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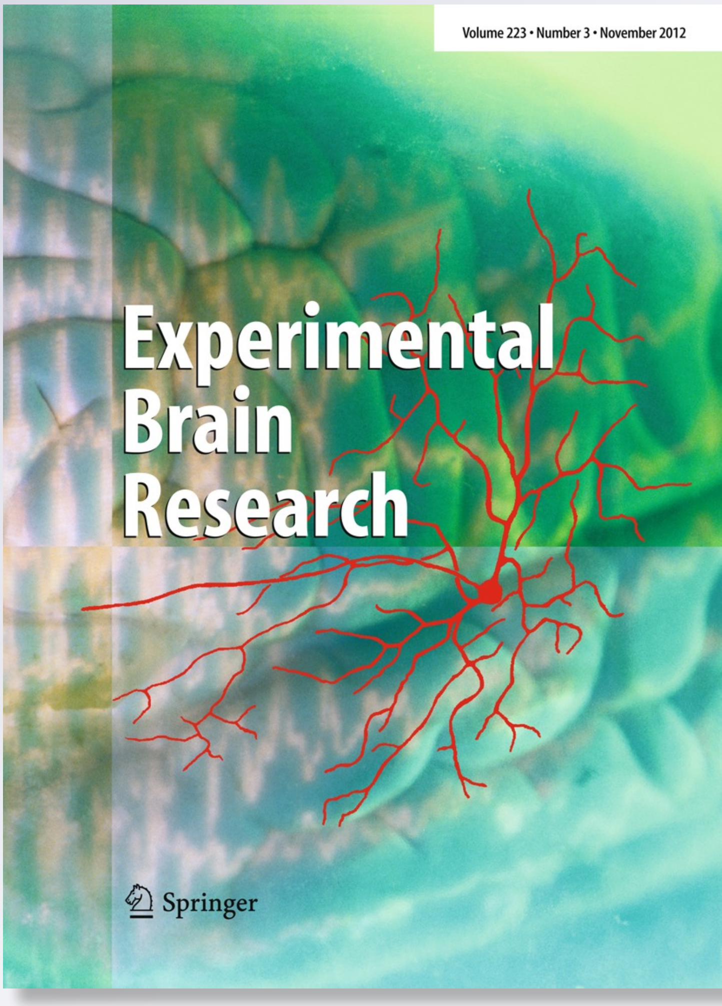

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RESEARCH ARTICLE

Object-based attention guided by an invisible object

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Abstract Evidence for object-based attention typically comes from studies using displays with visible objects, and little is known about whether object-based attention can occur with invisible objects. We investigated this issue with a modified double-rectangle cuing paradigm, which was originally developed by Egly et al. (J Exp Psychol Gen 123:161–177, 1994). In this study, low-contrast rectangles were presented very briefly, which rendered them invisible to subjects. With the invisible rectangles, we found a classical object-based attentional effect as indexed by the same-object effect. We also found the instantaneous object effect—object-based attention was dependent on the orientation of the rectangles presented with the target, providing evidence for the dynamic updating hypothesis (Ho and Yeh in Acta Psychol 132:31–39, 2009). These results suggest that object-based attention can be guided by an invisible object in an automatic way, with a minimal influence from high-level top-down control.

Keywords Attention · Object-based attention · Awareness · Same-object effect · Instantaneous object effect

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Introduction

Because neural resources are severely limited, efficiently processing visual information requires selecting only a fraction of the multitude of information available to the visual system at any one instant. Attention plays a central role in this selection process. Many studies have demonstrated that the unit of attentional selection can be spatial location (Brefczynski and DeYoe 1999; Eriksen and Yeh 1985; Kastner et al. 1999; McMains and Somers 2004; Posner et al. 1980); or visual feature (e.g., Liu et al. 2007; Maunsell and Treue 2006; Saenz et al. 2002; Serences and Boynton 2007; Treue and Martinez-Trujillo 1999; Zhang and Luck 2009). A seminal double-rectangle cuing paradigm developed by Egly et al. (1994) showed that attentional selection can also be object-based. In this paradigm, Egly and colleagues presented two parallel rectangles of equal length. A cue appeared at one end of a rectangle to indicate the possible location of a target. The target appeared at the validly cued location frequently (75 % of trials) and at invalidly cued locations occasionally (25 % of trials). There were two types of invalidly cued targets: one appearing at the uncued end of the cued object and the other appearing in the uncued object. Both of these invalidly cued targets were equidistant from the cued location. The object-based attention manifested as the same-object effect: subjects' detection of the invalidly cued target in the cued object is faster and more accurate than that appearing in the equidistant location in the uncued object.

The double-rectangle cuing paradigm has been widely used to investigate various properties of object-based attention (e.g., Abrams and Law 2000; Albrecht et al. 2008; Behrmann et al. 1998; Marino and Scholl 2005; Moore and Fulton 2005; Moore et al. 1998; Müller and Kleinschmidt 2003; Pilz et al. 2012; Pratt and Sekuler 2001; Richard et al. 2008; Shomstein and Behrmann 2006; Vecera and Farah 1994; Watson and Kramer 1999). All these studies focused on how visible objects guided attention (for a review, see Scholl 2001). However, little is known about whether object-based attention can occur with invisible objects or whether attention can select an object even when the object was invisible to us. Previous studies have shown that attention can select a spatial location (Bahrami et al. 2007; Jiang et al. 2006; Kanai et al. 2006; Mulckhuyse et al. 2007; Zhang et al. 2012) or a visual feature (Kanai et al. 2006; Melcher et al. 2005) without awareness, which stimulated the current study. Here, we aimed to use a modified double-rectangle cuing paradigm to test whether object-based attention can occur with invisible rectangles. In this modified paradigm, along with a cue or a target, low-contrast rectangles were presented against a dark background for only 10 ms, which rendered the rectangles invisible to subjects.

In the original double-rectangle cuing paradigm, the rectangles that the target appeared with were identical to those that the cue appeared with. With this paradigm, it is hard to tell whether object-based attention can be affected by a new (changed) object appeared with the target. The question makes ecological sense because the retinal inputs of our visual world change constantly. Two competing hypotheses have been proposed on this issue. One is the cued object hypothesis (Goldsmith and Yeari 2003). It proposes that when attention is cued to an object and selects it for further processing, it should be this cued object that forms the object representation and remains selected as a processing unit. Object-based attention is determined by the originally cued object, rather than the changed object presented after the cue. Lamy and Tsal (2000) provided evidence supporting this hypothesis. In their study, two similar objects (a rectangle and an hourglass) were presented in different colors. Before the target was shown, they swapped the cued object and the uncued object to decouple the location and the colored shape of the two objects. After the switch, detection of the target at the previously cued object location was faster than that at the previously uncued object location (which was now occupied by the cued object). This observation implied that it was the location belonging to the cued object (including the cued and uncued locations of the previously attended object), but not the colored shape of the cued object, that was selected.

The other hypothesis is the dynamic updating hypothesis proposed by Ho and Yeh (2009). They found that, when the cued object (e.g., the cued rectangle) suddenly disappeared from view, no object-based attentional effect was obtained. But if the cued object was replaced by a new object, attention was reallocated according to the new object, rather than remaining on the original object. This phenomenon is called the instantaneous object effect. Their result demonstrated that the changed object could guide the deployment of attention and determine object-based attention. Our second goal was to test these two hypotheses with invisible objects.

A very recent study by Chou and Yeh (2012) combined the double-rectangle cuing paradigm and the continuous flash suppression (CFS) technique (Tsuchiya and Koch 2005) to study the dependence of object-based attention on object awareness. They found that invisible rectangles could still induce the same-object effect and guide object-based attention. In the current study, a very different method was used to render objects invisible, thereby implicating a distinct underlying neural mechanism (see "Discussion"). Here, we not only examined the generalization of Chou and Yeh's finding, but also, for the first time, tested the dynamic updating hypothesis with invisible objects.

Methods

Subjects

A total of twelve human subjects (six male and six female, 21–25 years old) participated in the study. All subjects were naïve to the purpose of the study except for one subject (one of the authors). They were right-handed, reported normal or corrected to normal vision, and had no known visual disorders. They gave written, informed consent in accordance, and our procedures were approved by the human subject review committee of Peking University.

Apparatus, stimuli, and procedure

Visual stimuli were displayed on an IIYAMA color graphic monitor (model: HM204DT; refresh rate: 100 Hz; resolution: 1,024 × 768; size: 22 inches) at a viewing distance of 62 cm. Subjects' head position was stabilized using a chin rest. A white fixation cross was always present on a dark background (luminance: 1.6 cd/m^2) at the center of the monitor.

The study consisted of three experiments. Experiments 1 and 2 investigated whether visible and invisible objects could guide subjects' attention. Subjects participated in Experiments 1 and 2 on two different days, and the order of the two experiments was balanced across subjects. Experiment 3 checked the effectiveness of the awareness manipulation in Experiment 2 and was always before Experiment 2. The stimuli and procedures for the three experiments were very similar (Fig. 1). In Experiment 1, each trial began with the fixation cross presented for 500 ms. Then a cue frame was presented for 10 ms, which contained two vertical or horizontal rectangles (luminance: 31.9 cd/m^2; size: 1.6° × 16°). In the vertical rectangle condition, they were orientated as columns centered 7.2° left and right of fixation, and in the horizontal rectangle condition, they were oriented as rows centered 7.2° above and below fixation. The four ends of the two rectangles (i.e., the possible locations of cue and target) occupied the same locations in these two conditions. Horizontal and vertical rectangles appeared equiprobably and randomly in the experiment. The cue (luminance: 103 cd/m^2; size: 1.6° × 1.6°) was an empty square that overlapped one end of a rectangle. Following the cue frame and a 200-ms fixation display, a target frame was presented for 10 ms, which also contained two rectangles. The rectangles had the same properties as those in the cue frame except that the rectangle orientation consistency between the cue and the target frames was manipulated. In half of the trials, the rectangle orientations in the cue and the target frames were the same (the same orientation condition), and in the remaining trials, they were orthogonal to each other (the orthogonal orientation condition). The target (luminance: 103 cd/m^2; size: 1.6° × 1.6°) was a solid square that overlapped one end of a rectangle. Subjects were asked to press a button as rapidly as possible whenever a target was detected at any of the four rectangle ends. Their reaction times (RTs) were recorded.

Experiment 1 consisted of 20 blocks of 96 trials. In a block, the target appeared in 80 trials and was absent in the remaining 16 catch trials. Any response in a catch trial was recorded as an error. The target appeared at the cued rectangle end in 60 trials (the valid condition, VC). It could also appear at the uncued end of the cued rectangle in 10 trials (the

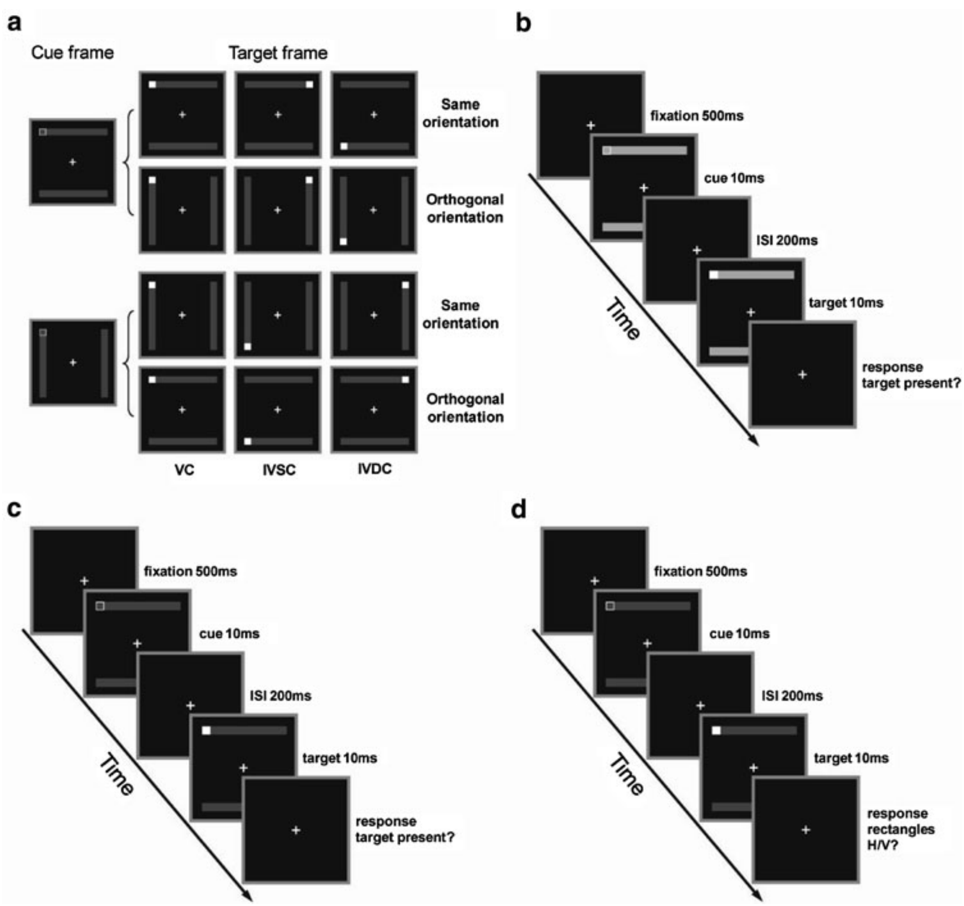

Fig. 1 Stimuli and experimental procedures. **a** Visual stimuli. The *rectangles* in the cue frame and the target frame were either the same or orthogonal to each other. The target appeared frequently at the cued rectangle end (the valid condition, VC). It could also appear at the uncued end of the cued rectangle (the invalid-same condition, IVSC) or at the equidistant end of the uncued rectangle (the invalid-different condition, IVDC). **b** Procedure of Experiment 1. A trial began with a 500-ms fixation, followed by a cue frame presented for 10 ms. After a 200-ms fixation display, a target frame was presented for 10 ms. Subjects were asked to press a button as rapidly as possible whenever a target was detected at any of the four rectangle ends. **c** Procedure of Experiment 2. It was identical to that of Experiment 1 except that the contrast of the rectangles was very low. The rectangles here are rendered with a higher contrast for illustration purpose. **d** Procedure of Experiment 3. It was similar to that of Experiment 2. The only difference is that subjects were asked to judge the rectangle orientation in the cue and target frames—horizontal or vertical?

invalid-same condition, IVSC) or at the equidistant end of the uncued rectangle in 10 trials (the invalid-different condition, IVDC). In other words, in all invalid-cue trials (i.e., the IVSC and IVDC conditions), the target appeared at a rectangle end, which was a reflection from the cued end across either the horizontal or vertical meridian. The target never appeared at the rectangle end diametrically opposite to the cued end. All conditions (VC, IVSC, IVDC, and catch trial) were randomized in a block. Subjects received the percentage of correct responses after each block.

The stimuli and procedure in Experiment 2 were the same as those in Experiment 1 except that the luminance of the rectangles in the cue and the target frames was 1.85 cd/m^2. The low contrast (Michelson contrast: 0.0725) and the short duration (i.e., 10 ms) of the rectangles rendered them invisible to subjects, as confirmed by Experiment 3 (see "Results"). Experiment 3 was identical to Experiment 2 except that, after stimulus presentation in a trial, subjects needed to make a forced choice judgment twice to indicate the orientation of the rectangles in both the cue and target frames.

Results

In Experiments 1 and 2, false alarm rates were 3.53 and 3.64 %, and miss rates were 0.39 and 0.42 %, respectively. There was no difference in false alarm rate and miss rate across conditions. Correct RTs shorter than 150 ms and beyond three standard deviations from the mean RT in each condition were removed, which resulted in 1.52 and 1.69 % removal rates in Experiments 1 and 2, respectively.

Experiment 1: Visible object

The first goal of Experiment 1 was to use the double-rectangle cuing paradigm to measure object-based attention as indexed by the same-object effect. A second goal of the experiment was to test the dynamic updating hypothesis (Ho and Yeh 2009). The first goal can be achieved by analyzing RTs when the orientation of the rectangles in the target frame was the same as that in the cue frame. The second goal can be achieved by analyzing RTs when their orientations were orthogonal to each other. Both the same-object effect and the instantaneous effect were quantified as the RT difference between IVSC and IVDC.

Correct RTs were submitted to a two-way repeated-measures ANOVA with orientation consistency (same vs. orthogonal) and target location (VC, IVSC vs. IVDC) as within-subject factors. The main effect of orientation consistency ($F_{(1,11)} = 0.005$, $p = .945$) was not significant. The main effect of target location was significant ($F_{(2,22)} = 196.435$, $p < .001$), and the interaction between orientation consistency and target location was significant ($F_{(2,22)} = 186.344$, $p < .001$) (Fig. 2).

We further compared RTs at three target locations (VC, IVSC, and IVDC) in the same orientation condition. RTs (mean ± SEM) for VC, IVSC, and IVDC were 341 ± 7 ms, 366 ± 8 ms, and 380 ± 7 ms, respectively. Paired *t* tests showed that their differences were significant (VC vs. IVSC: $t_{11} = 11.281$, $p < .001$; IVSC vs. IVDC: $t_{11} = 18.189$, $p < .001$). The difference between IVSC and IVDC demonstrated a classical object-based attention effect. Subjects' detection of the invalidly cued target in the cued object (IVSC) was faster than that appearing in the equidistant location in the uncued object (IVDC). The same-object effect was 14.7 ± 1.9 ms.

We then compared RTs in the orthogonal orientation condition. RTs (mean ± SEM) for VC, IVSC, and IVDC were 342 ± 7 ms, 380 ± 8 ms, and 364 ± 8 ms, respectively. Paired *t* tests showed that their differences were significant (VC vs. IVSC: $t_{11} = 11.544$, $p < .001$; IVSC vs. IVDC: $t_{11} = 15.569$, $p < .001$). Contrary to the same orientation condition, RTs for IVSC were slower than those for IVDC in the orthogonal orientation condition. The instantaneous object effect was 16.1 ± 2.1 ms. This result supports the dynamic updating hypothesis—when the cued rectangle was suddenly replaced by an orthogonal rectangle, object-based attention was reallocated according to the new rectangle rather than the original one.

Experiment 2: Invisible object

Data were analyzed in the same way as that in Experiment 1. A two-way repeated-measures ANOVA showed that the main effect of orientation consistency ($F_{(1,11)} = 0.471$, $p = .507$) was not significant, the main effect of target location was significant ($F_{(2,22)} = 56.825$, $p < .001$), and the interaction

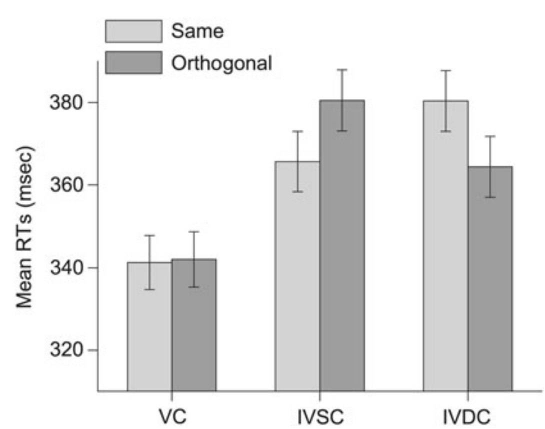

Fig. 2 Results of Experiment 1. Mean RTs are shown for VC, IVSC, and IVDC in the same and orthogonal orientation conditions. Data were averaged across twelve subjects. *Error bars* denote 1 SEM calculated across subjects

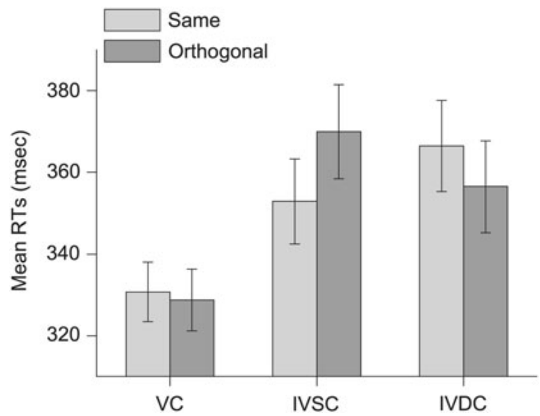

Fig. 3 Results of Experiment 2. Mean RTs are shown for VC, IVSC, and IVDC in the same and orthogonal orientation conditions. Data were averaged across twelve subjects. *Error bars* denote 1 SEM calculated across subjects

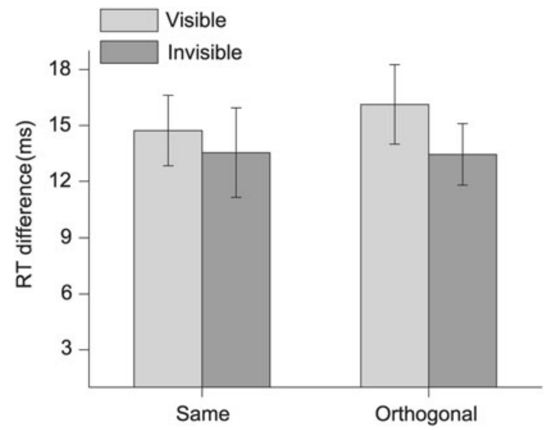

Fig. 4 Mean RT differences between IVSC and IVDC in the same and orthogonal orientation conditions in Experiments 1 (visible) and 2 (invisible). Data were averaged across twelve subjects. *Error bars* denote 1 SEM calculated across subjects

between orientation consistency and target location was significant ($F_{(2,22)} = 40.551$, $p < .001$) (Fig. 3).

Paired t tests were used to compare RTs at three target locations (VC, IVSC, and IVDC). In the same orientation condition, RTs for VC, IVSC, and IVDC were 331 ± 7 ms, 353 ± 10 ms, and 366 ± 11 ms, respectively. Their differences were significant (VC vs. IVSC: $t_{11} = 5.194$, $p = .001$; IVSC vs. IVDC: $t_{11} = 5.643$, $p < .001$). The difference between IVSC and IVDC demonstrated that the same-object effect (13.5 ± 2.4 ms) could occur with invisible objects.

In the orthogonal orientation condition, RTs for VC, IVSC, and IVDC were 328 ± 8 ms, 370 ± 12 ms, and 356 ± 11 ms, respectively. Paired t tests showed that their differences were significant (VC vs. IVSC: $t_{11} = 9.569$, $p < .001$; IVSC vs. IVDC: $t_{11} = 8.112$, $p < .001$). Contrary to the same orientation condition, RTs for IVSC were slower than those for IVDC in the orthogonal orientation condition. The instantaneous object effect was 13.4 ± 1.7 ms.

The above analyzes revealed that the same-object effect and the instantaneous object effect could occur with both visible and invisible objects. We further examined how awareness affected these two effects by comparing the data in Experiment 1 (visible object) and Experiment 2 (invisible object). RT differences between IVSC and IVDC were submitted to a two-way repeated-measures ANOVA with visibility (visible vs. invisible) and effect type (same-object effect vs. instantaneous object effect) as within-subject factors (Fig. 4). The main effects of visibility ($F_{(1,11)} = 0.750$, $p = .405$) and effect type ($F_{(1,11)} = 0.225$, $p = .645$) were not significant. The interaction between visibility and effect type ($F_{(1,11)} = 0.631$, $p = .444$) was also not significant. These results demonstrated that the same-object effect and the instantaneous object effect were independent of object awareness (Fig. 4).

Experiment 3: Awareness manipulation check

Two characteristics of the rectangles in Experiment 2—low contrast and brief presentation, rendered them invisible to subjects, as confirmed by the 2-AFC test in Experiment 3. Figure 5 shows the mean accuracies of subjects' judgment of the rectangle orientation in both the cue and target frames for VC, IVSC, and IVDC. None of the accuracies was significantly different from the chance level (all $t_{11} < 1.749$, $p > .108$) (Fig. 5). These results provided an objective confirmation that the rectangles were indeed invisible to subjects in Experiment 2. We rerun Experiment 3 after Experiment 2 and obtained similar results (data not shown here), which further demonstrate that our awareness manipulation is robust.

Discussion

Using a modified double-rectangle cuing paradigm, we investigated whether object-based attention could be guided by an invisible object. Experiment 1 used visible objects. It not only showed that the paradigm could yield a classical object-based attention effect (i.e., the same-object effect), but also revealed the instantaneous object effect, supporting the dynamic updating hypothesis. Experiment 2 demonstrated that both the same-object effect and the instantaneous object effect could occur with invisible objects. Notably, the magnitudes of the two effects were comparable between visible and invisible objects.

Recently, Chou and Yeh (2012) combined the double-rectangle cuing paradigm and the CFS technique (Tsuchiya and Koch 2005) to study the dependence of object-based attention on object awareness. Rectangles were presented in the nondominant eye and dynamic Mondrians (i.e., the

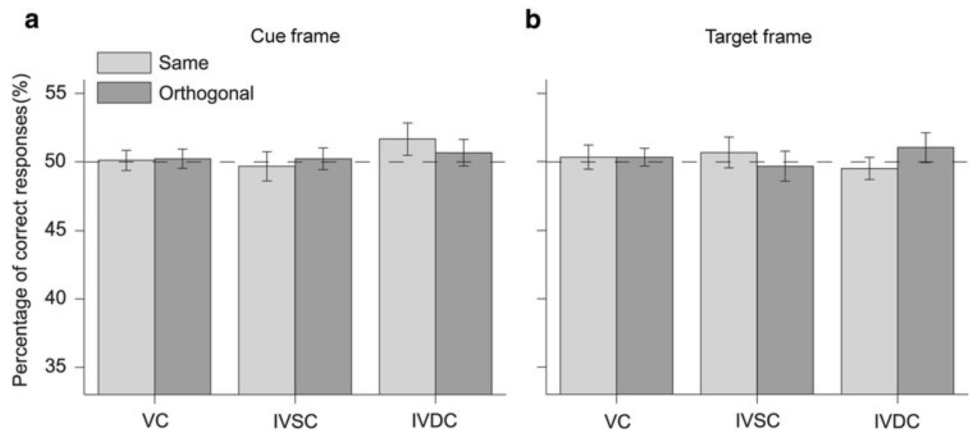

Fig. 5 Results of Experiment 3. Mean accuracies are shown for VC, IVSC and IVDC in the same and orthogonal orientation conditions (*Left* cue frame, *right* target frame). Data were averaged across twelve subjects. *Error bars* denote 1 SEM calculated across subjects

masks) were in the dominant eye. Due to the interocular suppression from the Mondrians, subjects were not aware of the rectangles. They found that the invisible rectangles could still induce the same-object effect and guide object-based attention. This study and ours provide strong evidence, supporting that object-based attention can be guided by an invisible object. In other words, object awareness is not necessary for object-based attention, and visible and invisible objects may trigger the same attentional process (Astle et al. 2010), making attention either shift faster within the cued object (Egly et al. 1994) or spread throughout the whole cued object, as compared with the uncued object (Richard et al. 2008; Weber et al. 1997).

The current study provides evidence for a long-standing debate whether attention and consciousness are independent (Fang and He 2005; Koch and Tsuchiya 2006, 2012; Watanabe et al. 2011). Previous studies have demonstrated that an invisible stimulus can capture attention to a spatial location (Bahrami et al. 2007; Jiang et al. 2006; Mulckhuyse et al. 2007; Zhang et al. 2012) or to a visual feature (Kanai et al. 2006; Melcher et al. 2005) for further processing. Here, we extended previous work to object-based attention: attention also can select an object even when the object is invisible to us. The ability of object-based attentional guidance by an invisible object seems to have an ecological function—some potentially important objects may be able to capture attention and undergo deeper processing before they enter consciousness. For example, a predator appearing in the peripheral visual field of a prey could trigger the prey's escape behavior even it is not consciously aware of the predator. Object-based attention without awareness might be intrinsically related to high-level unconscious processing, including word meaning, scene gist, object category, and face emotion (Naccache et al. 2002; Li et al. 2002; Fang and He 2005; Almeida et al. 2008; Jiang and He 2006; Yang et al. 2007). A recent fMRI study (Kouider et al. 2009) has shown that attention was necessary for unconscious face priming, providing direct evidence for this view.

It should be pointed out that, although both Chou and Yeh's study and ours demonstrated object-based attention without awareness, the neural mechanisms underlying the two phenomena might be different. Neuroimaging studies have shown that posterior parietal cortex, object-selective cortical areas in the ventral stream, as well as early visual cortex contributed to object-based attention (O'Craven et al. 1999; Müller and Kleinschmidt 2003; Shomstein and Behrmann 2006). Chou and Yeh used the CFS technique to suppress the rectangles from awareness. It is believed that CFS could block the processing of suppressed information in higher visual areas, especially in the ventral stream (Leopold and Logothetis 1996; Fang and He 2005; Almeida et al. 2008; Jiang and He 2006). Thus, posterior parietal cortex might be critical for the object-based attention in Chou and Yeh's study. In the current study, we used very weak stimuli to assure their invisibility. We believe that the weak stimuli were able to activate higher visual areas in both the dorsal and the ventral streams, although the activation magnitude could be much reduced compared to visible stimuli (Dehaene et al. 2001; Kouider et al. 2009). In the future, it is worthwhile to perform brain imaging studies to investigate the neural mechanisms of object-based attention with invisible objects.

A second finding of the current study is that object-based attention was dependent on the orientation of the rectangles presented with the target, regardless of subjects' awareness of the rectangles, which provides evidence for the dynamic updating hypothesis (Ho and Yeh 2009). After the cued object disappeared, the cued location remained operational and might be used to link to the new object (Brown and Denney 2007). The sudden onset of the new object may immediately capture attention (Enns et al. 2001; Franconeri and Simons 2003; Yantis 1993), which led to the instantaneous object effect. This finding seems to be contradictory to Lamy and Tsal's result (2000). We believe that the similarity between the originally cued object and later changed object may account for the discrepancy. They used two similar objects (a rectangle and an hourglass), but we used orthogonal rectangles.

In conclusion, we found that the same-object effect and the instantaneous object effect could occur even when objects were not consciously perceived, suggesting that object-based attention can be guided by an invisible object in an automatic way, with a minimal influence from top-down control.

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