & Levin, 1997), the opposite stand as suggested by Ariga et al. (2007) —awareness is necessary for attention—is unusual, had it not been applied to objects (as opposed to locations) as selection units. Although the current study was not designed to clarify this debate, we did demonstrate that awareness of object is *not* the gate of object-based attention and provided counterevidence to the latter position. Additionally, our finding is consistent with previous studies and suggests that stimuli suppressed from consciousness are not suppressed from further processing (e.g., He, Cavanagh, & Intriligator, 1996; Jiang et al., 2006; Moore et al., 1998; Ortells et al., 2006; Lo & Yeh, 2008).

Both the mainstream theoretical framework (e.g., Treisman & Gelade, 1980) and empirical evidence (e.g., Jiang et al., 2006; Mulckhuyse et al., 2007) indicate that a subliminal stimulus can capture attention to a specific *location* for future processing. In the current study, we extended this argument to *object-based attention*: Attention can "select" an *object* even when we are not conscious of it. The ability of object-based attentional guidance by an unconscious object seems to have ecological function: Although there are many unconscious objects in our visual world (Mack & Rock, 1998), they do modulate our visual attention in both location- and object-based manner to facilitate processing.

We propose that the attentional guidance from unconscious objects may play a fundamental role in many high level unconscious processing—for example, the gist of a scene (Li et al., 2002), the semantic meaning of a word (Naccache, Blandin, & Dehaene, 2002), the emotion on a face (Yang, Zald, & Blake, 2007), and the category of an object (Almeida, Mahon, Nakayama, & Caramazza, 2008): All of these unconscious processes imply implicit object recognition at different levels. Regardless of the awareness state, visual processing initially breaks up the visual scene into isolated fragments that are detected by individual neurons in the primary visual cortex and higher visual areas (Livingstone & Hubel, 1988). Visual perception of objects somehow reassembles the isolated fragments into complete objects. The problem of creating a unified percept from the responses of separate neurons is referred to as the "binding problem" (Treisman, 1996), and our finding here suggests that unconscious objects face the same binding problem as do conscious objects. In line with the *unconscious binding hypothesis*, which states that the unconscious mind not only encodes individual features but also binds features (Lin & He, 2009), we propose further that the attentional guidance by unconscious objects may be the mechanism for unconscious binding of features. This speculation bears some similarities to the main concept of the *feature integration theory* (Treisman & Gelade, 1980) that attention integrates separate features at the master map of location. Here, we demonstrate that unconscious objects also can be the interface for integration. We suggest that attention not only plays the critical role in feature integration in *conscious* vision but also integrates individual features that belong to an invisible object in *unconscious* vision. Ecologically, unconscious object-level process speeds object recognition and results in speedy and correct reaction to the object, which is important for survival.

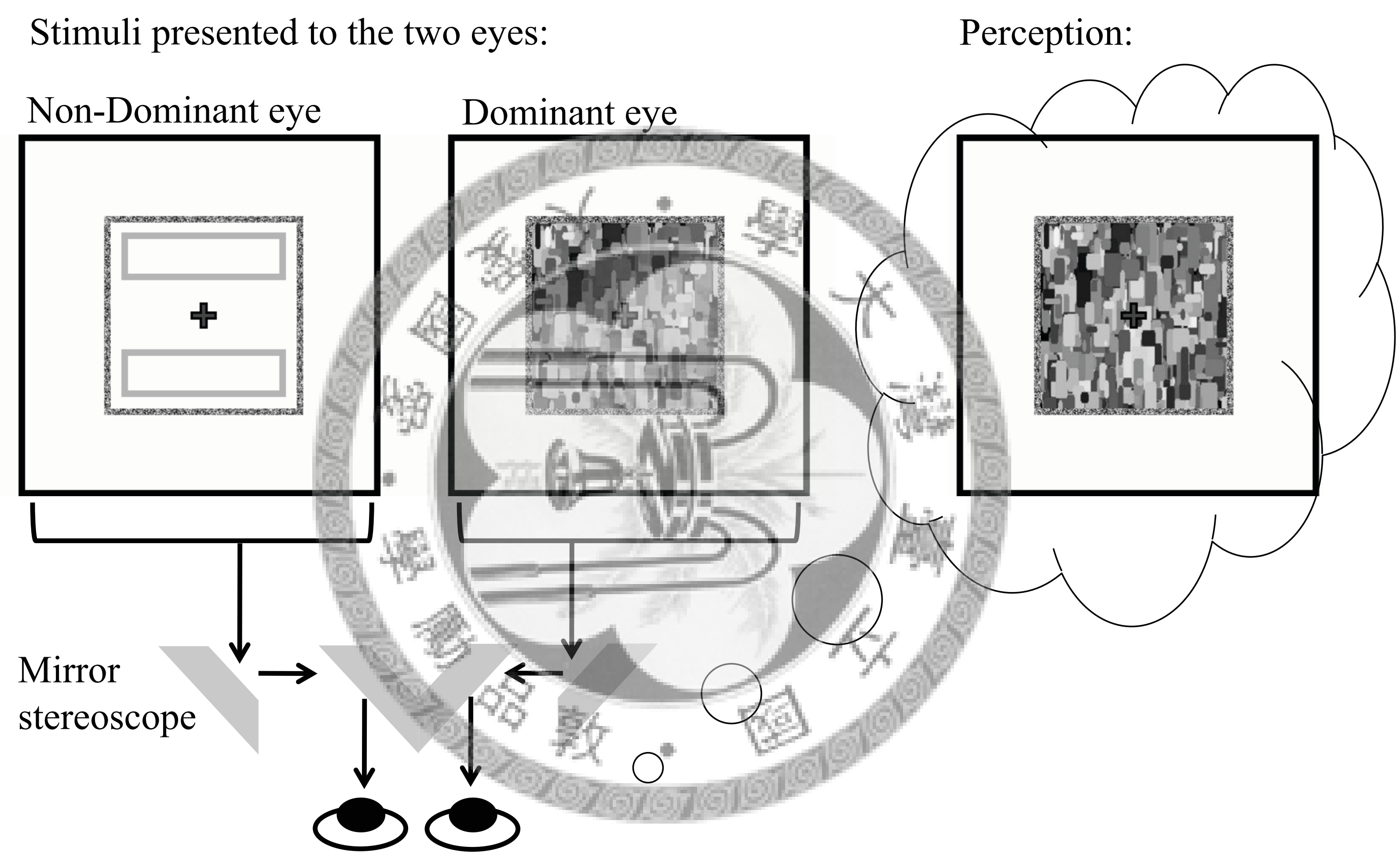


Figure 3. Stimuli rendered invisible with continuous flash suppression (Chapter 3).

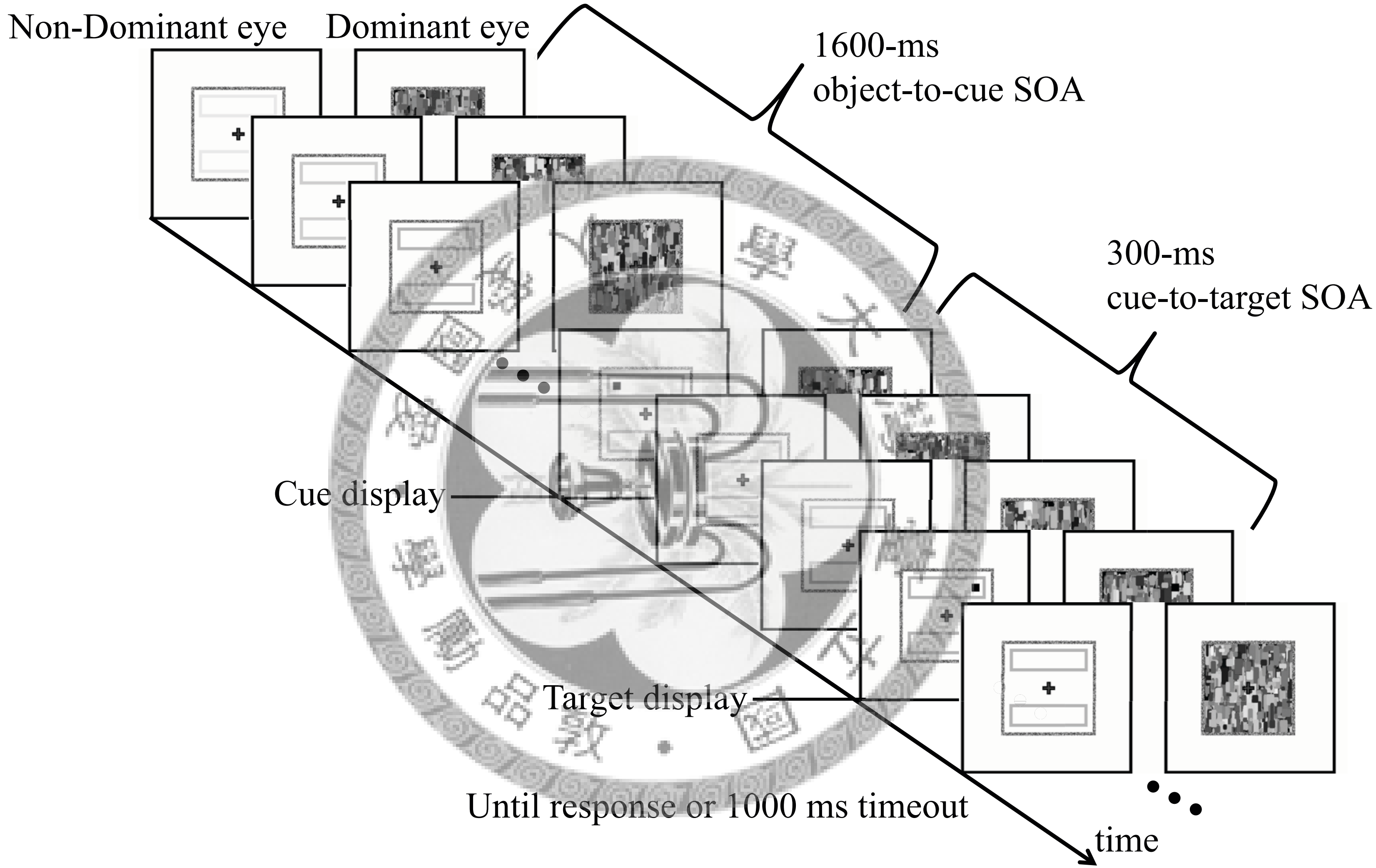


Figure 4. Procedure of the object trial in Chapter 3 (for the no-object trials, no rectangles were shown). Each frame lasted for 100 ms. This is an example of invalid-same object trial.

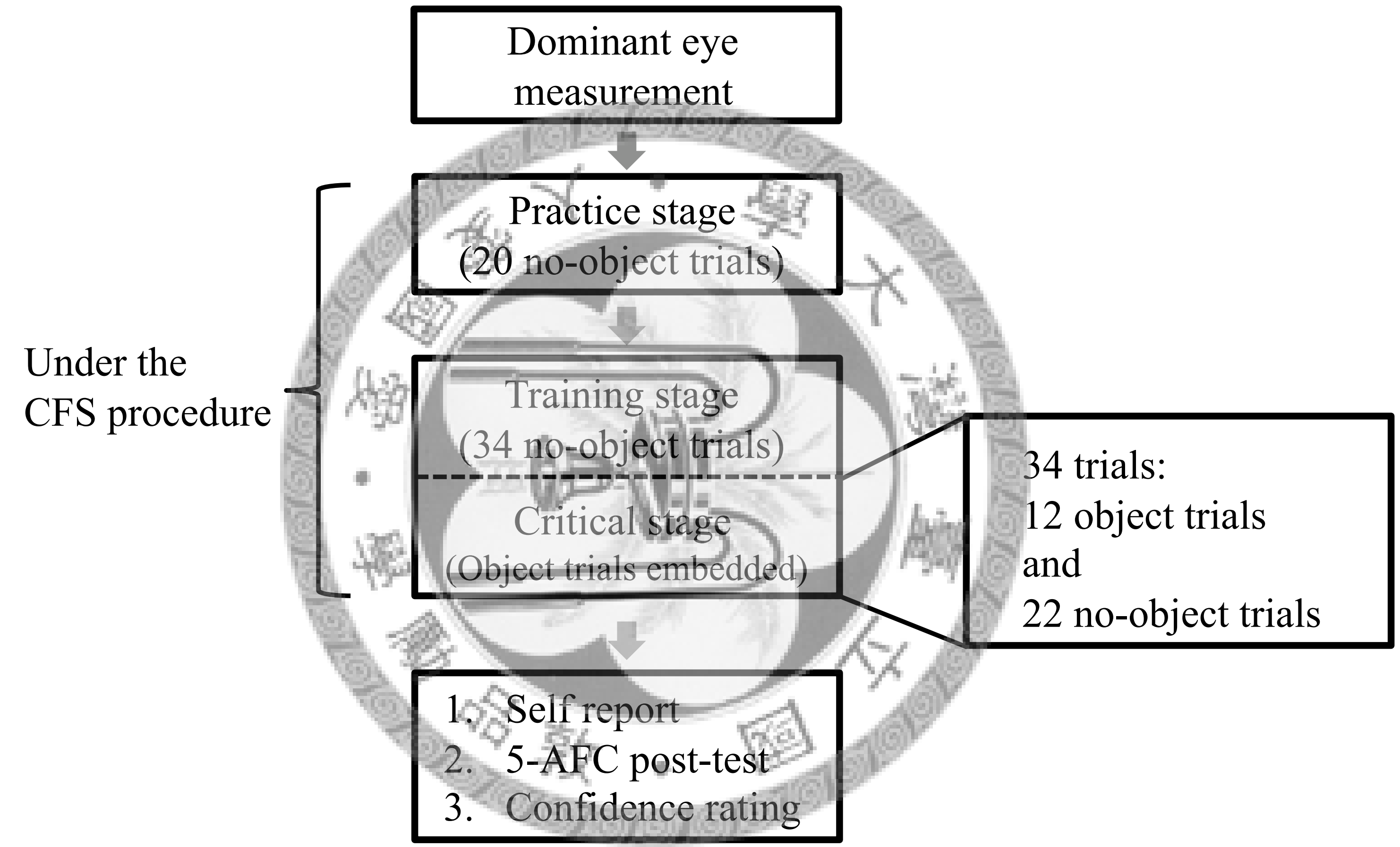
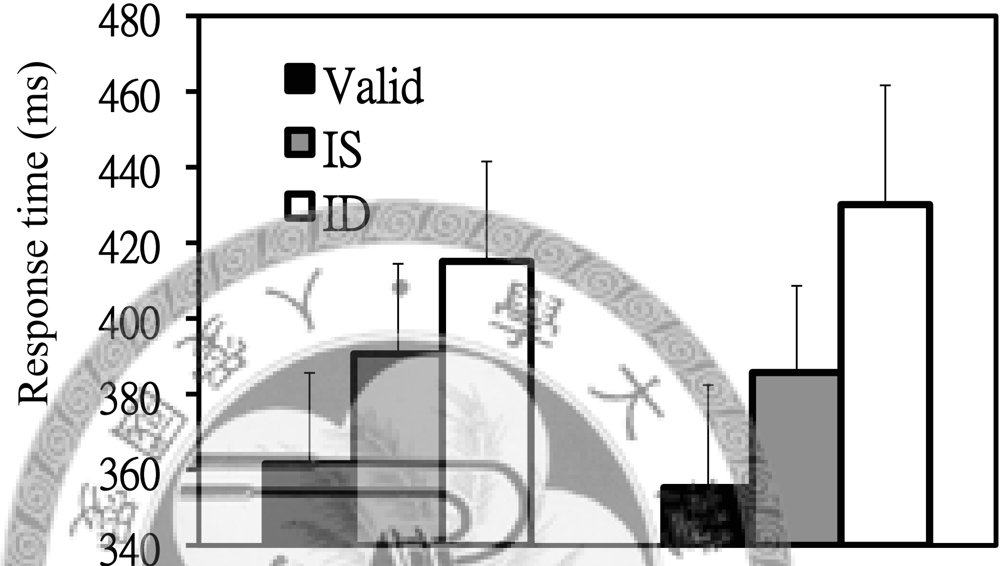


Figure 5. The structure of the experiment (Chapter 3).



	Aware group	**Unaware group**
Same-object advantage	24 ms	44 ms
Effect size (Cohen's d)	(0.30)	(0.56)
N	14	12
5-AFC	correct	Incorrect
Mean confidence rating	4.71	1.33

Note: N: number of participants; 5-AFC: five-alternative forced choice.

Figure 6. Mean response times as a function of awareness state (aware, unaware) under each condition (Chapter 3). Error bars represent one standard error from the mean.

Chapter 4

Distinct Mechanisms Subserve Location- and Object-Based Visual Attention

Chou, W. L., Yeh, S. L., & Chen, C. C. (submitted).

Abstract

Background. Visual attention can be allocated primarily to either a location or an object, named location- or object-based attention, respectively. Despite the burgeoning evidence in support of the existence of two kinds of attention, little is known about their underlying mechanisms in terms of whether they are achieved by enhancing signal strength or excluding external noises.

Methodology/Principal Findings. We adopted the noise-masking paradigm in conjunction with the double-rectangle method to examine the mechanisms of location- and object-based attention. Two rectangles were shown, and one end of one rectangle was cued, followed by the target appearing at (a) the cued location; (b) the uncued end of the cued rectangle; and (c) the equal-distant end of the uncued rectangle. Observers were required to detect the target that was superimposed at different levels of noise contrast. We explored how attention affects performance by assessing the *threshold versus external noise contrast (TvC) functions* and fitted them with a divisive inhibition model. Results show that location-based attention—lower threshold at cued location than at uncued location—was observed at all noise levels, a signature of signal enhancement. However, object-based attention—lower

threshold at the uncued end of the *cued* than at the *uncued* rectangle—can be found only in high-noise conditions, a signature of noise exclusion.

Conclusions/Significance. We found different underlying mechanisms for the two kinds of attention in terms of their TvC functions. Location-based attention operates by enhancing signal strength, whereas object-based attention operates by excluding external noise. This is the first study that systematically estimates the characteristics of attentional processes and directly compares location- and object-based attention using the popular double-rectangle method. Findings here shed a new insight into the current theories of object-based attention.

Introduction

Our visual world consists of multiple objects. However, due to limited capacity of our cognitive system, only a fraction of the perceived objects are selected for further processing. Hence, our visual system comprises mechanisms of attention that prioritize the processing of particular information. Over the last two decades, many studies have shown that visual attention can be allocated either to a spatial location or to an object, called location-based attention and object-based attention, respectively (Brawn & Snowden, 2000; Duncan, 1984; Egly et al., 1994; Gibson & Egeth, 1994; Posner, 1980; Tipper, Driver, Weaver, 1991). Egly et al. (1994) used a cueing paradigm with a double-rectangle display to demonstrate the coexistence of location- and object-based attention. They presented two outlined rectangles, with one end of one rectangle brightened as a cue to indicate the possible location of a target. The target was a small solid square, shown subsequently within one end of a rectangle. Location-based attention was indicated by the *spatial-cueing* effect: RTs were shorter when the target appeared at the cued location than uncued locations. Object-based attention was indicated by the *same-object advantage*: RTs were shorter when the target appeared at the uncued end of the *cued* rectangle than at the *uncued* rectangle, with an equal cue-to-target distance between the two. Concurring with Egly et al., a series of studies using various stimuli and tasks has demonstrated the spatial-cueing effect and the same-object advantage (e.g., Abrams & Law, 2000; Brown, Breitmeyer, Leighty, & Denney, 2006; Lamy & Tsal, 2000; Matsukura & Vecera, 2006; Moore & Fulton, 2005; Moore et al., 1998; Shomstein & Behrmann, 2008).

The *spreading hypothesis* has been proposed to explain the same-object advantage (e.g., Richard et al., 2008; Kasai & Kondo, 1997; Davis & Driver, 1997). The spreading hypothesis states that when attention is cued to a location within an object, attention will spread automatically from the cued location to the whole object. Such spread of attention allows the participant to have a better visual performance to a target within the cued object than the uncued object. Since the attentional modulation is triggered by a location cue and spreads to the whole object, the same-object advantage should be an instance of location-based attention. That is, the underlying mechanism of object-based attention is the same as that of location-based attention. In addition, it is shown that improvement of visual performance in a location-based attention task can be due to (a) the participant being more sensitive to a target at the cued location than that at the uncued one; and/or (b) the participant being less influenced by irrelevant visual information (Lu & Dosher, 1998). Hence, these two factors should be able to account for object-based attention as well, if it shares the same mechanism as location-based attention.

On the other hand, Shomstein and Yantis (2002) proposed the *prioritization hypothesis* to explain the same-object advantage. This hypothesis suggests that object-based attention reflects a specific attentional prioritization strategy rather than the modulation of an early sensory enhancement extending from the location-based attention. Accordingly, the prioritization hypothesis does not stand on a specific position regarding the similarity of the mechanisms between location- and object-based attention. At best, it would predict different mechanisms for the *exogenous* spatial-cueing effect and the strategically object-based scanning strategy. Therefore, the same-object advantage cannot be explained by a change in early sensory mechanisms.

Here, we are interested in the mechanisms that subserve location- and object-based attention, especially whether the mechanisms underlying these two types of attention are the same. Notice that previous investigations adopting the double-rectangle method generally used reaction time measurement with a single level of task difficulty (e.g., Abrams & Law, 2000; Brown et al., 2006; Egly et al., 1994; Lamy & Tsal, 2000; Moore & Fulton, 2005; Moore et al., 1998; Shomstein & Behrmann, 2008). Reaction time measurement may reflect increased processing speed, response biases, or a combination of the two (Ratcliff, 1978), making it hard to infer the underlying mechanisms. In addition, while an estimation of response variability is important to evaluate certain theories of location-based attention (Lu & Dosher, 1998), it is difficult to separate measurement error from the experimental procedure and the variability of the internal responses in the reaction time measurement.

Therefore, in this study, we used a noise-masking paradigm (Legge, Kersten, & Burgess, 1987; Lu & Dosher, 1998; Nagaraja, 1964; Pelli, 1991) that can evaluate the variability in the response of the visual system in the double-rectangle method to examine the mechanism(s) of location- and object-based attention. In a typical noise-masking paradigm, the task of the observer is to detect a pre-designated target that is superimposed on a patch of white noise. In the context of our experiment, the target was a periodic pattern defined by Gabor function—which is a product of a sine wave and a Gaussian envelope—while the noise was a random modulation of luminance. The intensity of the noise mask was defined by contrast—the maximum luminance modulation in the mask divided by the mean luminance. By systematically measuring the target threshold at different external noise levels, we can measure *the threshold versus external noise contrast (TvC) functions*. This information allows an estimation of the response properties and variability of the target detection mechanisms, thus providing a more comprehensive estimation of various perceptual mechanisms (Chen & Tyler, 2001; Legge et al., 1987; Lu & Dosher, 1998; Nagaraja, 1964; Pelli, 1991; Wu & Chen, 2010). Figure 7 shows examples of how TvC function might be affected by different attention conditions. If the TvC functions of attended and unattended conditions are horizontally shifted copies of each other (Figure 7A)—that is, the same external noise level can have different effects in the attended and unattended conditions—this suggests that attention allows the participants to exclude irrelevant information (i.e., noise) in the stimuli more easily. On the other hand, it is possible that the TvC functions of attended and unattended conditions are *vertically* shifted copy of each other (Figure 7B). That is, the same target would have different thresholds in the attended and unattended conditions. This suggests that the participant has a different sensitivity to the target. Hence, the effect of attention is to enhance the sensitivity to the target.

By taking advantage of the double-rectangle method, we evaluated the TvC functions of attended and unattended location/object within a single paradigm. The participants were required to detect a Gabor target superimposed on a noise pattern (mask) in a two-alternative intervals choice task (Figure 8). The displays consisted of two vertical rectangles (outline drawing), one on each side of fixation. Four possible locations of cue (or target) are at the ends of the rectangles. The target occurred at either (a) the cued location (the *valid* condition); (b) the uncued location but within the cued object (the *same-object* condition); or (c) an equidistant location within the uncued object (the *different-object* condition). Then, we measured the TvC functions for all the different conditions so that we can compare location- and object-based attention and infer their mechanisms directly. If their mechanisms are identical, they should show the same kind of shift in the TvC functions.

Results

Figure 9 shows the result averaged across three participants. The blue circles and solid curve denote the TvC function for the valid condition; red squares and dash curve, the same-object condition; and green triangles and dash-dot curve, the different-object condition. To account for the individual difference in overall sensitivity to the target, we scaled each threshold by that measured at zero noise contrast of the valid condition of the corresponding participant before averaging. When there is no noise mask, the threshold for the valid condition is lower than that for both invalid conditions. The difference was 2 dB ($t(2) = 3.46$, $p = .037 < .05$) between the valid cue and both the invalid conditions. Such difference between the valid and invalid conditions remained as the mask increased. Thus, the TvC functions of the invalid conditions look like a vertically shifted copy of the valid condition on log-log coordinates. Such general facilitation on target detection suggests that the effect of the valid cue was to increase the sensitivity to the target (Chen & Tyler, 2010; Cohn & Lasley, 1974; Foley & Schwarz, 1998; Lu & Dosher, 1998; Pestilli & Carrasco, 2005; Zenger, Braun, & Koch, 2000).

The target detection thresholds were not influenced by the low contrast noise mask for all attention conditions. As a result, all TvC functions were flat at low noise contrasts. When the noise contrast reached a critical value, the threshold began to increase with noise contrast. Here, whether or not the cue and the target were within the boundary of an object had an effect. The threshold increment for the different-object condition started at a lower noise contrast than that for the same-object condition. As a result, the TvC function for the different-object condition showed a leftward shift from the TvC function for the same-object condition. This suggests that the noise effect on target detection in the same-object condition is different from that in the different-object condition.

Model

We fitted the TvC functions by a version of the divisive inhibition model (Chen & Foley, 2004; Foley, 1994; Meese, Summers, Holmes, & Wallis, 2007; Ross & Speed, 1991; Snowden & Hammett, 1998; Teo & Heeger, 1994; Watson & Solomon, 1997; Wilson & Humanski, 1993) modified to account for the noise-masking experiment (Chen & Tyler, 2010; Goris, Wagemans, & Wichmann, 2008; Lu & Dosher, 1998). Chen and Tyler (2010) and Lu and Dosher (1998; 2000) used a similar model to account for the cueing effect in a noise-masking paradigm. Figure

10 shows a diagram of this model. This model contains several stages: The first stage is a band of linear filters, each with its own orientation and spatial frequency tuning and location selectivity. The excitation of a linear filter is then half-wave rectified, raised to a power and scaled by a divisive inhibition input to form the response of the target detector. The decision variable is the ratio of the response of the target detector and the noise from different sources.

The first stage of each mechanism j is a linear operator within a spatial sensitivity profile $f_j(x,y)$. The excitation of this linear operator to the i-th image component $g_i(x,y)$ is given as

$$E_{ij}' = \Sigma_x \Sigma_y f_j(x,y)\, i_i(x,y) \qquad (1)$$

where the linear filter fj(x,y) is defined by a Gabor function (see Methods section) . Suppose that the image component $g_i(x,y)$ has a contrast C_i. Summing over x and y, Eq. (1) can be simplified to

$$E_{ji}' = Se_{ji} C_i \qquad (1)'$$

where Se_{ji} is a constant defining the excitatory sensitivity of the mechanism to the stimulus (j = t for the target and j = m for the mask). Detailed derivation of Eq. (1)' from Eq. (1) has been discussed elsewhere (Chen, Foley, & Brainard, 2000; Chen & Tyler, 1999).

The excitation of the linear operator is half-wave rectified (Foley, 1994; Foley & Chen, 1999; Teo & Heeger, 1994) to produce the rectified excitation E_{ji}

$$E_{ji} = \max(E_{ji}',0) \qquad (2)$$

where max denotes the operation of choosing the greater of the two numbers.

The response of the j-th detector is the excitation of the j-th filter, E_j, raised by a power p, in which $E_j = \Sigma_i E_{i,j}$ is the sum of excitations produced by all image components, and is then divided by a divisive inhibition term I_j plus an additive constant z. That is,

$$R_j = E_j^p / (I_j + z) \tag{3}$$

where I_j is the summation of a non-linear combination of the excitations of all relevant mechanisms to mechanism j. This divisive inhibition term I_j can be represented as

$$I_j = \Sigma_i (Si_{j,i}\ C_i)^q \tag{4}$$

where $S_{j,i}$ is the weight of the contribution from each component to the inhibition term. Here, we assume that the noise mask produces little excitation in the target and, in turn, negligible contribution.

The contribution of a detector to the visual performance is limited by the noise. We consider two sources of noise in this model: the internal noise inherited in the system, and the external noise provide by the noise patterns. The variability of the internal noise, σ_a^2, is a constant for all detectors in the model. The variability of the external noise, σ_e^2 is proportional to the square of the contrast noise mask; that is, $\sigma_e^2 = w_m * C_m^2$, where w_m is a scalar constant that determines the amount of contribution of the noise mask to the variance of the response. Pooling these two noise sources, the variance of the response distribution in each detector is

$$\sigma_r^2 = (\sigma_a^2 + \sigma_e^2) \tag{5}$$

In the context of our experiment, the observer compared the response to the stimuli in both intervals at the three possible target locations. The observer can detect the target if the difference between the response to the target+mask, $R_{j,\ t+m}$, and that to the mask alone, $R_{j,m}$, is greater in at least one channel than is the limitation imposed by the noise. In practice, we need to consider only the mechanism that produces the greatest response difference between the target+mask and the mask alone conditions. Thus, we can drop the subscript j for this study. That is, the decision variable d’ is,

$$d' = (R_{m+t} - R_m) / (2\sigma_r^2)^{1/2} \qquad (6)$$

The threshold is defined when d’ reaches unity.

Table 1 shows the parameter of the model. To reduce the mathematical redundancy in the model, we fixed the sensitivity to the target, Se_t, for the valid cue condition to be 100 and the size of the internal noise, σ_a^2 to be 1. As shown in the Results section, the TvC functions for the invalid conditions are vertically shifted copies of the valid condition on log-log coordinates. This suggests the sensitivity to the target, Se_t, to be different for the valid and invalid conditions. The TvC function for the different-object condition shifted to the left from that of the same-object condition. This suggests that the contribution of the external noise to the response variance, w_m, to be different in the same-object and the different-object conditions. Notice that in the valid condition, the target and the cue were also presented within the boundary of the same object. Therefore, we constrained all parameters to be the same across conditions except for sensitivity to the target, Se_t, and the contribution of the external noise, w_m. This model fits the data well; the root of mean squared error (RMSE) was 0.27. This model explains 98.61% of all variance in the averaged data.

Table 1
The estimated parameters of the model.

	Conditions		
	Valid	Same-Object	Different-Object
Se_m	2.47	2.47	2.47
Se_t	100*	93.99	93.99
Si_t	308.75	308.75	308.75
z	1.62	1.62	1.62
w_m	5.71	5.71	11.48
σ_e	1*	1*	1*
p	3.11	3.11	3.11
q	2*	2*	2*

Note: * Fixed value, not afree parameter.

To further validate our interpretation of the data, we tried various constraints to the model. If we constrained the sensitivity to the target, Se_t, to be the same for all conditions, the sum of squared error (SSE) of the model increased significantly [$F(1,12) = 73.82$, $p < .0001$] even when we took the number of free parameters into account. Similarly, constraining the contribution of the external noise, w_m, to be the same for both invalid conditions significantly increased the SSE [$F(1,12) = 16.63$, $p = .0015 < .05$]. Therefore, the change of sensitivity to the target is necessary to explain the spatial-cueing effect while the change of the contribution of the external noise is necessary to explain the same-object advantage. We also found that more free parameters in the model never produced a significant improvement of goodness-of-fit. Thus, no extra factors are necessary to explain our results.

Discussion

The current study systematically probed the target threshold improvement by location- and object-based attention with different noise levels using the double-rectangle method, and the results suggest that location- and object-based attention involve different mechanisms. Location-based attention operates by enhancing signal strength, whereas object-based attention operates by excluding external noise. This study is the first to demonstrate the discrepancy in the TvC functions of location- and object-based attention within a single task.

In previous studies, location- and object-based attention were examined separately by the noise-masking paradigm. Location-based attention was observed in both no-noise and high-noise conditions (Dosher & Lu, 2000; Lu & Dosher, 2000), consistent with our results here. However, Han, Dosher, and Lu (2003) found that object-based attention is also observed in both no-noise and high-noise conditions, inconsistent with our findings here. Notice that Han et al. (2003) compared the performances of tasks that required participants to attend to only *one* object versus *two* spatially separated objects. Object-based attention was indexed by higher accuracy of reporting two attributes belonging to a single object than different objects, and it was shown in both no- and high-contrast noise conditions in Han et al.'s study. It is reasonable to argue that their participants may have changed their attentional window—like a zoom lens (Eriksen & Yeh, 1985)—from "wide" in the two-object condition to "small" in the single-object condition. Accordingly, the differences between the two-object and single-object conditions not only are the number of attended objects but also the size of spatial attention (Davis, Driver, Pavani, & Shepherd, 2000).

This argument is supported by a study with an identical design as Han et al.'s (2003). The magnitude of the same-object advantage was modulated by the required precision of judgments: The higher the task precision, the larger the difference in performance between the two-object and the single-object conditions (Liu, Dosher, & Lu, 2009). Assuming that attentional window is wide in the two-object condition, the density of attentional resource should be low due to the reciprocal relationship between size and density of attentional distribution (Eriksen & St. James, 1986; LaBerge & Brown, 1989). The low-precision task that requires less resources can be performed equally well with less attentional resource in the two-object condition as opposed to the one-object condition—leading to reduced or no same-object advantage. The critical comparison in their study—two-object and single-object conditions—may not reflect object-based attention but rather a change in the window size of spatial attention. Indeed, the modulation pattern of "object-based" attention in Han et al.'s study is similar to the modulation pattern of location-based attention (Dosher & Lu, 2000; Lu & Dosher, 2000): Both can be observed in no-noise and high-noise conditions. However, the double-rectangle method compares the same-object and different-object conditions based on an equal cue-to-target distance between the two conditions; in using the double-rectangle method, we rule out the confounding of location-based attention in the current study and find that object-based attention is observed only in high-noise conditions, indicating that external noise exclusion plays a critical role in object-based attention.

The qualitative difference between the intrinsic mechanisms of location- and object-based attention suggests that object-based attention is not an outcome of the spreading from the location-based attention, which is a finding arguing against the well-accepted *spreading hypothesis* (e.g., Davis & Driver, 1997; Kasai & Kondo, 1997; Richard et al., 2008). Instead, we suggest that object-based attention might reflect attentional orienting that is independent of location-based attention rather than the modulation of an early sensory enhancement extending from the location-based attention. This argument is also against the *prioritization hypothesis* proposed by Shomstein and Yantis (2002), who claim that object-based attention reflects strategic prioritization regardless of location-based effects and neither is it due to object-based perceptual enhancement. However, using the noise-masking paradigm, we provide evidence for the underlying mechanism of object-based attention. The current finding of the leftward-shifted copies of the TvC functions in the same-object and different-object conditions suggests that the underlying mechanism of object-based attention is to exclude external noise, an evidence of object-based perceptual enhancement.

Conclusion

The current study measured the thresholds in different levels of task difficulty and revealed the underlying mechanisms of location- and object-based attention—which are difficult to evaluate from conventional reaction time measurements—and sheds a new light to current theories of object-based attention. Here, we overturn two widely accepted theories that object-based attention is due to the "spread" or "prioritization" of attention. In addition to revealing the underlying mechanisms of location- and object-based attention, the current finding fills the gap between previous physiological (Fink, Dolan, Halligan, Marshall, & Frith, 1997; He et al., 2008; He et al., 2004; Wager et al., 2004) and behavioral evidence (Chou & Yeh, 2008; Matsukura & Vecera, 2009; List & Robertson, 2007; Shomstein & Yantis, 2004) that have demonstrated the discrepancy in location- and object-based attention by providing important convergent evidence from a novel aspect using the noise masking paradigm to the double-rectangle method.

Materials and Methods

Ethics Statement

The use of human participants was approved by the IRB of National Taiwan University Hospital and followed the guideline of Helsinki Declaration. The written informed consent was obtained from each participant.

Apparatus

The stimuli were presented on two Viewsonic 15-in. CRT monitors, each driven by a Radeon 7200 graphic board, which provided 10-bit digital-to-analog converter depth. A Macintosh computer controlled the graphic board. Lights from the two monitors were combined by a beam splitter. This two-monitor setup allowed us to present the target on one monitor and the cue and the external noise patch (mask) on the other. This arrangement provided the advantage of independent control of the contrast of the target while ensuring that the context (the cue and the external noise patch) was identical in two intervals of a trial. The viewing field was 10.7° horizontal by 8° vertical. The resolution of the monitors was 640 horizontal by 480 vertical pixels, giving 60 pixels per degree at a 128 cm viewing distance. The refresh rate of the monitors was 66 Hz. We used the LightMouse photometer (Tyler & McBride, 1997) to measure the full-detailed input-output intensity function of the monitors. This information allowed us to compute linear lookup table settings to linearize the output within 0.2%. The mean luminance of the displays was 74.9 cd/m^2.

Stimuli and Display

Figure 8 illustrates the stimuli and sequence of events for a trial. The displays are comprised of a pair of adjacent vertical rectangles. The fixation was a small dot. Each rectangle (1.63° × 4.88°, with a stroke width 0.13°) was centered 3° from fixation. The cue and the target were all Gabor patches (1.3 cycle/deg vertical Gabor) defined by the equation:

$$G(x,y,c,u_x,u_y) = L + L*c*\cos(2\pi f x)*\exp(-\frac{(x-u_x)^2}{2\sigma^2})*\exp(-\frac{(y-u_y)^2}{2\sigma^2}),$$

where L was the mean luminance, c was the contrast of the pattern ranging from 0 to 1, f was the spatial frequency, σ was the scale parameter (standard deviation) of the Gaussian envelope, and u_x and u_y were the horizontal and the vertical displacements of the pattern, respectively. Both patterns had a spatial frequency (f) of 1.3 cycles per degree and a scale parameter (σ) of 0.3536°. Both cue and target were vertically oriented. The contrast of the cue (c) was -6 dB or 0.5. The pixel gray-levels of each external noise frame were sampled from a Gaussian distribution.

Procedure

A two-alternative intervals choice paradigm was used to measure the target threshold (illustrated in Figure 8). For each trial, the cue was presented randomly at one of four possible locations in each interval. The target was presented at (a) the cued location (valid trials); (b) uncued end within the cued object (same-object trials); or (c) uncued end within the uncued object (different-object trials) in one of the intervals. The display sequence of each interval was as follows: (a) a fixation display consisted of a central fixation point and two outline rectangles; (b) a 16-ms cue display; (c) a 64-ms fixation display; and (d) a 96-ms target display containing a target and four mask patches. The cue-to-target stimuli onset asynchrony (SOA) was 80 ms. The inter-stimuli-interval (ISI) within a trial was 600 ms and the inter-trial-interval (ITI) was 800 ms. An audio tone indicated the beginning of each trial. Auditory feedbacks were provided for a correct response and an incorrect response.

There were three attention (valid, same-object, and different-object) conditions within each block of seven external noise levels ($-\infty$, -26, -22, -18, -14, -10, -6 dB), and the sequence of blocks was in random order. We used the PSI threshold-seeking algorithm (Kontsevich & Tyler, 1999) to measure the threshold at 75% correct response level. There were 40 trials following two practice trials for each threshold measurement. Four thresholds within a single block—two for the valid condition, one for the same-object and one for the different-object conditions—were measured in an interleave way within one block. This arrangement let the total number of valid trials (84 trials) twice as many as the total number of the same-object or different-object trials (42 trials) in a single block. Therefore, the spatial cue predicted the target location with 50% validity within every single block. The sequence of trials within a single block was pseudo-randomized: each four trials contained two valid trials, one same-object trial, and one different-object trial with a random sequence for the four trials. The TvC function of the valid condition is the average of two threshold measurements of valid condition within each single block. Each data point reported was an average of four to eight repeated measures. Participants were well informed about the relationships between the cue and the target, and they also were told that the two outline rectangles were task-irrelevant. The task was to determine which interval contained the target and to press a corresponding key of a computer keyboard.

Participants

Three observers participated in this study. WL is an author of this article, and RY and TH were paid participants who were naïve as to the purposes of this study. All participants had normal or corrected-to-normal visual acuity. The trials took about 10 hours, divided into three or four periods, for each participant. During the experiments, participants could take a brief rest at any time they needed one.

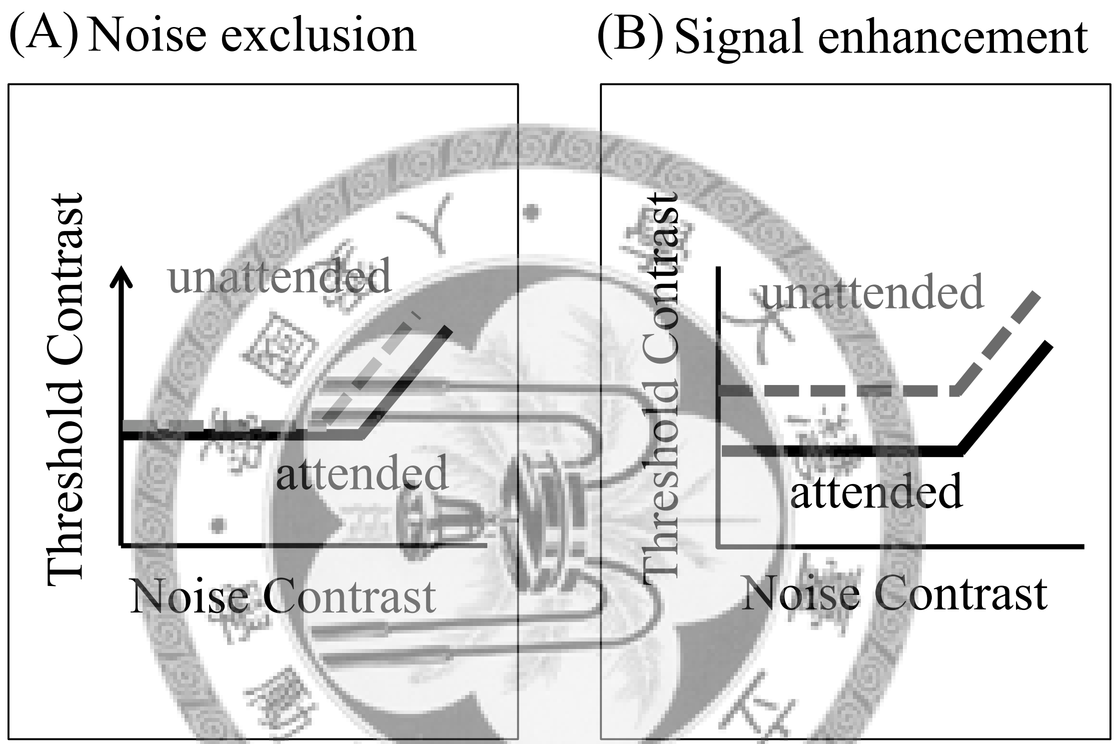


Figure 7. Performance signatures in threshold contrast versus external noise contrast (TvC) functions (Chapter 4). (A) Suppose that the TvC functions for the attended condition (solid line) is a rightward-shifted copy of the unattended (dashed line) condition. It means that the same external noise level can have different effects on target detection in the attended and unattended conditions. This suggests that attention allows the participants to exclude noise in the stimuli more easily. (B) If the TvC functions are a vertically shifted copy of each other—that is, the same target would have different thresholds in the attended and unattended conditions—this suggests that the participant has a different sensitivity to the target in the two conditions. Hence, the effect of attention is to enhance the sensitivity to the target.

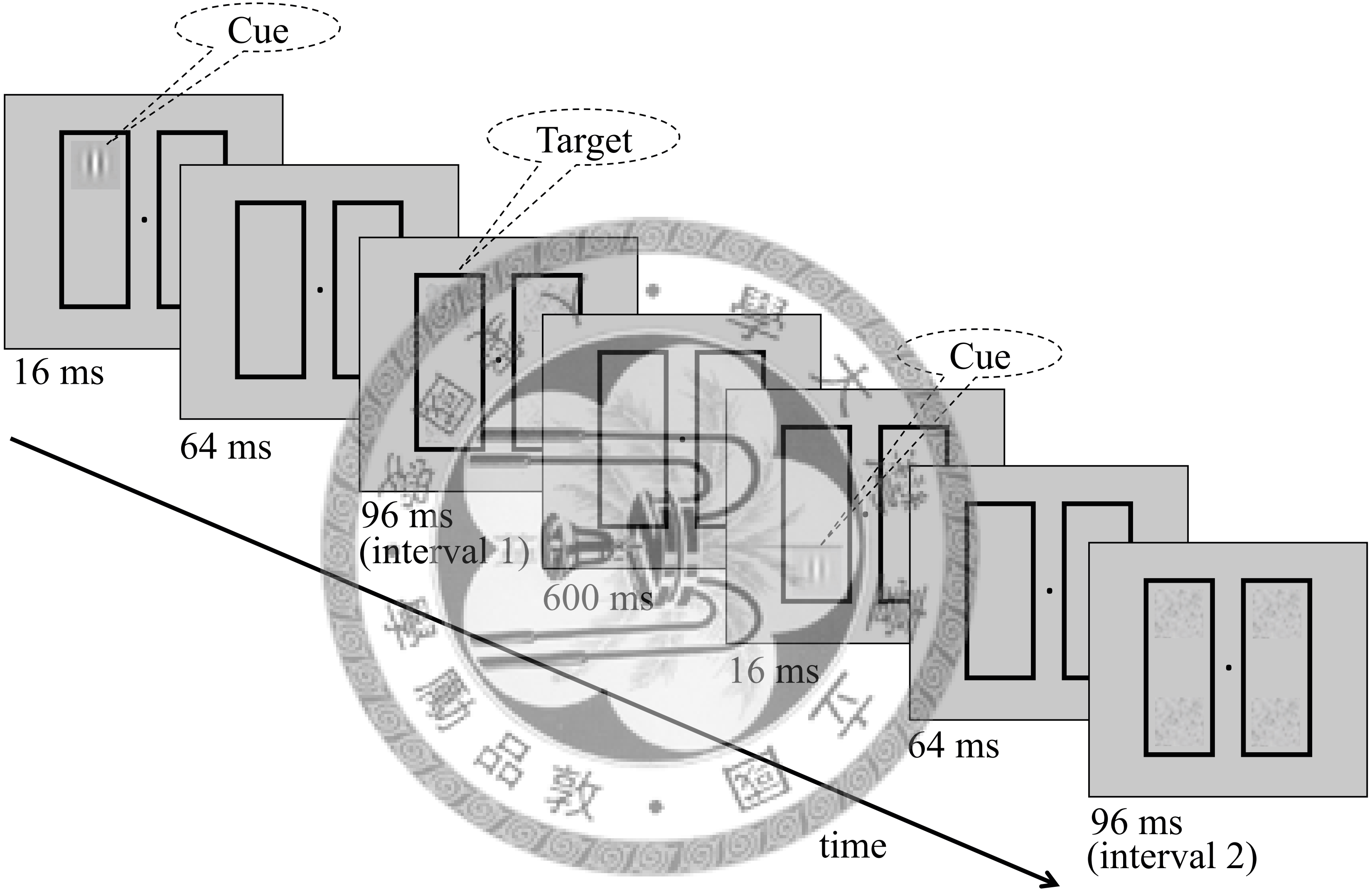


Figure 8. Schematic overview of a typical valid trial with the target showing in interval 1 (Chapter 4). The task was to detect the target (a Gabor patch) superimposed on different levels of noise (mask) contrast in a two-alternative forced-choice paradigm. In each interval, a cue was flashed first for 16ms, followed by a 65 ms blank, and then a stimulus presentation (either target-plus-noise mask or noise mask alone). Two intervals were separated by a 600 ms blank. The rectangles and the fixation point were always onscreen.

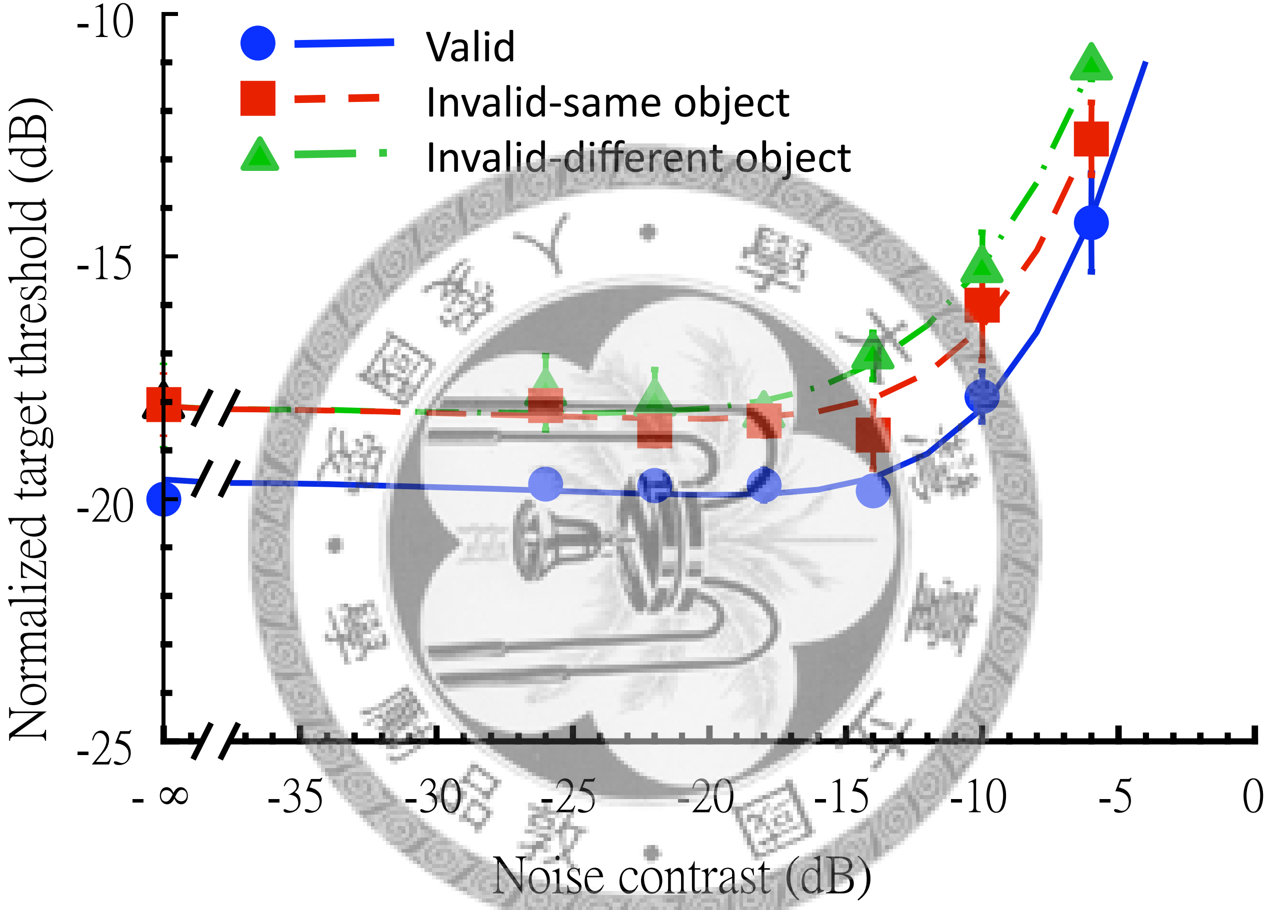


Figure 9. Target threshold versus noise contrast functions (Chapter 4). Each data point represents the average of the normalized threshold from three observers. The blue circles and the solid curve denote the TvC function for the valid condition; the red squares and the dashed curve, the same-object condition; the green triangles and the dash-dot curve, the different-object condition. The smooth curves are fits of the model discussed in the text. The error bars are the estimated one standard error of normalized individual difference.

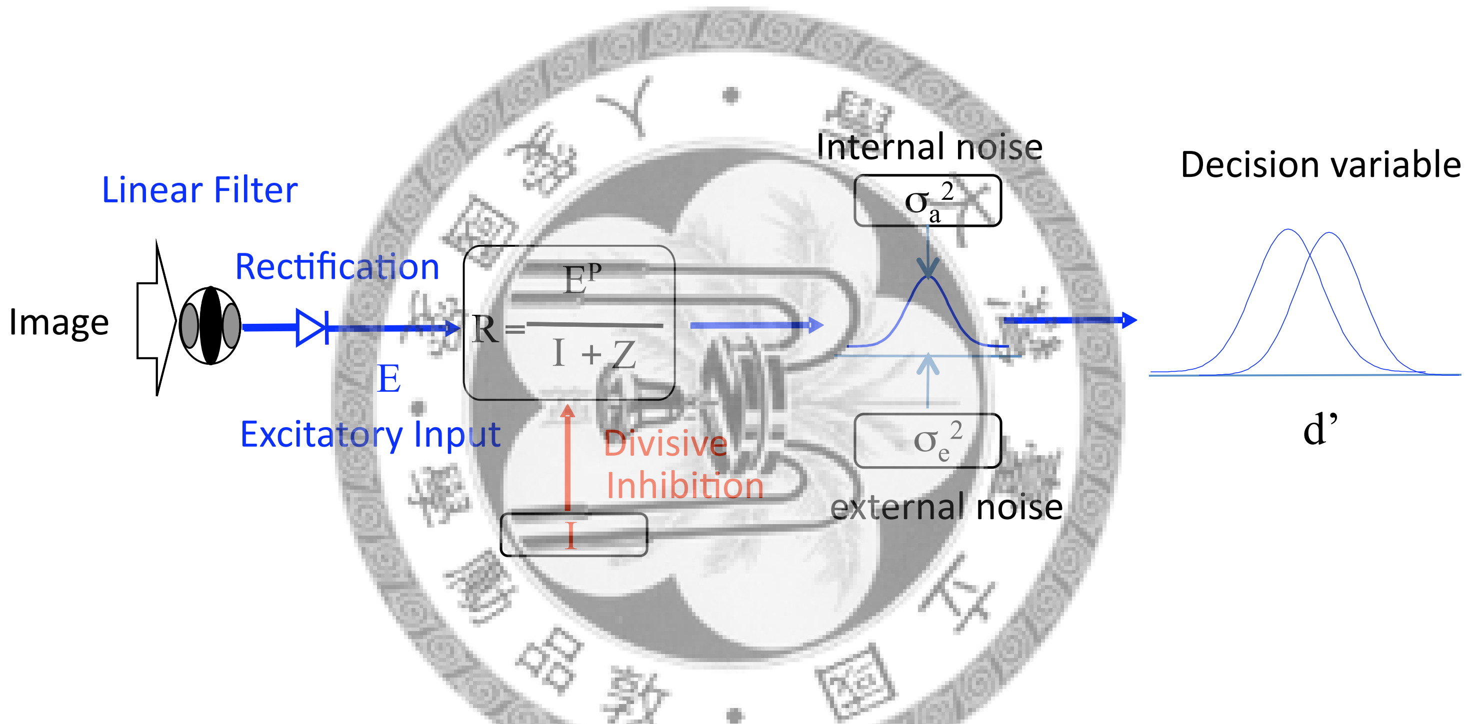


Figure 10. Diagram of the model used to fit the data (Chapter 4). See text for details.

Chapter 5

Location- and Object-Based Inhibition of Return are Affected by Different Kinds of Working Memory

Chou, W. L., & Yeh, S. L. (2008). Location- and object-based inhibition of return are affected by different kinds of working memory. *Quarterly Journal of Experimental Psychology, 61*, 1761-1768.

Abstract

Castel, Pratt, and Craik (2003) have shown that inhibition of return (IOR, the delayed response to a recently cued item) is disrupted by a secondary task that involves spatial working memory (WM), and they suggest that IOR is mediated by spatial WM. However, they did not specify what kind of IOR was involved. We used a dual-task paradigm to examine whether the two kinds of IOR (location- and object-based IOR) are affected by two kinds of secondary task that involve spatial and non-spatial WM, respectively. The results show that location-based IOR was disrupted by a spatial secondary task while the object-based IOR was disrupted by a non-spatial secondary task. The present study further elaborates the conclusion of Castel et al. (2003) by differentiating the effect of the two kinds of WM (spatial vs. non-spatial) on the two kinds of IOR (location based vs. object based).

Introduction

When you search for a pen on your desktop, the best strategy is to remember where you have already looked and not search there again. Human behaviour observed in psychological experiments reveals a phenomenon similar to this strategy. Inhibition of return (IOR; Posner, Rafal, Choate, & Vaughan, 1985) refers to the increased reaction time (RT) when a target appears at a recently cued location. This phenomenon was first demonstrated by Posner and Cohen (1984). They used three outlined boxes with the central box as a fixation and brightened the left or right box briefly as a non-informative peripheral cue. Compared to RT in detecting the target at the uncued box, they found a facilitatory effect (i.e., shorter RT) when the cue-to-target stimulus onset asynchrony (SOA) was shorter than 150 ms and an inhibitory effect (i.e., longer RT) when the SOA was longer than 300 ms. The initial RT benefit was explained by the summoning of attention to the cued location, replaced by a subsequent inhibition to the previously cued location after attention had returned to the central fixation. Although earlier studies (e.g., Posner & Cohen, 1984) emphasized that it was the cued location that was inhibited (but see Tipper, Weaver, Jerreat, & Burak, 1994), recent studies have shown that IOR can also be object based (e.g., Chou & Yeh, 2005; Gibson & Egeth, 1994; Jordan & Tipper, 1998; Tipper et al., 1991).

Tipper et al. (1991) first demonstrated object-based IOR in a dynamic display by using two objects rotated around an imaginary circle. The cued object rotated from its original location, and the inhibition associated with it was also shown to move. However, Schendel, Robertson, and Treisman (2001) note that the objects used in this experiment retained their relative locations topologically while rotating around the fixation point. Thus, the objects may simply help to set up a frame of reference in which attentional orienting operates on relative locations, but not on objects. Such a dynamic display has also been criticized as being confounded with the left-to-right attentive tracking strategy, and object-based IOR was found only under certain experimental conditions (Muller & von Muhlenen, 1996).

There are also studies that have shown object-based IOR in static displays. Jordan and Tipper (1998) found that the magnitude of IOR of an object was significantly larger than that of an empty location. They interpreted their results with the view that when objects are cued, both location and object-based IOR can operate, while when only locations are cued only location-based IOR is involved. As they have admitted, these displays were unavoidably associated with space representation as well as object representation.

In our previous study (Chou & Yeh, 2005), we used overlapping objects to avoid interference from location-based effects (e.g., Duncan, 1984; Haimson & Behrmann, 2001) and successfully demonstrated that object-based IOR can occur for spatially overlapping objects. Using overlapping objects to probe object effect has an important advantage, in that location effects are undifferentiated or operate equally across objects. Additionally, using overlapping objects is justifiable on ecological grounds: The retinal images of many real-world objects are usually overlapped.

Notably, IOR can occur with SOA as long as three seconds (e.g., Samuel & Kat, 2003; Tipper, Grison, & Kessler, 2003): With such a long duration some memory process must be involved in maintaining the information. Indeed, Castel et al. (2003) found that a secondary task disrupts IOR, but only when the secondary task involved spatial, as opposed to non-spatial, working memory (WM). Based on this they suggested that IOR is mediated by a spatial WM system.

Note that Castel et al. (2003) used outline boxes as placeholders, and thus their participants may have viewed these boxes as locations, objects, or both (Tipper et al., 1994). In other words, location- and object-based IOR cannot be differentiated in such displays. A question that naturally follows is whether the two kinds of IOR are both mediated by spatial WM. Because location-based IOR relies on memory of spatial information, spatial WM is critical. In object-based IOR, which is revealed when spatial information is irrelevant (e.g., Chou & Yeh, 2005; Tipper et al., 1991), non-spatial WM is more likely to be involved.

Accordingly, we hypothesized that location-based IOR is mediated by spatial WM, and object-based IOR is mediated by non-spatial WM. We adopted a dual-task paradigm based on the assumption that if adding a secondary task interferes with performance on the primary task, they must be competing for a single resource. We used two kinds of secondary task, such that one (the direction task) involved spatial WM while the other (the object task) did not. To examine the role of WM type on location- and object-based IOR, we designed two conditions suitable for probing the effect of each, rendering a 2 × 2 design: two types of task versus two kinds of IOR. It was predicted that the direction task would disrupt location-based IOR only, and the object task would disrupt object-based IOR only.

Experiment 1

The display for probing object-based IOR consisted of two overlapping triangles (Figure 11A), while that for probing location-based IOR consisted of six dots (Figure 11B), removing the lines in the triangles display. The participants were told that there were two triangles or six marked locations, depending on the experiment, and post-experiment inquiry confirmed that they treated the triangles as individual objects and the dots as locations.

A luminance change detection task was used as the primary task throughout. In addition, two types of secondary task were used: a direction task, in which the participants reported the direction of the to-be-remembered item, and an object task, in which the participants were required to memorize its identity.

Method

Participants

A total of 160 undergraduates of National Taiwan University participated in eight experiments (1a–1h; $N = 20$ for each experiment) in exchange for course credit. All reported normal or corrected-to-normal vision and were naive as to the purpose of these experiments.

Stimulus materials

Stimulus presentations were controlled by an IBM 486 personal computer and were presented on a 14'' ViewSonic monitor. The computer program DMDX (Forster & Forster, 2003) was used to present the stimuli and to collect the RT data. Participants sat at a viewing distance of 60 cm in a dimly lit chamber, with their heads supported by a chinrest.

The two kinds of display (triangles, dots) were crossed with the two kinds of secondary task (direction, object). Half the participants conducted one of the four dual-task experiments (Experiments 1a–1d), and the other half conducted one of the four single-task controls (Experiments 1e–1h). In the control experiments, only the main task, in which all stimuli were the same as those in their comparable dual-task experiments, was performed, and the participants were told to ignore the direction/object symbols.

In the triangles condition, the fixation display contained a central white cross (0.67° × 0.67°) and two overlapping outline (0.29° in width) triangles (9.46°/side), presented on a grey background. One of the triangles (randomly chosen) was green and the other red, and one was inverted and the other upright (also randomly chosen). On the corners of the triangles were three dots (0.95° in diameter), the same colour as the triangles. In the cue display, one of the triangles (and its end dots) was brightened; this was defined as the cued object. In the memory display, a rightward or a leftward arrow (3° × 0.95°) was presented for the direction task, whereas a dumbbell or a two-way arrow was presented for the object task. In the target display, one of the six dots was either brightened or dimmed. In the dots condition, the displays were the same as those in the triangles condition except that the lines joining the individual dots were removed.

Design

A cueing paradigm was used for the primary task, and we compared the RT obtained between valid and invalid trials. IOR was indexed by longer RT in valid trials. In the triangles condition, the target appeared on one of the three dots of the cued triangle (a valid trial), or on one of the three uncued-triangle dots (an invalid trial). In the dots condition, similarly, the target appeared on one of the three cued dots (a valid trial), or on one of the three uncued dots (an invalid trial).

Each experiment contained 96 trials, divided into four blocks of 24, with an equal number of valid and invalid trials. An effort was made to balance the possible combinations of target locations within each block. A total of 24 practice trials preceded the formal trials, and the participants were allowed to take short self-paced breaks between blocks.

Procedure

The participants initiated each block by pressing the space bar. At the beginning of each trial, an auditory tone (100 ms) and a fixation display (1,020 ms) were shown first, followed by the cue (255 ms), fixation (340 ms), memory (425 ms), fixation (340 ms), and target displays. The target display appeared at 1,360 ms SOA after the onset of the cue and stayed for 1,000 ms or until the participants responded, whichever happened first.

In Experiments 1a–1d (dual task), after the target display, the words "left or right?" or "dumbbell or two-way arrow?" were presented on the screen until a response was made. After the response, the entire display turned blank for an inter-trial interval (ITI) of 1,000 ms, and then the next trial began. The participants' primary task was to judge as quickly and accurately as possible whether the target was brightened or dimmed by pressing corresponding keys on the computer keyboard. They were informed that the cued object or location was not predictive of the subsequent target. In addition to the primary task, participants were asked to memorize the direction of the arrow (in the direction task), or the identity of the object (in the object task) and to press a corresponding key after responding to the primary task.

In Experiments 1e–1h (single task), the target display was followed by a blank for an ITI of 1,000 ms, and then the next trial began.

Results

RTs below 200 ms were excluded (less than 1%), and only trials with correct responses for both primary and secondary tasks were included in the analysis. Results are shown in Table 2. There was no speed–accuracy trade-off for the effects based on RT reported below, because there were no differences in error rates across conditions. As a baseline, all single-task experiments (1e–1h) showed longer RT in valid trials than in invalid trials—that is, IOR effects were obtained when no secondary task was performed, all Fs(1, 19) > 4, ps < .05.

In the dots condition, IOR (presumably location based) was obtained when the secondary task was an object task—Experiment 1b, $F(1, 19) = 6.53$, MSE = 167.96, $p < .05$—but not when it was a direction task—Experiment 1a, $F(1, 19)$ = 0.83, MSE = 289.01, $p > .1$. In the triangles condition, IOR (presumably object based) was found when the secondary task was a direction task—Experiment 1c, $F(1, 19)$ = 5.19, MSE = 256.33, $p < .05$—but not when it was an object task—Experiment 1d, $F(1, 19) = 0.99$, MSE = 119.05, $p > .1$.

Discussion

We obtained typical IOR effects in single-task conditions, as shown in many other studies (e.g., Chou & Yeh, 2005; Gibson & Egeth, 1994; Jordan & Tipper, 1998, 1999; Posner et al., 1985; Tipper et al., 1991). Most importantly, in the dual-task experiments, IOR was disrupted by a spatial WM task in the dots condition and by a non-spatial WM task in the triangles condition.

These results support our hypothesis: Location-based IOR and object-based IOR are mediated by spatial WM and non-spatial WM, respectively. The error rates between the direction-task and object-task conditions were equal, suggesting no difference in difficulty or memory load between the two secondary tasks.

However, up to this point the support for our hypothesis is given only by cuing effects in independent experiments and not by direct comparisons. To confirm the critical results directly, in Experiment 2 the secondary task type (direction or object) was varied within each participant.

Experiment 2

To compare the direction task condition with the object task condition within the same participant group, we designed the secondary task type as a within-subject factor, ensuring that any disparity between the two conditions would not be caused by individual differences. Also, we made some changes in the stimuli in order to further approximate typical location and object cueing paradigms.

Method

Participants

Two groups of 30 undergraduates each, with the same characteristics as those described in Experiment 1, participated in Experiments 2a and 2b.

Stimuli, design, and procedure

The stimuli and procedure were the same as those in Experiment 1 except for the following. In Experiment 2a, six green dots were presented, and one of the dots was cued by presenting a white dot (0.6 in diameter, Figure 11C). In the target display, one dot was brightened or dimmed. In Experiment 2b, we used three white Vs (0.1 in width) and white dots (0.6 in diameter) on the corners of one triangle as the cue display (Figure 11D). One of the triangles (and its end dots) was brightened or dimmed as the target display. Each participant performed the direction and object tasks in different blocks, in a counterbalanced order. Experiment 2a contained 216 trials, in which one sixth were valid trials. Experiment 2b contained 144 trials, in which half were valid trials. Trials were divided into six blocks, with three blocks of the direction task and three of the object task.

Results

RTs below 200 ms were excluded (less than 1%). Again, there was no speed–accuracy trade-off, because there were no differences in error rates across conditions (Table 2).

A repeated measure ANOVA with the within-subject factors of trial type (valid, invalid) and task type (direction, object) was conducted for Experiments 2a and 2b separately. In both experiments the main effects of trial type and the interaction effects of trial type and task type were significant, all Fs(1, 29) > 4, ps < .05. Simple main effects in Experiment 2a (dots display) showed that IOR (presumably location based) was obtained, $F(1, 58) = 13.7$, $MSE = 397$, $p < .001$, with an object task, but not with a direction task, F(1, 58) = 0.30, MSE = 397, $p > .5$. In Experiment 2b (triangles display), IOR (presumably object based) was obtained, $F(1, 58) = 11.07$, $MSE = 324$, $p < .005$, with a direction task, but not with an object task, $F(1, 58) = 0.008$, $MSE = 324$, $p > .5$.

To compare Experiments 2a and 2b, the data were submitted to a three-way ANOVA with the factors of trial type (valid, invalid), task type (direction, object), and display type (dots, triangles). The first two factors were within subject while the last was between subject. The three-way interaction was significant, $F(1, 58) = 9.25$, $MSE = 419$, $p < .005$, confirming that the two types of task affected the two types of

IOR differently.

Discussion

Experiment 2 replicated the results of Experiment 1. Since the task type was a within-subject factor in Experiments 2a and 2b, the result patterns in this study were not caused by individual differences. Again, error rates between direction task and object task conditions were equal. The two kinds of secondary task probed different kinds of WM but not degree of difficulty or memory load.

General Discussion

We used a dual-task paradigm to examine whether different kinds of IOR (location based vs. object based) are mediated by different kinds of WM (spatial vs. non-spatial). Our answer is "yes", based on the interaction of task type and display type that we found in this study. When participants needed to memorize the direction of an arrow, only location-based IOR was disrupted, while when participants needed to memorize the identity of an object, only object-based IOR was disrupted.

The disruption of location-based IOR by the direction task indicates that they compete for the same resource, possibly spatial WM. Castel et al. (2003) also showed that IOR was disrupted by a direction task, and they concluded that IOR was mediated by a spatial WM system. In addition to replicating their results, we also differentiate the effects of two kinds of WM on object-based IOR. This is important because it constrains their conclusions. Our finding that object-based IOR was disrupted by a non-spatial secondary task further indicates that object-based IOR is mediated by a non-spatial WM system.

One could argue that the participants might treat the dots as objects (rather than locations) and that the number of objects is a critical factor in determining what kind of WM is involved. Thus, spatial WM would be involved when there are many objects in the display (the dots), and non-spatial WM would be involved when the display contains a relatively small number of objects (the triangles). Although not entirely impossible, there is no a priori reason to assume that displays with more objects involve spatial WM while those with fewer objects involve non-spatial WM. Furthermore, the participants were told that there were marked locations in the displays, and we confirmed with them after completion of the experiment that they indeed viewed the triangles as two objects, and the dots as six locations.

One may also argue that it is the degree of stimulus complexity, not object versus location, which determines which kind of WM is involved. In other words, when the display is more complex (such as the triangles display), non-spatial WM is critical for IOR, but not spatial WM, and when the display is relatively simple (such as the dots display), spatial WM becomes critical. This argument makes the assumption that viewing more complex displays involves object representation and that object WM is operating to maintain such information. Again, although not impossible, complexity is an ill-defined concept that does not provide a noncircular explanation, let alone prediction. For example, the opposite case might also be true: that more (rather than fewer) complex displays involve spatial WM.

Using different displays such as dots and overlapping objects to probe location- and object-based effect separately is the first step toward examining the role of different types of WM in location- and object-based IOR. It is worth trying other displays for follow-up studies, such as the double-rectangle paradigm of Egly et al. (1994), which is useful to compare location and object effects in a single condition. Jordan and Tipper (1999) have used this paradigm by presenting two spatially separate rectangles with a peripheral cue appearing at one end of one rectangle. They found longer detection RT at the uncued end of the cued object than at that of the uncued object, demonstrating object-based IOR in static displays. Converging evidence may be sought by applying the two kinds of secondary task to the two kinds of IOR, as we have done in the current study.

To our knowledge, the present study is the first one to show a double dissociation pattern of location- and object-based IOR by manipulating different WM types, and it thus provides new insights into the mechanisms involved in each. It is possible that the inhibited location is held in spatial WM, such that intervening tasks using the same WM processes disrupt the trace of the inhibited location. In contrast, the inhibited object is held in a different form of WM, so that tasks involving non-spatial WM disrupt the trace of the inhibited object.

In conclusion, our findings further elaborate the results of Castel et al. (2003) by differentiating the effect of the two kinds of WM (spatial vs. non-spatial) on the two kinds of IOR (location based vs. object based) and suggest that the two kinds of IOR can operate differently within the WM system.

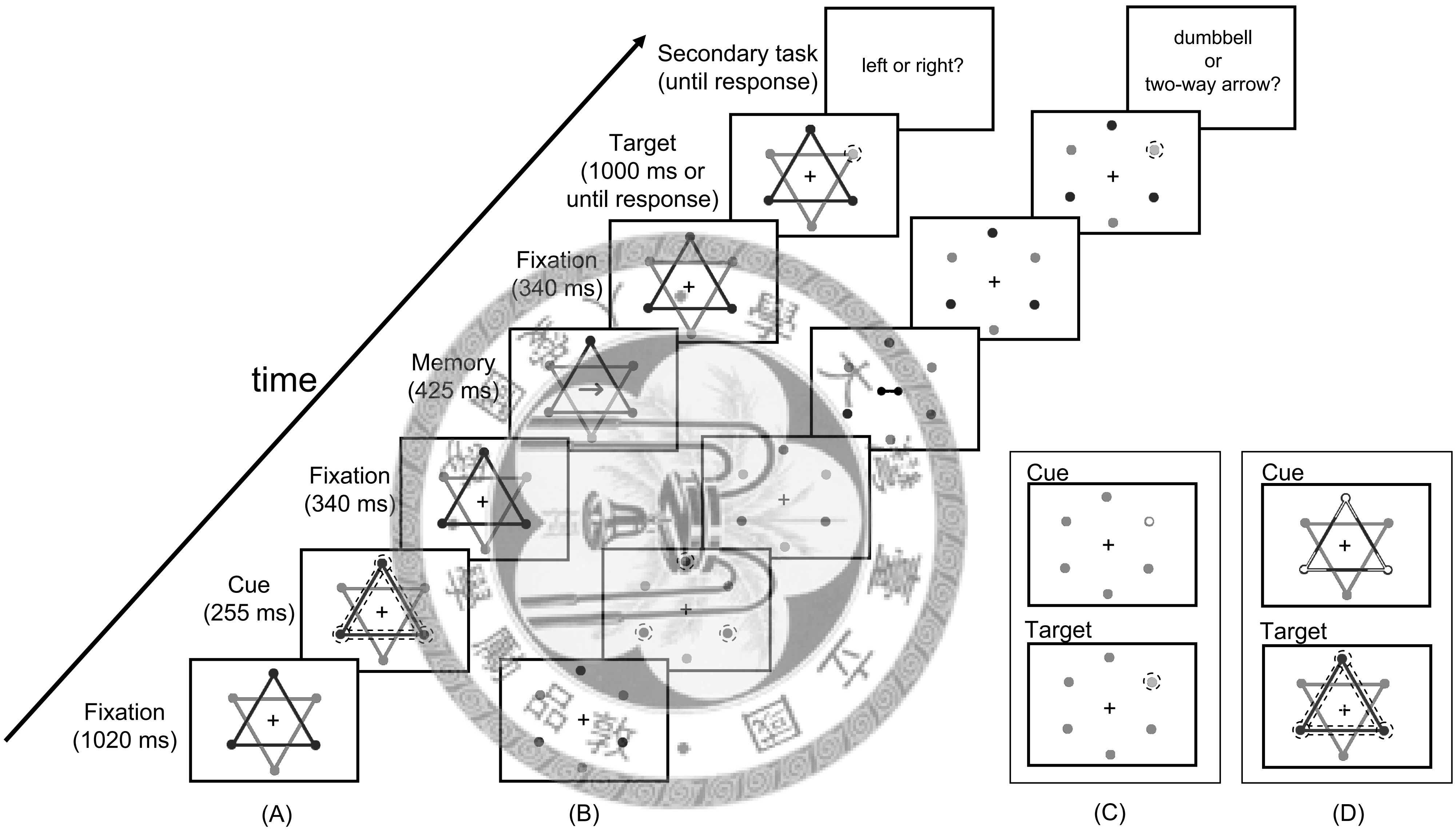


Figure. 11. Illustration of the display sequence (Chapter 5). (A) Experiment 1, the *triangles display*. (B) Experiment 1, the *dots display*. (C) Experiment 2, the *dots display* (the cue and the target). (D) Experiment 2, the *triangles display* (the cue and the target). The dotted lines (not shown in the experiment) denote the luminance enhancement. These examples are brightened-target trials.

Table 2.
Reaction time, percent error, IOR, and standard error of IOR in each experiment (Chapter 5)

	Valid	Invalid	IOR
	RT (PE)	RT (PE)	RT (SE)
Experiment 1			
Dual-task Experiments			
1a Dots/Direction Task	581 (12)	576 (11)	5 (5)
1b Dots/Object Task	552 (8)	541 (9)	11 (4)
1c Triangles/Direction Task	541 (7)	529 (6)	12 (5)
1d Triangles/Object Task	529 (7)	532 (6)	-3 (4)
Single-task Experiments (control)			
1e Dots/Direction Symbol	542 (11)	529 (9)	13 (5)
1f Dots/Object Symbol	496 (5)	484 (3)	12 (4)
1g Triangles/Direction Symbol	521 (7)	510 (5)	11 (5)
1h Triangles/Object Symbol	502 (5)	492 (4)	10 (5)
Experiment 2			
2a Dots/Direction Task	559 (5)	556 (5)	3 (5)
2a Dots/Object Task	572 (7)	553 (5)	19 (6)
2b Triangles/Direction Task	570 (5)	554 (7)	16 (5)
2b Triangles/Object Task	554 (5)	555 (5)	-1 (4)

Note: RT = reaction time (in ms); PE = percentage error; IOR = inhibition of return (in ms); SE = standard error.

Chapter 6

Optimizing Attention Deployment in Object-Based Attention: The Role of Cue Validity

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Abstract

We adopted the two-rectangle method (Egly et al., 1994) and manipulated the cue validity with respect to a particular location or the whole object. The results indicated a spatial-cueing effect and a same-object advantage with informative location-based and object-based cues, respectively (Experiment 1A and 2), and both spatial-cueing effect and same-object advantage when both kinds of cues were informative (Experiment 1B). Unlike previous studies in which the two kinds of cues were co-varied, this study differentiates the two, and the results obtained are inconsistent with either the spreading hypothesis or the prioritization hypothesis of object-based attention. As explained by our optimization hypothesis, we demonstrate here that the validity of the location cue is not the causal reason for the same-object advantage; object-based cue validity—the probability that the target will appear on the cued object as a whole—plays a decisive role in object-based attention.

Introduction

Optimal allocation of the limited human cognitive resources—such as visual attention—to survival-relevant or informative stimuli may be an essential ability through evolution. Indeed, past studies have demonstrated that observers can allocate visual attention optimally depending on the target-present probability of each location, evidenced by increased accuracy and decreased reaction times at the location in proportion to the assigned probability (Geng & Behrmann, 2002; Shaw & Shaw, 1977). Moreover, attention deployment can be guided by implicit knowledge of spatial context cues—for example, the structure of distractors (Chun & Jiang, 1998; Peterson & Kramer, 2001). In addition to a visual search task, in the cueing paradigm (Posner, 1980), cue validity—usually defined as the probability that a target will appear at a given location—has also been manipulated to show that visual attention can be allocated optimally according to the probability assignment: more liberal for more likely and more parsimonious for less likely locations (e.g., Muller & Findlay, 1987).

The attention allocation first was described using metaphors such as an internal spotlight (Posner, 1980), a zoom lens (Eriksen & Yeh, 1985), or a gradient structure (Downing & Pinker, 1985); all imply that attention operates in a location-based manner. Over the last two decades, however, growing evidence has shown that attention operates not only in a location-based but also in an object-based manner: Attention can select grouped parts across different locations together (i.e., an object) and then highlight the processing of information belonging to the selected object (Duncan, 1984). Behavioral studies have demonstrated the dissociation of location- and object-based attention; for example, different types of working memory are involved (Chou & Yeh, 2008; Matsukura & Vecera, 2009) and they have different time courses (List & Robertson, 2007; Shomstein & Yantis, 2004). Physiological studies have shown that different brain areas are responsible for location- and object-based attention (Fink et al., 1997; He et al., 2008).

Note that previous manipulations of cue validity are all location-based, especially those adopting the popular cueing paradigm of Posner (1980). We are interested in whether our visual system can also calculate the usefulness of the cue based on the object as a whole by combining all manipulated location probabilities within that object. Dissociating the cue validity based on location from that based on object is a worthwhile approach to examine this question because it promises new insights into current theories of attention. Ecologically, our visual world is full of objects in different locations, and both locations and objects may carry useful information upon which we can properly act. Location information can be more relevant than object information in some situations and vice versa. Visual systems seem to meet a problem in guiding attention—based on either spatial location or visual object. Thus, we propose an optimization hypothesis: Attentional deployment depends on the more useful (higher utility) selection base. If *location-based cue validity*—denoting the probability of target presentation at the *cued location*—is high and *object-based cue validity*—denoting the probability that the target's occurring at the *cued object as a whole*—is low, attentional deployment will depend on location-based attention, and vice versa. If location- and object-based cue validities are both high or low, location- and object-based attention influence the allocation of attention interactively (e.g., Egly et al., 1994; Jordan & Tipper, 1999).

In contrast to our optimization hypothesis, both the spreading hypothesis (Davis & Driver, 1997; Kasai & Kondo, 1997; Richard et al., 2008; Roelfsema, Lamme, & Spekreijse, 2000) and the prioritization hypothesis (Shomstein & Yantis,

2002) of object-based attention would make the opposite prediction. The spreading hypothesis states that when attention is cued to a location within an object, attention will spread automatically from the cued location to the whole object. Consequently, an informative cue that can guide attention to a specific location within an object should cause attention to spread throughout the whole cued object. The prioritization states that there is an inherent predisposition to assign higher priority to locations within an attended object than to locations elsewhere (Shomstein & Yantis, 2004). Regardless of object-based cue validity, object-based attention is expected when there is an informative location-based cue by both the spreading hypothesis and the prioritization hypothesis.

To pit our optimization hypothesis against these two influential hypotheses of object-based attention, we manipulated independently *location-based cue validity* and *object-based cue validity* using the double-rectangle method of Egly et al. (1994). Egly et al. used a cueing paradigm with a double-rectangle display to demonstrate the coexistence of location- and object-based attention. They presented two outline rectangles, with one end of one rectangle brightened as a cue to indicate the possible location of a target. The target was a small solid square, shown subsequently within one end of a rectangle. Location-based attention was indicated by the *spatial-cueing effect*: RTs were shorter when the target appeared at the cued location than at uncued locations. Object-based attention was indicated by the *same-object advantage*: RTs were shorter when the target appeared at the uncued end of the *cued* than at the *uncued* rectangle, with an equal cue-to-target distance between the two. As with Egly et al., a series of studies using various stimuli and tasks have demonstrated both the spatial-cueing effect and the same-object advantage (e.g., Avrahami, 1999; Lamy & Tsal, 2000; Moore et al., 1998).

In the original design of Egly et al. (1994), the probability that the target would appear at a cued *location* was 75%, and the probability that the target would appear at a cued *object* was 87.5% (combining the cued end with the uncued end of the cued object: 75% plus 12.5% equals 87.5%). That is, the cue was informative for both location- and object-based attention. As with Egly et al., almost all previous studies confounded object-based cue validity with location-based cue validity: They were either both high (e.g., Abrams & Law, 2000; He et al., 2004; Lamy & Tsal, 2000; Moore et al., 1998; Shomstein & Behrmann, 2008) or both low (e.g., Jordan & Tipper, 1999; List & Robertson, 2007). We intend to differentiate the two kinds of cue validity and expect to find different results. Applying the double-rectangle method, a single peripheral cue can be informative or non-informative, defined either by location or object.

Note that the two critical conditions—location-based cue is informative but object-based cue is non-informative and vice versa—are omitted in the literature, and our optimization hypothesis makes testable predictions for each. Three experiments were designed for this purpose. In Experiment 1A, the target would appear at the cued location more often than the uncued locations, while the target would appear at the cued object with the same frequency as with the uncued object. According to the optimization hypothesis, with an informative location-based cue and a non-informative object-based cue, the spatial-cueing effect—but not the same-object advantage—is expected. In Experiment 1B, we aim to replicate the conventional spatial-cueing effect and the same-object advantage with a slight adjustment of the cue validity to see whether the absence of the same-object advantage in Experiment 1A was caused by the manipulation of object-based cue validity. In Experiment 2, we further designed a situation with a non-informative location-based cue and an informative object-based cue and expect to find the same-object advantage but not the spatial-cueing effect.

General Method

Participants

Forty-two paid volunteers who were students of National Taiwan University participated in this study (*N* = 12, 12, and 18 in Experiments 1A, 1B, and 2, respectively). All participants had normal or corrected-to-normal vision and were naïve as to the purpose of the experiment.

Apparatus, Stimuli, and Procedure

The stimuli were presented on a VGA monitor with the resolution of 640 × 480 pixels in a 256-color mode. Participants sat in a dimly lit chamber with a viewing distance of 57 cm. Head position was maintained using a chin rest.

The displays (Figure 12) comprised a pair of adjacent grey rectangles, oriented either vertically or horizontally. Each rectangle (1.3° × 7.9°, with a stroke width of 0.2°) was centered 3.3° from fixation. The fixation was a grey plus sign (0.4° × 0.4°). The cue (three 1.3° × 0.2° white lines, overlapping one end of a rectangle) and the target (1.3° × 1.3° solid grey square) were located at one end of the rectangles.

Each trial began with a 1000-ms fixation display containing the fixation cross and two rectangles. The rectangles appeared either to the left and right or above and below the fixation. Following the fixation display, the cue display was presented for 100 ms. After 100 ms, the cue display was replaced by the fixation display, and the fixation display was presented for another 200 ms. The target (or nothing on catch trails) was then presented and remained visible until the participants responded or for 1000 ms if there was no response. The next trial began after a 500-ms inter-trial interval, during which the screen was blank.

The participants were asked to fixate at the fixation throughout each trial, and their task was to press the space bar of a computer keyboard in front of them as rapidly as possible whenever they detected the target. A 500-ms feedback beep was provided if the participant made a response to a catch trial.

Design

A spatial pre-cue was presented at one end of a rectangle, and the target followed in one of four conditions: at the cued location (valid), at the uncued location within the cued object (invalid-same object; IS), at the near end of the uncued object (invalid-different object; ID), or at the far end of the uncued object (invalid-far; IF). The distance between the cue and the target were equal in the IS and ID conditions, making any RT difference between IS and ID conditions not attributable to location.

The order of trials was randomized for each subject. There were four blocks of 96 trials in each of Experiment 1A and 1B and 76 trials in Experiment 2. A rest period was offered between blocks. Before the experiment, each subject was given 20 practice trials randomly selected from the experimental trials. In Experiment 1A, there were 32 valid trials, 8 IS trials, 24 ID trials, 16 IF trials, and 16 catch trials in a block, making the proportion of valid, IS, ID, and IF trials 40%, 10%, 30%, and 20% of target-present trials, respectively. In Experiment 1B, there were 40 valid trials, 8 IS trials, 24 ID trials, 8 IF trials, and 16 catch trials in a block, making the proportions of valid, IS, ID, and IF trials 50%, 10%, 30%, and 10%, respectively. In

Experiment 2, the target never appeared at the rectangle end diametrically opposite the cued location (i.e., there was no IF condition). There were 20 trials in each block of the valid, IS, and ID trials, making equal proportions of each (i.e., 33%). Sixteen catch trials were embedded in a block.

Results

Data from trials in which RTs were faster than 150 ms (less than 3.1%), and errors including false alarms (less than 2.5%) and misses (less than 0.4%) were excluded in all experiments. The mean correct RTs (Figure 13) were collapsed across rectangle orientation since orientation did not affect RTs, nor did it interact with validity ($ps > .05$). There were no differences in error rates across conditions, indicating no speed-accuracy trade-off.

The collapsed data in Experiment 1 were submitted to a two-way repeated-measures ANOVA with a between-subjects factor of experiment (Experiment 1A, 1B) and a within-subjects factor of cue validity (valid, IS, ID, IF). The main effect of cue validity was significant [$F(3, 66) = 5.95$, $MSE = 130$, $p < .005$], as was the interaction of experiment and cue validity [$F(3, 66) = 3.47$, $MSE = 130$, $p < .05$], indicating that the manipulation of probability between these two experiments affected the RT results.

We focus on the spatial-cueing effect—RT difference between the valid and IS condition—and the same-object advantage—RT difference between the IS and ID condition. In Experiment 1A, the planned comparison showed faster RTs for valid than for IS trials ($p < .05$), replicating the finding that the cue captured participants' attention to the cued location (e.g., Posner, 1980). Moreover, the cue led to slower responses when the target appeared at the cued object (IS) than at the uncued object (ID) ($p < .05$). This result is a reversed pattern of the conventional same-object advantage but consistent with the location-based probability manipulation (the proportions of IS and ID are 10% and 30%, respectively). In summary, when the target appeared at the cued and uncued *objects* with equal probability, the response was modulated only by the location-based probability. This finding supports our optimization hypothesis but not the spreading hypothesis and the prioritization hypothesis.

In Experiment 1B, planned comparisons showed faster RTs for valid than for IS, ID, and IF trials ($ps < .05$). And the cue led to faster responses when the target appeared at the cued object (IS) than at the uncued object (ID and IF) ($ps < .05$). The difference between the RTs of the ID and IF trials were marginally significant ($p = .08$). When both the location-based cue and object-based cue were informative, Experiment 1B replicated the typical result patterns in studies using the double-rectangle method—both the spatial-cueing effect and same-object advantage are found.

Comparing Experiments 1A and 1B reveals that the object-based cue validity is crucial in obtaining the same-object advantage, and this result supports our hypothesis. Note that the arrangement of proportions of IS and ID trials in Experiment 1B (10% for IS and 30% for ID) was identical to that in Experiment 1A. This implies that the absence of the same-object advantage in Experiment 1A is determined by the non-informative object-based cue validity but not the unequal probability between the IS and ID trials.

In Experiment 2, when the object-based cue was informative and the location-based cue was non-informative—each possible target location has equal chance to contain the target—only the same-object advantage (faster RTs for valid and IS trials than for ID trials, *ps* < .05) was obtained. Again, this result supports our optimization hypothesis.

General Discussion

Unlike previous studies, in which the effect of location- and object-based cue validity on attention deployment were always co-varied, we manipulated the two kinds of cue validity independently and probed the spatial-cueing effect and the same-object advantage—which are indicative of location- and object-based attention, respectively—in a single task. We found the spatial-cueing effect when the location-based cue was informative (Experiment 1A), the same-object advantage when the object-based cue was informative (Experiment 2), and both spatial-cueing effect and same-object advantage when both location- and object-based cues were informative (Experiment 1B). The current study supports our optimization hypothesis: The most informative aspect—either location- or object-based attention—dominates the deployment of attention.

Previous studies have established boundary conditions for the same-object advantage. For example, object-based attention occurs only when the target location is uncertain (Shomstein & Yantis, 2002; but see Chen & Cave, 2008) for search prioritization to occur, or when the object is covered by the extent of spatial attention (Goldsmith & Yeari, 2003) and with sufficient object exposure duration (Chen & Cave, 2008; Shomstein & Behrmann, 2008) for object representation to be formed. The present study further establishes the important role of probability distribution with respect to the whole object, in contrast to that of a particular location. The result pattern across Experiments 1 and 2 clearly demonstrates that the participants allocated their attention in proportion to the locations within the boundary of an object, and only informative object-based cues led to object-based attention.

Current influential theories of object-based attention—for example, the spreading hypothesis (Richard et al., 2008) and the prioritization hypothesis (Shomstein & Yantis, 2002)—do not take object-based cue validity into account. Both theories predict that object-based attention influences attention deployment spontaneously—either by spreading or by search prioritization—even when the object-based cue is non-informative; however, the results of the current study demonstrate that an informative object-based cue is necessary for object-based attention to occur. Shomstein and Yantis (2004) claimed that both object configuration and the probability of target appearance in each location contributed to the assignment of attention. Our optimization hypothesis, in contrast, emphasizes that the object configuration itself is not sufficient for object-based attention. Instead, the object-based cue validity—defined by the summed probability of locations within the boundary of an object—does play a critical role.

Notice that in the current study, the experimenter did not provide knowledge about the cue validity to the participants, and the participants' subjective reports after they performed the experiment indicated that they were not aware of the relation between the cue and the target. Our results, thus, suggest that the participants can learn the usefulness of the cue according to the location- and object-based aspects, respectively, during the experiment. This result is consistent with studies demonstrating spatial configuration cueing effects—attention is guided by implicit knowledge of the spatial arrangement or layout (e.g., Chun & Jiang, 1998; Peterson & Kramer, 2001)—and further extends the perceptual learning to a more complex, object-based, cue-to-target spatio-temporal relationship.

The findings of the current study suggest that attentional resources can distribute proportionally to not only a location but also an object—bearing some similarity to Shaw and Shaw's (1977) attention-sharing model—and the flexible sharing of attentional resources among locations or objects depends on the optimization principle we proposed. The optimal attentional deployment determines observers' performance—the more attentional resource, the better the performance—and leads to the most efficient behavior in our spatial environment full of multiple objects.

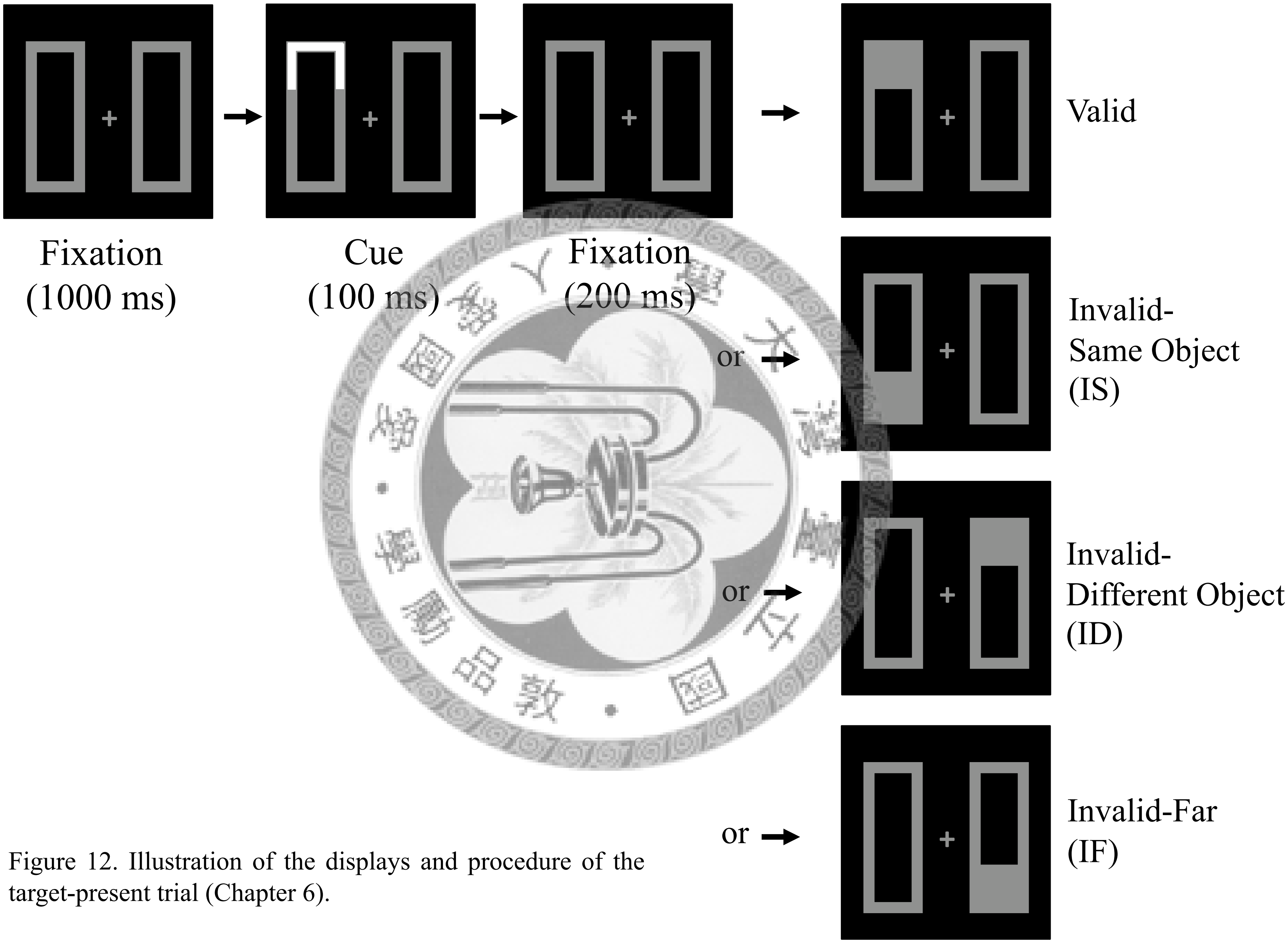

Figure 12. Illustration of the displays and procedure of the target-present trial (Chapter 6).

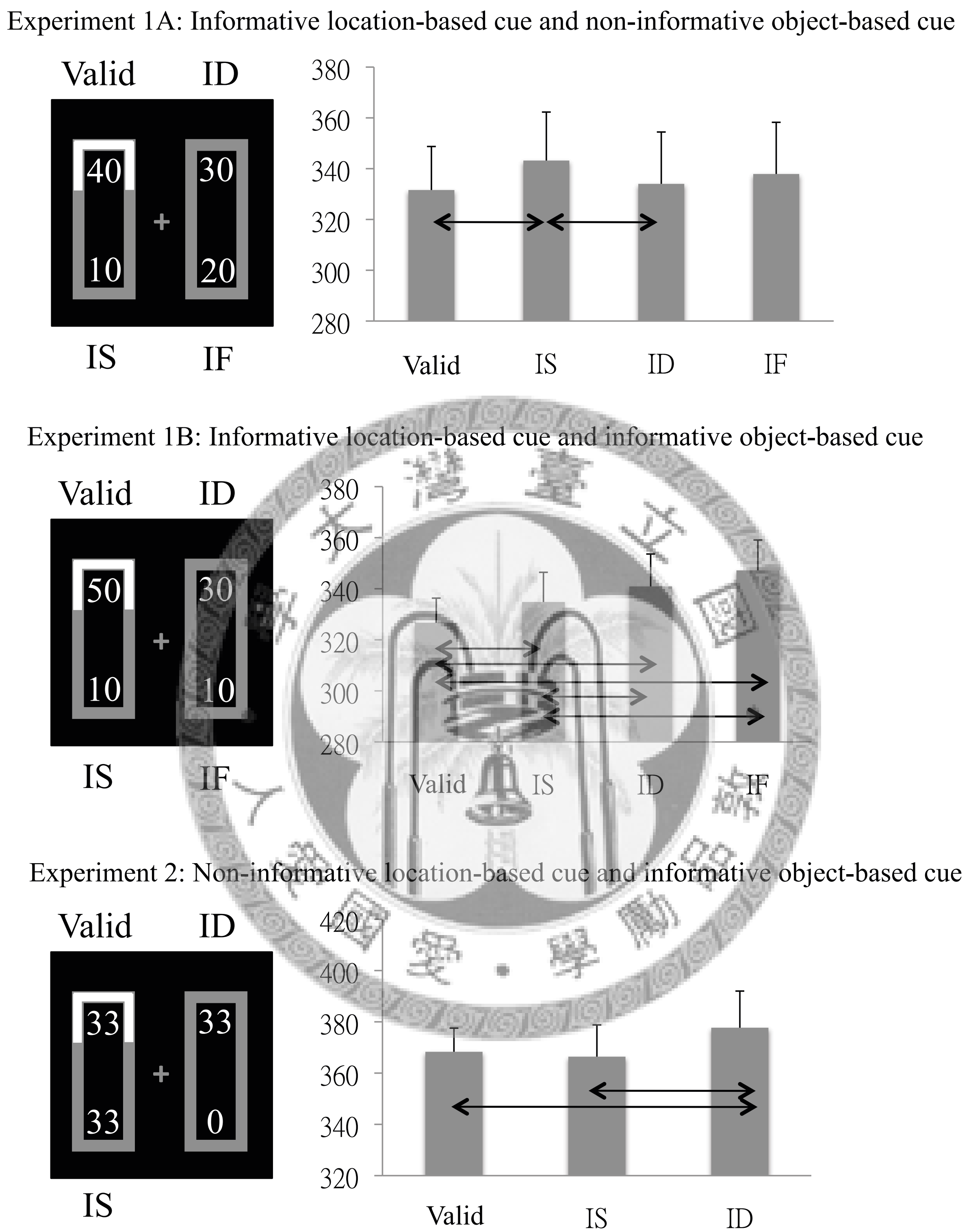

Figure 13. Mean RTs under each condition (Chapter 6). Error bars represent one standard error. Arrows indicate significant difference (p<.05). IS: invalid-same object; ID: invalid-different object; IF: invalid-far. The numbers in the display example indicate the probability that the target will appear at that location.

Chapter 7

General Discussion

This thesis examines mechanisms of location-based and object-based attention with a series of five studies. These findings support the notion that location-based and object-based attention are two qualitatively different forms of attention. Location-based attention and object-based attention are influenced by consciousness in different ways, have different underlying mechanisms, involve different kinds of working memory, and rely on different aspects of cue validity. These findings challenge current theories of attention while providing new insights into them. The consciousness-dependent hypothesis and the optimization hypothesis are proposed to explain the current findings.

Studies in section I (chapters 2–4) take a bottom-up approach. The stimulus visibility was systematically manipulated and the results support qualitatively different mechanisms for location-based and object-based attention. In chapter 2, by manipulating awareness of the “trigger” of attention (the cue), we demonstrate that consciousness modulates object-based attention but not location-based attention. We found the *same* location-based effects by using suprathreshold cues and subliminal cues; however, the two kinds of cues led to a reversed pattern of object-based effects: A suprathreshold cue led to a *same-object advantage* and a subliminal cue led to a *different-object advantage*. We thus propose that a suprathreshold cue strengthens the *within-object link* while a subliminal cue strengthens the *between-object link*. A consciousness-dependent hypothesis is proposed and implies that location-based attention operates in the same way regardless of status of awareness; however, object-based attention operates for *object recognition* in an obvious way and for *action* in an implicit way. Future brain image study is suggested to test the new hypothesis and elaborate the possible brain areas that may involve in location- and object-based attention in different states of consciousness.

In chapter 3, by manipulating awareness of the "host" of attention (the object), this study investigated whether object-based attention is modulated by participants' awareness of objects. This study provides the first evidence that the selection unit of attention can be at an object level even when these objects are invisible—a level higher than previous evidence given for a subliminally cued location. We suggest that attention plays a fundamental role in binding features of both the conscious and unconscious mind. Putting the findings of chapters 2 and 3 together, it is shown that conscious status of the "trigger of attention" (cue) influences attention deployment; however, conscious status of the "host of attention" (object) does not influence attention deployment. This implies that the kind of information—location or object—to be suppressed is a critical factor determining the effect of consciousness.

In chapter 4, by manipulating the visibility of the target, we adopted the noise masking paradigm to examine the underlying mechanisms of location-based attention and object-based attention. We found qualitatively different underlying mechanisms for the two kinds of attention in terms of their *threshold versus external noise contrast (TvC) functions*. Location-based attention operates by enhancing signal strength, whereas object-based attention operates by excluding external noise.

In section II (chapters 5 and 6), we focus on the role of higher-level cognitive factors in location-based and object-based attention: working memory and cue validity. In chapter 5, we used a dual-task paradigm to examine whether the location-based attention and object-based attention are affected by two kinds of secondary tasks that involve spatial and non-spatial working memory, respectively. The results show that location-based effect was disrupted by a spatial secondary task whereas the object-based effect was disrupted by a non-spatial secondary task. This finding clearly implies that location-based attention and object-based attention involve different kinds of working memory or share the cognitive resource with different kinds of working memory.

In chapter 6, we wonder how cue validity influences location-based and object-based attention. We manipulated cue validity with respect to a particular location or the whole object by combining validity within its boundary. Results indicated that location-based attention and object-based attention operate with informative location-based and object-based cues, respectively, and both kinds of attention coexist when both kinds of cues are informative. We demonstrate that the validity of the location cue is not the cause of object-based attention; object-based cue validity—the probability that the target will appear on the cued object as a whole—plays a decisive role in object-based attention. An optimization hypothesis is proposed: Attention deployment depends on the more useful (higher utility) selection base. If *location-based cue validity*—denoting the probability of target presentation at the *cued location*—is high and *object-based cue validity*—denoting the probability that the target occurs at the *cued object as a whole*—is low, attention deployment will depend on location-based attention, and vice versa. If location- and object-based cue validities are both high or low, location- and object-based attention influence the allocation of attention interactively. The results can be adequately explained by the optimization hypothesis.

Conclusion

In this thesis, we overturn the widely held belief in a unified account of location-based and object-based attention (see Mozer & Vecera, 2005, for a review) by providing evidence showing qualitative differences in location-based and object-based attention in several aspects. Rather than viewing object-based attention as a consequence of spread from *location*-based attention (Richard et al., 2008) or as a grouped array of attended *locations* (Vecera, 1994), our findings support the notion that location-based attention and object-based attention are two qualitatively different forms of attention with different underlying mechanisms. Moreover, in this thesis we present new testable theories for object-based attention: the consciousness-dependent hypothesis and the optimization hypothesis. Future study is needed to test these new theories and elaborate them.

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Appendix A

Object-based Inhibition of Return: Evidence from Overlapping Objects

Chou, W. L., & Yeh, S. L. (2005). Object-based inhibition of return: Evidence from overlapping objects. *Chinese Journal of Psychology*, *47,* 1-13.

Abstract

Inhibition of return (IOR) refers to the delayed response to a location or an object that has recently been cued. Previous studies showing object-based IOR in either dynamic or static displays have used spatially separate stimuli that unavoidably involved spatial representation. It thus remains unclear whether the object-based IOR is a special case limited to the condition in which objects are separated in a 2-dimensional space. To rule out confounding with location-based IOR, we used two overlapping triangles constituting a "Star of David" in this study to examine whether and under what conditions object-based IOR can be observed. An object cuing paradigm was used in which one of the two triangles was brightened as the cued object. The target was a luminance change in one of the three disks connected to the vertexes of the cued or the uncued triangle. The participants judged whether the target brightened or dimmed. Results show that object-based IOR can occur for spatially overlapping object under two necessary conditions: A long enough cue-to-target SOA and the existence of an attractor that is presented after the cue and before the target.

When you search your desktop for a pen, the best strategy is to remember where you have already searched and not to search there again; looking in new places rather than the old ones makes your search more efficient. Human performance observed in psychological experiments indeed reveals a phenomenon similar to this search strategy: The reaction time (RT) increases when a target appears at a location that has recently been cued, an effect called "inhibition of return" (IOR; Posner, Rafal, Choate, & Vaughan, 1985). Posner and Cohen (1984) are the first to demonstrate the IOR effect. They used three outline boxes presented on a horizontal axis, with the central box as fixation and the right or the left box being brightened briefly as a peripheral cue. The target was a small filled square within the box, and the participants were instructed to respond to the target as quickly as possible. The target was usually in the central box (p = .6), but it could occur in either peripheral box (p = .1 on each side). They found, on the one hand, a facilitatory effect in which RT to detect the target was shorter at the cued box than at the uncued box when the cue-to-target stimulus onset asynchrony (SOA) was shorter than 150 msec (i.e., 0, 50, and 100 msec). On the other hand, RT was longer at the cued box than at the uncued box when the SOA was longer than 300 msec (i.e., 300 and 500 msec).

Posner and Cohen (1984) argued that the initial RT benefit to the cued box is due to the summoning of attention by the cue. However, this early facilitatory effect is replaced by a subsequent inhibition to the previously cued location after attention had presumably shifted back to the central fixation (as targets occurred mainly in the central box). Although Posner and Cohen (1984) concluded that the cued location in visual space is facilitated early and inhibited later, such an account of space-based attention may be confounded with the possibility that their participants viewed these boxes as objects, rather than, or in addition to, viewing them as locations. Indeed, the three boxes used in their displays can be considered as either locations or objects, or both (Tipper, Weaver, Jerreat, & Burak, 1994; Jordan & Tipper, 1998). Nevertheless, Posner and Cohen's (1984) original paradigm is used by many follow-up studies, and the existence of location-based IOR has been well established (see review of Klein, 2000).

To distinguish location-based IOR from object-based IOR is important, as illustrated by the following example. Ecologically, it may be helpful to inhibit places that have just been searched before; say, for a sheep to search for fresh grass that has not been eaten already, assuming that the target (fresh grass) of a sheep in this example is more or less in a 2-dimensional space. However, it is unlikely that inhibiting previously searched places can also be helpful, as in the case of a lion looking for a running rabbit in the forest. Just as for lions, for humans, there are always multiple objects that may change locations, and one object may overlap the other in the environment. In such an environment that is dynamic, 3-dimensional, and full of multiple objects, inhibiting an already searched or attended location may in fact turn out to be inefficient for searching.

Indeed, several studies have shown some IOR phenomena to be object-based. Tipper, Driver, and Weaver (1991) first demonstrate object-based IOR in a dynamic display in which the cued object rotates 90˚ from its original location after being cued, and the inhibition associated with it also moves with the object. However, the objects used in their experiment retain their relative locations when rotating around the fixation point. Thus, the objects may help set up a frame of reference in which attentional orienting operates on relative locations, but not on objects (Schendel, Robertson, & Treisman, 2001). Such a dynamic display, as that used by Tipper et al. (1991), has also been criticized as being confounded with left-to-right attentive tracking, and dynamic object-based IOR has been demonstrated only under certain experimental conditions (Muller & von Muhlenen, 1996).

There are also studies that have shown object-based IOR in static displays. Jordan and Tipper (1998), for example, found that the magnitude of IOR in the apparent-object-present condition (i.e., an illusory object induced by four "pacmen" had been cued) is significantly larger than that from the apparent-object-absent condition (i.e., only a location had been cued). They interpreted their results in the view that when objects are cued there are both location- and object-based IOR effects, while when only locations are cued, there is only location-based IOR. In this case, assuming the two kinds of IOR are additive, the object-based effect is inferred indirectly by the comparison of the magnitude of presumably location- plus object-based IOR and that of location-based IOR alone. Again, the results seem to be obtained only under certain circumstances (McAuliffe, Pratt, & O'Donnell, 2001). In a subsequent study, Jordan and Tipper (1999) used two spatially separate rectangles with a peripheral cue appearing at one end of a rectangle (see also Egly, Driver, & Rafal, 1994). They found longer detection RT at the uncued end of the cued object relative to the uncued end of the uncued object, demonstrating more directly object-based IOR in static displays.

Note that for the studies showing object-based IOR in either dynamic or static displays, spatially separate stimuli are used (e.g., McAuliffe et al., 2001; Tipper et al., 1991; Tipper, Jordan, & Weaver, 1999; Jordan & Tipper, 1998; 1999). This raises the question whether object-based IOR is a special case limited to the condition where objects are separated in 2-dimensional space. This is an important question because if only the objects which occupy different 2-dimentional spaces can reveal the object-based IOR, the effect is unavoidably associated with not only object representation, but also space representation. In other words, if the object-based IOR can only be found when objects are spatially separate, it means that the space representation is crucial to the object-based effect.

In this study, overlapping objects were used to avoid confounding from location-based effects (e.g., Duncan, 1984; Haimson & Behrmann, 2001) and to see whether object-based IOR occurs for spatially overlapping objects. This arrangement of stimuli is justifiable on ecological grounds: The retinal images of many real-world objects are usually overlapped.

The stimuli used in the present study (Figure 1) are similar to those in Brawn and Snowden (2000). One of the objects was brightened as a cue, but this exogenous object cue was uninformative as to which object the target will appear. Using this display, they find an object-based facilitatory effect: Shorter RT when the target appears at the cued object than at the uncued object. More importantly, they demonstrate that attention can select one of the two overlapping objects (see also Stuart, McAnally, & Meehan, 2003). The cue-to-target SOA was less than 300 msec in their study, and curiously, they did not manipulate longer SOAs to see whether an IOR effect can also be found with overlapping objects. Adopting the object cuing paradigm used by Brawn and Snowden (2000), we examine whether object-based IOR occurs for a long enough SOA.

In fact, in a similar display using overlapping objects, Schendel et al. (2001) do not find object-based IOR even when the SOA is extended to 725 msec. Likewise, Theeuwes and Pratt (2003) also fail to find depth-specific

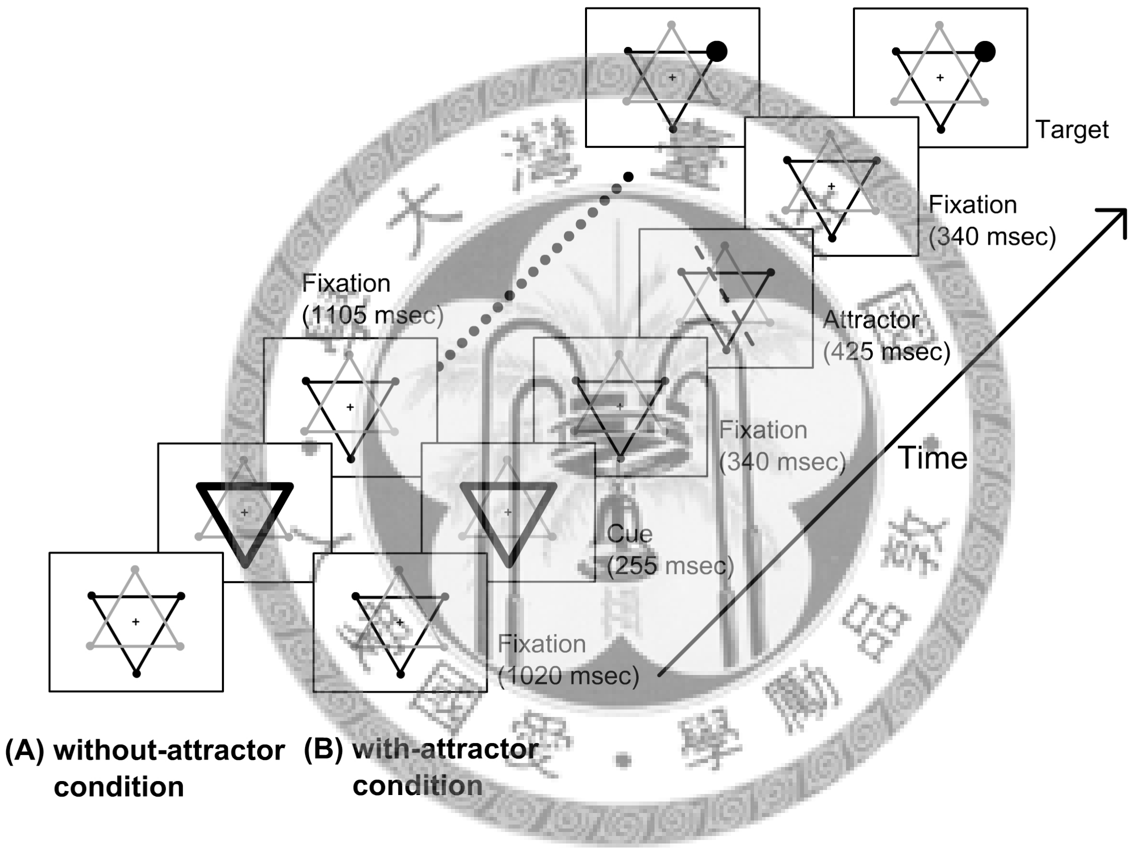


Figure 1. Illustration of the display sequence used in this study (not to scale). In the actual experiment, the background was gray and one of the triangles and its connecting disks were green, while the other triangle and its connecting disks were red. (A) The *without-attractor* condition. (B) The *with-attractor* condition. The attractor was a black dotted line shown on the 4th frame and was presented at 45º, 180º, or 315º. The cue and the target were equally likely to occur for the two triangles.

IOR when the SOA is 883 msec, and they term it "depth-blind" IOR. In Theeuwes and Pratt (2003), after a specific object in the x-y-z coordinate was cued, the effect of IOR spread across the z-dimension: Namely, IOR occurs for the depth planes in front and behind the cued object. Although two objects at different depth planes are different from two overlapping objects at the same depth plane, it is reasonable to infer from this result that no object specific IOR for overlapping objects can be observed at this SOA (883 msec).

It has been shown that the more complex the object is, the longer the SOA it requires for obtaining the object-based effect (Ho & Atchley, in press). The stimulus displays used in Schendel et al. (2001) and in Theeuwes and Pratt (2003) are more complex than those of Jordan and Tipper (1998; 1999). While the former two studies fail to find object-based IOR, the latter successfully demonstrate its existence. We suspect that it may be due to the shorter SOAs (725 and 883 msec) used in the former two studies than those in Jordan and Tipper (1998; 1999; 1186 and 1166 msec). Hence, there is reason to believe that their experiments (Schendel et al., 2001; Theeuwes & Pratt, 2003) did not provide a strong test of the possible existence of object-based IOR and their designs are not fair to answer whether object-based IOR can be observed from overlapping objects. We are thus curious whether the object-based IOR for spatially overlapping objects can be observed if the cue-to-target SOA is extended to an even longer duration.

Another hint of using long enough SOA to obtain the object-based IOR can be found in Law, Pratt, and Abrams (1995). Using a cuing paradigm with 1800 msec cue-to-target SOA, they show that participants are slower to detect a color patch (i.e., the target) if the color matches that of a patch presented earlier at the same location (i.e., the cue). This is interpreted as an IOR effect based on the non-spatial attribute of color (but see Fox & de Fockert, 2001). Although it is unclear whether such feature-based IOR is applicable to the object-based IOR, it is nonetheless a case that shows an object-related IOR in a long (1800 msec) cue-to-target SOA condition.

To examine the effect of SOA on object-based IOR, we first use a long enough SOA to see whether IOR with overlapping objects can be obtained, and then compare it with a shorter SOA to test our first hypothesis in this study: A long enough SOA is necessary for object-based IOR. As noted, our object display is more complex than that in Jordan and Tipper (1998), who successfully demonstrated the object-based IOR from spatially separate objects. Thus we chose a slightly longer cue-to-target SOA (1360 msec) than the SOA used by them (1186 msec). As a comparison, we also used a short cue-to-target SOA, which was 884 msec, similar to that in Theeuwes and Pratt (2003; 883 msec). We predict that only the long SOA can lead to the object-based IOR, but not the short one, if a long enough SOA is necessary for obtaining the object-base IOR for spatially overlapping objects.

Another concern regards the nature of IOR as implied in the name "inhibition of return," Posner and Cohen (1984) remarked, "...if attention is not drawn away from the cued location, no net inhibition is found," (p. 541). Without manipulating the probability that the target appeared in the central box, Posner and Cohen (1984) replicated the IOR effect with a simpler method. In the aforementioned three-box displays, after the brightening of one of the boxes on the two sides (which serves as a peripheral cue), the central box was brightened briefly (as a neutral cue) before the onset of the target. It is assumed that on each trial, the participant's attention is first summoned by the peripheral cue and then by the central cue before the onset of the target display. This is why the IOR effect is attributed to the participant's attention being inhibited from returning to the previously cued location (but see Danziger & Kingstone, 1999). We call a stimulus such as the central cue in Posner and Cohen (1984) the "attractor" because it occurs after the offset of the peripheral cue and captures the participant's attention, taking it away from the previously cued location.

Recently, the role of attractor in location-based IOR has been carefully examined by Pratt and Fischer (2002). They found that the attractor is needed only at a short SOA (200 msec). At longer SOAs (400 and 800 msec), the location-based IOR can be observed regardless of whether an attractor is present (see also McAuliffe et al., 2001), indicating that attractor is not necessary for location-based IOR. However, in their design, although the presence or absence of an attractor does not seem to affect location-based IOR at longer SOAs, such a result cannot exclude the possibility that participants' attention had still returned to the central fixation from the cued location. Note that their participants knew that the cue was uninformative and thus to stay on fixation was the best strategy for the task at hand. Thus the participants may endogenously shift their attention from the cued location to the fixation location even without an attractor, especially in the long cue-to-target SOA conditions. It is hitherto unclear whether "the removal of attention" from the cued location is crucial for location-based IOR.

Adopting the original notion of Posner and Cohen (1984), the paradigm that reveals object-based IOR used by Tipper and his colleagues (1991; 1994) always contains an attractor following the peripheral cue (see also Abrams & Dobkin, 1994; McAuliffe et al., 2001; Jordan & Tipper, 1998; 1999). However, it has not been directly tested whether an attractor in object-based IOR is necessary, and so comes our second hypothesis: An attractor presented in between the sequential presentation of the cue and the target is necessary for object-based IOR with overlap ping objects.

Because we aim to examine the object-based IOR without confounding from the location-based IOR, the attractor we use is meant to be another object that can attract participants' attention from the originally cued object. This is quite different from the brightening of the central fixation used in previous studies that demonstrate location-based IOR (Abrams & Pratt, 1996; Pratt & Abrams, 1995; Pratt & Fischer, 2002; Pratt, Spalek, & Bradshaw, 1999; Snyder, Schmidt, & Kingstone, 2001; Tipper, Weaver, & Watson, 1996). The use of different kinds of attractor involves the relationship between object-based representation and location-based representation, which is beyond the scope of this study. What is emphasized here is that assuming object-based IOR occurs in object-based representation, the attractor used should be more like an object rather than a symbol that signifies a particular location (such as the fixation dot or cross used in previous studies). For this purpose, we use a long line that is also overlapped with the two overlapping objects as an attractor.

To reiterate, the two goals of the present study are: First, whether there exists object-based IOR for overlapping objects. The object-based facilitatory effect has been found, but the inhibition, the object-based IOR, does not seem to have been demonstrated consistently, especially for overlapping objects (e.g., Brawn & Snowden, 2000; Theeuwes & Pratt, 2003; Schendel et al., 2001). Second, we test, with overlapping objects, whether a long enough SOA and/or an attractor are necessary for object-based IOR.

Experiment 1

Method

Participants. Sixteen undergraduates of National Taiwan University participated in the experiment to fulfill course requirements. All reported normal or corrected-to-normal vision and were naïve as to the purpose of this experiment.

Stimulus materials. Stimulus displays were controlled by an IBM 486 personal computer and presented on a 14' ViewSonic monitor. A computer program, DMDX (Forster & Forster, 2003), was executed to present the stimuli and collect the RT data. Participants sat at a viewing distance of 60 cm in a dimly lit chamber, with their heads supported by a chinrest.

Each trial consisted of four kinds of display, including the fixation, the cue, the attractor, and the target display. In the fixation display, the fixation was a central white cross (0.67° × 0.67°) against a gray background, and two outline (0.29° in width) triangles (one inverted and one upright triangle, with each side extended 9.46°) were presented, one overlapping the other. One of the triangles (randomly chosen) was green and the other red. Three disks of .95° in diameter, centered 5.71° from the fixation cross, were connected to the three ends of each triangle and painted with the same color as the connecting triangle. In the cue display, one of the triangles was brightened and defined as the cued object. In the attractor display, a black dotted line (9.46° × .29°) that was slightly longer than the sides of the triangles was presented on fixation at orientations –45, 0, or 45 degrees (randomly chosen) from vertical. The line was centered on the same central location as the two overlapping triangles. In the target display, one of the six disks connected to the two triangles was either brightened or dimmed, and the other five disks remained unchanged.

Design. The relation between the cue and the target was manipulated in an object cuing paradigm. In the valid condition, the target was located on one of the three disks connected to the cued triangle. In the invalid condition, the target was located on one of the three disks connected to the uncued triangle. If there is object-based IOR, RT to the target in the valid condition should be longer than that in the invalid condition. In addition, the role of attractor is examined by comparing the with-attractor condition with the without-attractor condition. If an attractor is necessary, the object-based IOR should be found only in the with-attractor condition, but not in the without-attractor condition.

The four conditions (valid/invalid × with-attractor/without-attractor) were repeated 12 times within a block of 48 trials, with their orders randomized. There were four blocks of these trials in total, with an effort to balance the possible combinations of target locations. Sixteen practice trials preceded the formal 192 trials, and the participants could take short self-paced breaks between blocks.

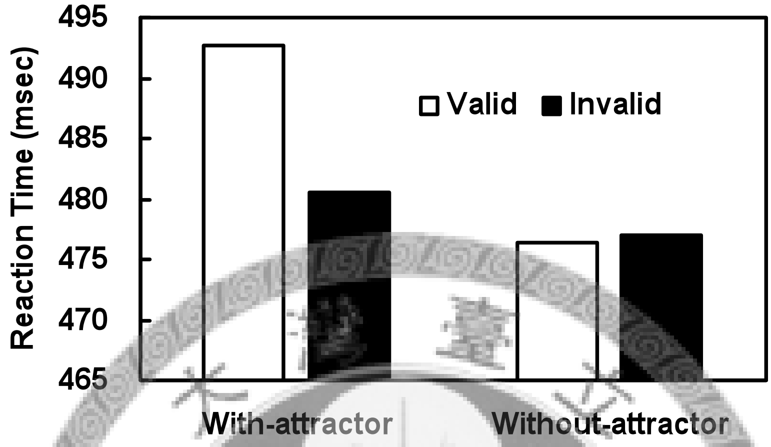
Procedure. The stimulus sequence is illustrated in Figure 1. The participants began each block of trials by pressing the space bar. At the beginning of each trial, an auditory tone was sounded for 100 msec, and at the same time, a fixation display was shown for 1020 msec. After the fixation display, the cue display was presented for 255 msec and replaced by the fixation display again. In the without-attractor condition, following the cue display, the fixation display was shown for 1105 msec. The target display appeared at 1360 msec SOA after the onset of the cue and stayed for 1000 msec or until the participants responded, whichever happened first. The whole display turned blank for an ISI of 500 msec, and then the next trial began. In the with-attractor condition, the cue-to-target SOA was still 1360 msec, but an attractor display was added in between the cue display and the target display. The attractor display was shown 595 msec after the onset of the cue display and stayed for 425 msec. Two fixation displays, one before and one after the attractor display, were each presented for 340 msec.

In the experiment, the participant judged whether the target was brightened or dimmed by pressing the "F" key on the computer keyboard with the left index finger if it was brightened and pressing the "J" key with the right index finger if it was dimmed. The participants were informed that the brightened triangle (the cued object) was not predictive of the subsequent target and targets were equally likely to appear on cued vs. uncued objects. They were instructed to respond as quickly and accurately as possible. Before the practice trials and before each block of the experiment, the participants were informed of the necessity of maintaining fixation throughout the trial.

Results and Discussion

In all experiments of this study, trials with an incorrect response or a RT less than 200 or longer than 1,000 msec are excluded as error trials, and less than 1% of trials are removed in each experiment. Figure 2A illustrates the mean RTs in this experiment. A repeated measure of the analysis of variance (ANOVA, a software provided by Chen & Cheng, 1999) was conducted with the attractor (with-attractor, without-attractor) and the cuing (valid, invalid) as the within-subjects factors. Neither the main effect of attractor nor the main effect of cuing is significant, *p*s > .05. However, the two-way interaction is significant [$F(1, 15) = 7.07$, $MSe = 94.13$, $p < .05$]. Planned comparisons showed that the effect of cuing is significant only in the with-attractor condition [$F(1, 30) = 8.30$, $MSe = 144.20$, $p < .01$], and the effect of attractor is significant only when the cue is valid [$F(1, 30) = 9.17$, $MSe = 231.86$, $p < .01$]. In the with-attractor condition, RT is significantly longer when the cue is valid ($M = 493$ msec) than when it is invalid ($M = 480$ msec). In the

(A) Experiment 1



(B) Experiment 2

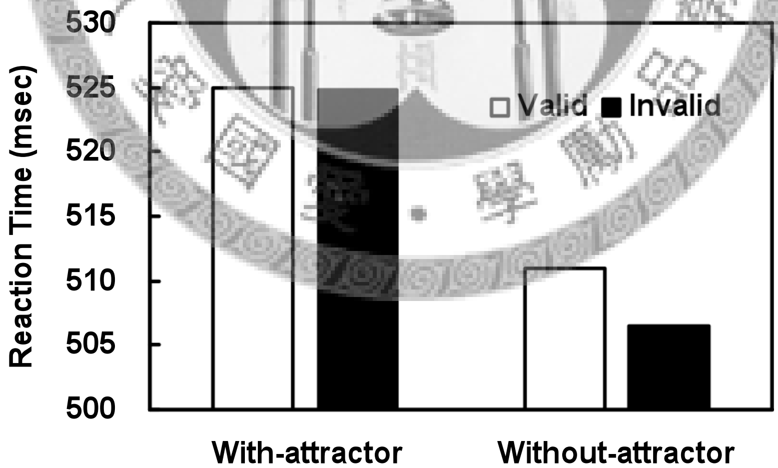


Figure 2. (A) The results of Experiment 1. (B) The results of Experiment 2.

without-attractor condition, however, no difference in RT is found between valid cue (*M* = 476 msec) and invalid cue (*M* = 477 msec).

The percentage of errors for each condition is shown in Table 1. Analysis of error rates indicates that the speed-accuracy trade-off for differences in the effect can be ruled out. Neither the main effect of attractor nor the main effect of cuing is significant, *F*s < 1. The two-way interaction does not reach the significance level, either [$F(1, 15) = 1.45$, $p > .05$]. Therefore, this experiment yields two important results. First, we found that participants responded slower to targets at cued objects than at uncued objects, demonstrating object-based IOR by cuing attention to one of the two overlapping objects. Previous studies showing object-based IOR used spatially separate stimuli that unavoidably involved spatial representation. By using spatially overlapping objects to avoid such confounding in this experiment, we demonstrate that object-based IOR can also occur for spatially overlapping objects. Thus, the object-based IOR is not a special case limited to the condition in which objects are separated in a 2-dimensional space. Second, the object-based IOR is found in the with-attractor condition, but not in the without-attractor condition, thus indicating the necessity of an attractor in demonstrating object-based IOR.

Table 1. Percentage of errors in Experiment 1 and 2.

	With-attractor		Without-attractor	
	Valid	Invalid	Valid	Invalid
Experiment 1	5.3	4.4	4.3	5.3
Experiment 2	5.6	5.0	3.4	5.0

Experiment 2

With displays of overlapping-objects similar to that in our Experiment 1, Theeuwes and Pratt (2003) and Schendel et al. (2001) do not find any object-based IOR effects when the cue-to-target SOA are 883 and 725 msec respectively. We are thus curious whether the object-based IOR observed in our Experiment 1 is due to the long SOA used in that experiment. In Experiment 2, we used the same displays and procedure as those in Experiment 1 but changed the cue-to-target SOA to 884 msec to see whether a long SOA is necessary for object-based IOR in the overlapping-object display. If it is, changing the SOA close to that used by Theeuwes and Pratt (2003) and Schendel et al. (2001) should then make the object-based IOR we observed in Experiment 1 disappear.

Method

Participants. Another group of twenty undergraduates with the same characteristics as described in Experiment 1 participated in this experiment.

Stimuli, Design, and Procedure. The stimuli, design, and procedure were the same as those in Experiment 1 except for the following: The cue-to-target SOA was shortened to be 884 ms in this experiment. In the without-attractor condition, following the cue display, the fixation display remained unchanged for 629 msec. The target display appeared at 884 msec SOA after the onset of the cue, and stayed for 1000 msec or until the participants responded, whichever happened first. In the with-attractor condition, the cue-to-target SOA was still 884 msec, but an attractor display was added in between the cue display and the target display. The attractor display was shown 357 msec after the onset of the cue display and stayed for 425 msec. Two fixation displays, one before and one after the attractor display, were each presented for 102 msec.

Results and Discussion.

Figure 2B shows the mean RTs for valid and invalid trials of the with-attractor and without-attractor conditions. Only the main effect of attractor is significant [$F(1, 19) = 18.32$, $MSe = 283.26$, $p < .01$]. RT is significantly longer in the with-attractor condition (M = 525 msec) than the without-attractor condition (M = 509 msec). However, the effect of cuing is not significant [$F(1, 19) = 0.29$, $MSe = 364.65$, $p > .1$].

The mean error rate for each condition is shown in Table 1. Analysis of error rates indicates that the speed-accuracy trade-off for differences in the effect can be ruled out. Neither the main effect of attractor nor the main effect of cuing is significant, ps > .1. The two-way interaction is not significant, either [$F(1, 19) = 2.20$, $p > .1$].

As predicted, no object-based IOR is observed when the cue-to-target SOA is shortened to be 884 msec in this experiment. Examining the results of Experiments 1 and 2 together indicates that both an attractor and a long cue-to-target SOA are necessary for object-based IOR. In Experiment 1, with an SOA of 1360 msec, object-based IOR is observed only when an attractor is presented in the time sequence between the cue and the target. In Experiment 2, with an SOA of 884 msec, even when an attractor is presented, still no object-based IOR is found. Although both the attractor and the long SOA are necessary for the object-based IOR, they are not inevitably two independent and additive factors. It is possible that the presence or absence of the attractor may modify the SOA for observing the object-based IOR. The patterns of results in Figure 2A and 2B seem to suggest that this might be the case.

Because the display in the with-attractor condition is more complex than that in the without- attractor condition, it is not surprising that participants need longer time to respond in the former condition (M = 525 msec) than in the latter (M = 509 msec). We also observe the same trend in Experiment 1, although the effect is not statistically significant in that experiment.

General Discussion

We obtained several important results in this study. First, participants responded slower to targets at cued objects than at uncued objects, demonstrating object-based IOR by cuing attention to one of two overlapping objects (Experiment 1). Second, the object-based IOR was found in the with-attractor condition, but not in the without-attractor condition, thus indicating the necessity of an attractor in demonstrating object-based IOR (Experiment 1). Third, when the cue-to-target SOA was not sufficiently long, the object-based IOR observed in Experiment 1 disappeared even when an attractor was present (Experiment 2).

As mentioned in the Introduction, the findings of object-based IOR in past studies used spatially separate stimuli that involved spatial representation (e.g., Jordan & Tipper, 1998; 1999; Tipper et al., 1994), which raises the question whether object-based IOR is limited to objects that do not overlap. We used overlapping objects in this study and demonstrated object-based IOR. The overlapping objects we used are similar to those in Brawn and Snowden (2000). Nevertheless, by prolonging the cue-to-target SOA to 1360 msec (as compared to the 200-300 msec used in their study), we have extended their finding of a facilitatory effect to an inhibitory effect and showed that object-based IOR can occur for overlapping objects. This major result provides an answer to the unsolved question in previous studies: Object-based IOR is not a special case limited to the condition where objects are spatially separate.

Furthermore, when a long SOA is used versus a short SOA (Experiment 1 vs. Experiment 2), object-based IOR is obtained only in the with-attractor condition, but not in the without-attractor condition. The attractor used in our experiments is a long onset line, which is considered an object and has been used to examine the object-based attention in several studies (e.g., Duncan, 1984; Lavie & Driver, 1996). Since abrupt onset object or new object can capture attention (Theeuwes, 1991; Yantis & Jonides, 1984), the onset line pulls participants' attention away from the attended object (i.e., the cued triangle). The necessity of attractor in IOR found in this study thus indicates that withdrawing attention from the attended object is crucial for object-based IOR to be observed. The conclusion is consistent with the long-held notion of IOR which assumes that RT is delayed because attention is inhibited from returning to a cued location (or object) and that where attention resides determines whether the facilitation or the inhibition will be found (Posner & Cohen, 1984).

Our results are also consistent with Ro and Rafal (1999). They used two moving objects, similar to Tipper et al. (1991), while manipulating the salience of the attractor (a neutral cue) and found that the likelihood of producing object-based IOR increases with the salience of the attractor. They emphasize, nonetheless, that the object-based facilitatory effect is found at long SOAs (600 and 900 msec) when no attractor is used. We do not find the sustained object-based facilitatory effect in the without-attractor condition at 884 msec SOA in Experiment 2, however. This discrepancy may be due to differences between Ro and Rafal's (1999) study and our study, such as detection vs. discrimination tasks, dynamic vs. static displays, and spatially separate objects vs. overlapping objects.

As mentioned, the role of the attractor in location-based IOR has been examined by Pratt and Fischer (2002). Their results indicate that the attractor is not necessary for location-based IOR in long-SOA conditions. We do not think their results are irreconcilable with the notion that "withdrawing attention from the attended location is critical to IOR". Spatial representation may be a special case regarding the role of attractor. In the space domain, the central fixation, usually also the medial position between possible target sites, naturally indicates a neutral location of the display. And that is also usually the most likely location at which the participants maintain their attention. Thus, during the interval between the peripheral cue and the target, especially in long-SOA conditions, participants may shift their attention from the cued location to the fixation location endogenously, even without an attractor.

In other words, if the cue-to-target SOA is long enough, participants can actively withdraw attention from the attended location without being triggered by an attractor. This may explain why in Pratt and Fischer (2002) the attractor seems irrelevant only in long-SOA conditions. However, for the overlapping objects used here and the color target used in Law et al. (1995), alternative non-target objects or colors (i.e., neutral objects or colors) are not typically available to relocate the participant's attention, and thus a presented attractor becomes necessary. Our results are consistent with Law et al.'s (1995) notion that in order to demonstrate IOR, it is necessary to direct attention to a value of a specific stimulus dimension, and then to shift attention from that particular value of the cued stimulus dimension to another value.

In addition to an attractor, an adequately long cue-to-target SOA is also necessary for object-based IOR in overlapping-object display. In Experiment 2, we used the same display and procedure as those in Experiment 1 but changed the cue-to-target SOA from 1360 msec to 884 msec, an SOA similar to that in Theeuwes and Pratt (2003). The absence of IOR in this short SOA condition is consistent with Theeuwes and Pratt's (2003) study: Their results of "depth-blind" IOR suggest that IOR cannot be restricted to one of the overlapping objects at 883 msec SOA.

To sum up, we have shown that object-based IOR can occur with overlapping objects, but only when an attractor is sandwiched between the cue and the target display, and when the cue-to-target SOA is long enough. Object-based IOR is not a special case limited to the condition where objects are spatially separate.