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Prioritization to visual objects: Roles of sensory uncertainty

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Abstract Two hypotheses, attentional prioritization and attentional spreading, have been proposed to account for object-based attention. The attentional-prioritization hypothesis posits that the positional uncertainty of targets is sufficient to resolve the controversy raised by the competing attentional-spreading hypothesis. Here we challenge the sufficiency of this explanation by showing that object-based attention is a function of sensory uncertainty in a task with consistent high positional uncertainty of the targets. In Experiment 1, object-based attention was modulated by sensory uncertainty induced by the noise from backward masking, showing an object-based effect under high as compared to low sensory uncertainty. This finding was replicated in Experiment 2 with increased task difficulty, to exclude that as a confounding factor, and in Experiment 3 with a psychophysical method, to obtain converging evidence using perceptual threshold measurement. Additionally, such a finding was not observed when sensory uncertainty was eliminated by replacing the backward-masking stimuli with perceptually dissimilar ones in Experiment 4. These results reveal that object-based attention is influenced by sensory uncertainty, even under high positional uncertainty of the targets. Our findings contradict the proposition of attentional spreading, proposing instead an automatic form of object-based attention due to enhancement of the perceptual representation. More importantly, the attentional-prioritization hypothesis based solely on positional uncertainty cannot sufficiently account for object-based attention, but needs to be developed by expanding the concept of uncertainty to include at least sensory uncertainty.

Keywords Attentional prioritization · Uncertainty reduction · Object-based attention · Attentional spreading

Objects are considered as the units of selective attention, because participants' attentional performance is better for stimuli in a single object than those in separate objects. This benefit is indexed as the *object-based effect* and has been observed in myriad tasks (Duncan, 1984; Egly, Driver, & Rafal, 1994; Mitchell, Stoner, & Reynolds, 2004; Vecera, 2000). Although object-based attention has been explored further with neurophysiologic measurements (Baldauf & Desimone, 2014; Cohen & Tong, 2015; He, Humphreys, Fan, Chen, & Han, 2008; Martinez et al., 2006), a theoretical framework for object-based attention has not yet been fully determined.

One theory of object-based attention is the *attentional-prioritization hypothesis*, which proposes that an attended object is prioritized by selective attention; therefore, stimuli in the attended object receive a higher priority of perceptual selection than those in an unattended object (Shomstein, 2012; Shomstein & Yantis, 2002, 2004). Importantly, this prioritization of perceptual selection relies on the positional uncertainty of targets. Specifically, perceptual selection automatically prioritizes the target with a certain or predictable position, thus ruling out object-based attention; otherwise, the attended object is prioritized, resulting in an object-based effect (Shomstein & Yantis, 2002, 2004). The other hypothesis, *attentional spreading*, postulates that attention spreads across an

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object enclosing a spatial cue, resulting in a better perceptual representation of stimuli within the attended object than of those in unattended objects (Chen & Cave, 2006, 2008; Richard, Lee, & Vecera, 2008). Notably, automaticity is an important characteristic of attentional spreading, such that the object-based effect is predicted regardless of the positional uncertainty of targets.

The obvious distinction between attentional prioritization and attentional spreading is the automaticity of object-based attention. This distinction was thought to be resolved by determining the role of positional uncertainty in object-based attention (Chen & Cave, 2006; Richard et al., 2008; Shomstein & Yantis, 2002, 2004). The attentional-prioritization hypothesis is reinforced by findings that an object-based effect is present when the position of the target is uncertain, but this object-based effect is eliminated when the position of the target is certain (Drummond & Shomstein, 2010; Shomstein & Yantis, 2002, 2004). In contrast, the attentional-spreading hypothesis is reinforced by the presence of an object-based effect even when the position of the target is certain (Chen & Cave, 2006; Richard et al., 2008). Furthermore, the object-based effect has been modulated by target uncertainty when positional uncertainty is controlled (Collegio, Kakpovi, Whitman, & Shomstein, 2014). Therefore, positional uncertainty may be fundamentally insufficient for distinguishing attentional prioritization from attentional spreading if other forms of uncertainty are also relevant.

For example, sensory input from visual stimuli can be less informative in poor lighting or conditions of poor visual contrast, thus becoming uncertain and difficult to interpret. Sensory uncertainty regarding the targets can be experimentally induced by adding distractors (Palmer, Ames, & Lindsey, 1993) or noise (Dosher, Han, & Lu, 2010), such that the distractors or noise may allow other stimuli to be regarded as targets by mistake. Since sensory information is accumulated over time (Cisek, Puskas, & El-Murr, 2009; Heekeren, Marrett, & Ungerleider, 2008), the target can somehow become integrated with subsequent stimuli. Such integration may also affect the sensory ambiguity and uncertainty of targets (Luck, Hillyard, Mouloua, & Hawkins, 1996; Shiu & Pashler, 1994). In some experiments, backward masking of the target has been manipulated to define the degree of sensory uncertainty. Specifically, a one-itemed mask at the target position is used to create low sensory uncertainty, because such a mask makes the target distinct from the background and reduces the possibility of mistaking the target because of noise. In contrast, a four-itemed mask induces high sensory uncertainty, which distributes at every candidate position for the target and makes the target indistinguishable from the other stimuli. In this manipulation, the sensory input from targets is identical whether they are followed by single or multiple backward masking; thus, there is no difference in target perception between conditions of low and high sensory uncertainty. This manipulation implies that the perceptual processing of targets at an early stage is probably similar and that sensory uncertainty may exert its influence at a decision level or a late stage of perception, by producing noise.

In the present study, we expected that the involvement of sensory uncertainty in object-based attention would be capable of resolving the substantial controversy over attentional spreading versus attentional prioritization—that is, over the perceptual enhancement versus prioritized perceptual selection of the attended object. The attentional-spreading hypothesis proposes that attention is allocated to the cued object; thus, this object gains more attentional resources and enhances the perceptual representation of targets within it (Richard et al., 2008; Wannig, Stanisor, & Roelfsema, 2011). This object-based perceptual enhancement of targets should not be curtailed by a subsequent mask, and thus the object-based effect would not be eliminated by sensory uncertainty that affected the late stage of perception. That is, the object-based effect should be observed regardless of the degree of sensory uncertainty. In contrast, the attentional-prioritization hypothesis proposes that perceptual selection is prioritized according to the positional uncertainty of targets (Shomstein, 2012; Shomstein & Yantis, 2002, 2004). Since the positional information related to targets is likewise unpredictable at both degrees of sensory uncertainty, the sensory uncertainty should likewise not affect the object-based effect if attentional prioritization is based purely on positional uncertainty. However, the attentional prioritization of selection may be influenced not only by positional but also by sensory uncertainty, since attentional selection has been reported to rely on various forms of uncertainty (Collegio et al., 2014; Davis, Kramer, & Graham, 1983; Dosher & Lu, 2000; Lu, Lesmes, & Dosher, 2002; Shiu & Pashler, 1994). If the hypothesis of attentional prioritization can be extended to include uncertainty in a broader sense, the object-based attentional prioritization of perceptual selection might then be influenced by sensory uncertainty. Here we manipulated different degrees of sensory uncertainty and maintained high positional uncertainty of the targets, which allowed for a critical evaluation of the role of sensory uncertainty in object-based attention and a distinction between attentional prioritization and attentional spreading.

In the present study, object-based attention was investigated with a dual-rectangle paradigm (Egly et al., 1994) by manipulating sensory uncertainty and maintaining high positional uncertainty. First, the target was briefly presented to achieve data-limited processing (Duncan, 1983, 1984; Ho, 2011), which is essential for sensory uncertainty (Luck et al., 1996; Shiu & Pashler, 1994). Importantly, sensory uncertainty was differentiated through distinct patterns of backward masking, as in previous studies (Luck et al., 1996; Shiu & Pashler, 1994). That is, low and high sensory uncertainties were defined, respectively, by a one-itemed mask that followed the target in the same position and a four-itemed mask that was distributed at every candidate position for the target. Moreover, the position of the targets remained uncertain because the target was presented unpredictably within or outside the cued object following an invalid cue. In the present study, we tested the attentional-spreading and attentional-prioritization hypotheses by determining the role of sensory uncertainty in object-based attention. According to the attentional-spreading model, the object-based effect should be observed, because attentional spreading theoretically enhances the perceptual representation of the target in the attended object automatically. In contrast, the attentional-prioritization model could have different predictions for the present task, depending on the definition of uncertainty. If attentional prioritization is modulated merely by positional uncertainty (Drummond & Shomstein, 2010; Shomstein & Yantis, 2002, 2004), the object-based effect should be observed in the high positional uncertainty of the present task and independent of sensory uncertainty. Note that this prediction would not allow us to differentiate attentional prioritization from attentional spreading, because both models predict an object-based effect under both low and high sensory uncertainty. However, if attentional prioritization can be modulated by uncertainty in a general sense, such as by sensory uncertainty, as we proposed in this study, the object-based effect should be observed under high sensory uncertainty, but should be reduced or even disappear under low sensory uncertainty. Therefore, we could distinguish attentional prioritization from attentional spreading by evaluating the role of sensory uncertainty in object-based attention. Four experiments were conducted. In Experiment 1, the relationship between the object-based effect and sensory uncertainty, defined by one- and four-itemed masks, was explored. In an attempt to consolidate the results of Experiment 1, an additional three experiments were implemented, to exclude the confounding factor of task difficulty in Experiment 2, to obtain converging evidence through measurement of the perceptual threshold in Experiment 3, and to refute an explanation of positional uncertainty in Experiment 4.

Experiment 1

Method

Participants Twenty (14 females, six males; age = 19.3 ± 1.49 years old) students taking an introductory psychology course at Tsinghua University took part in this experiment in exchange for extra course credit. They were right-handed with normal or corrected-to-normal vision and were naive to the experiment. Informed consent was obtained from all participants.

Apparatus and stimuli The experiment was programmed in MATLAB (R2009a) using Psychophysics Toolbox 3.0 (http://psychtoolbox.org/) (Brainard, 1997). The stimuli were presented on a 17-in. CRT monitor viewed from a distance of approximately 70 cm. A custom keyboard was used to collect responses. The screen was set to 1,024 × 768 pixels with a refresh rate of 85 Hz.

The background was gray in color (RGB: 128, 128, 128; luminance = 25.8 cd/m^2). A black dot (RGB: 0, 0, 0; luminance = 6.4 cd/m^2) was displayed in the center of the screen with a visual angle of 0.4° × 0.4°. Two solid black rectangles were oriented vertically or horizontally (see Fig. 1). Each rectangle subtended a 6.48° × 1.06° of visual angle, with a 4.42° visual angle of separation between them. The cue (RGB: 255, 255, 255; luminance = 28.3 cd/m^2) consisted of three white lines that perfectly circumscribed one end of a rectangle. The target (RGB: 255, 255, 255; mean luminance = 20.7 cd/m^2; 1° × 1° of visual angle), in Calibri font, and the mask ("#"; RGB: 255, 255, 255; mean luminance = 37.2 cd/m^2; 1.06° × 1.06° of visual angle) appeared at the inner ends of the rectangles.

Procedure and design Each trial began with a display containing a black dot and two rectangles for a preview time of 500 ms. The cue was then flashed at one of the four ends of the two rectangles for 100 ms and was followed by an interstimulus interval of 100 ms. The target, a T or an F, appeared at one end of a rectangle for 100 ms and was followed by the mask for 500 ms. In the mask display, a one-itemed mask was located at the same position as the target, or a four-itemed mask was distributed across all ends of both rectangles. If no response was obtained during the mask display, another display with the fixation dot was added until 1,200 ms had passed or until a response was given. The intertrial interval was randomized between 600 and 800 ms. The response keys were "S" and "L" on the keyboard, which corresponded to the F and T stimuli, counterbalanced between participants.

The program contained four blocks that each consisted of two sessions with the same pattern of masks. There were five trials per session, and feedback was added after each trial for 1,500 ms during the practice program. Next, participants were shown the experiment program, with 80 trials in each session and without feedback after each trial. The entire experiment took approximately 40 min.

A 3 (Validity: valid, invalid same-object, invalid different-object) × 2 (Mask: one-itemed, four-itemed) × 2 (Orientation: horizontal, vertical) within-subjects factorial design was implemented. Validity was defined as the target appearing at the cued location (valid), at the uncued end of the cued rectangle (invalid same-object), or at the end of the uncued rectangle nearest the cue (invalid different-object). The valid cue, invalid same-object cue, and invalid different-object cue appeared in a ratio of 3:1:1 and were randomly intermixed within a block. Additionally, Orientation and Mask were between-block factors, and blocks

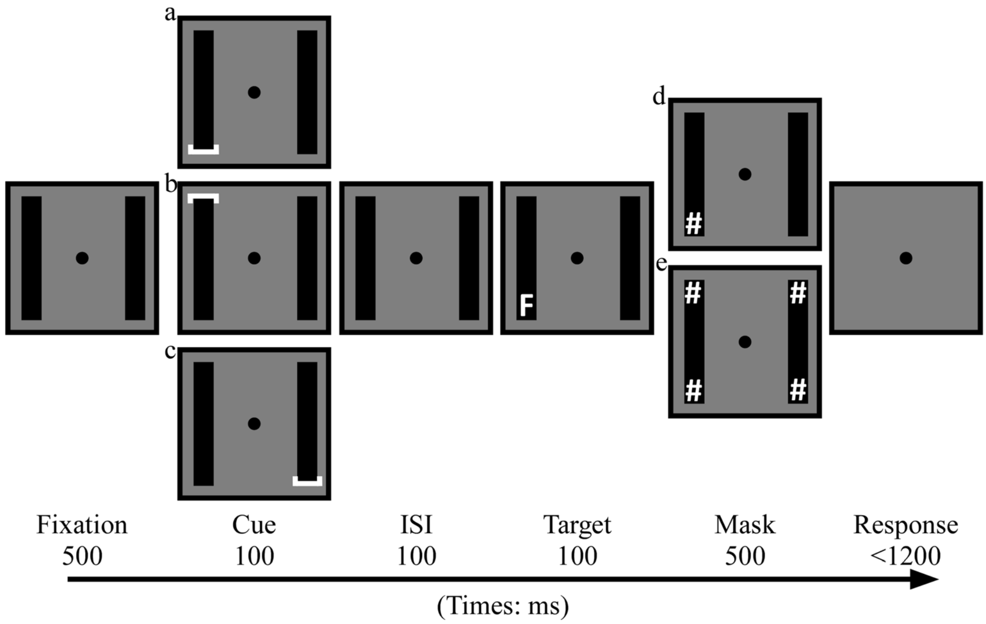

Fig. 1 Stimuli, sequence of events, and experimental design of Experiment 1. The task was to discriminate the target letter (T or F). The validity defining the relationship between the target and the cue was a within-block factor, including the (a) valid condition, (b) invalid same-object condition, and (c) invalid different-object condition. A one-itemed mask (d) and a four-itemed mask (e) followed the target in separate blocks. Only the vertical rectangles are presented here

of these combined factors were counterbalanced across subjects using a balanced Latin square design. In half of the blocks, the target was followed by the one-itemed mask, and in the other half it was followed by the four-itemed mask. The orientations of the rectangles, vertical and horizontal, were also counterbalanced between blocks.

Data analysis Participants with mean reaction times exceeding 2.5 standard deviations of the sample mean or accuracy below 60% were excluded from the subsequent analysis.

In the analysis, accuracy was considered the independent variable because of the data-limited manipulation (Collegio et al., 2014; Ho, 2011). A 3 × 2 × 2 within-subjects analysis of variance (ANOVA) was conducted. Subsequently, the space-based effect (referring to better performance in the valid condition than in the invalid same-object condition) and the object-based effect (better performance in the invalid same-object condition than in the invalid different-object condition) were distinguished via separate 2 × 2 × 2 ANOVAs. The Greenhouse–Geisser correction for degrees of freedom was used whenever the assumption of sphericity was violated. For multiple comparisons, p values were adjusted using the Bonferroni correction.

Results

According to the criterion of data exclusion, one participant was excluded because of long reaction times, so the data from 19 individuals contributed to the results.

The 3 (Validity: valid, invalid same-object, invalid different-object) × 2 (Mask: one-itemed, four-itemed) × 2 (Orientation: horizontal, vertical) ANOVA on mean accuracy showed significant main effects of validity [$F(2, 36) = 35.32$, $p < .001$, $\eta_p^2 = .66$; 92.9% in the valid condition, 79.1% in the invalid same-object condition, and 78.1% in the invalid different-object condition] and mask [$F(1, 18) = 12.43$, $p = .002$, $\eta_p^2 = .31$; 85.4% and 81.3% for the one- and four-itemed masks, respectively]. See Fig. 2 for a visualization. Importantly, a significant interaction between validity and mask was observed [$F(1, 18) = 3.60$, $p = .037$, $\eta_p^2 = .17$], suggesting that the performance of discriminating the target at different levels of validity was influenced by the sensory uncertainty induced by the masking patterns. No other significant main effect or interaction was observed ($p > .05$).

Space-based effect This effect was examined by conducting a 2 (Space: valid, invalid same-object) × 2 (Mask: one-itemed, four-itemed) × 2 (Orientation: horizontal, vertical) ANOVA. We found significant main effects of space [$F(1, 18) = 41.44$, $p < .001$, $\eta_p^2 = .70$; 92.9% vs. 79.1%] and mask [$F(1, 18) = 4.42$, $p = .05$, $\eta_p^2 = .20$; 87.2% vs. 84.8%]. No other main effect or interaction was significant ($p > .05$).

Object-based effect The 2 (Object: invalid same-object, invalid different-object) × 2 (Mask: one-itemed, four-itemed) × 2 (Orientation: horizontal, vertical) ANOVA revealed a significant main effect of mask [$F(1, 18) = 6.78$, $p = .018$, $\eta_p^2 = .27$; 80.7% vs. 76.5%]. However, no significant main effect of object was observed [$F(1, 18) < 1$, $p > .05$; 79.1% vs.

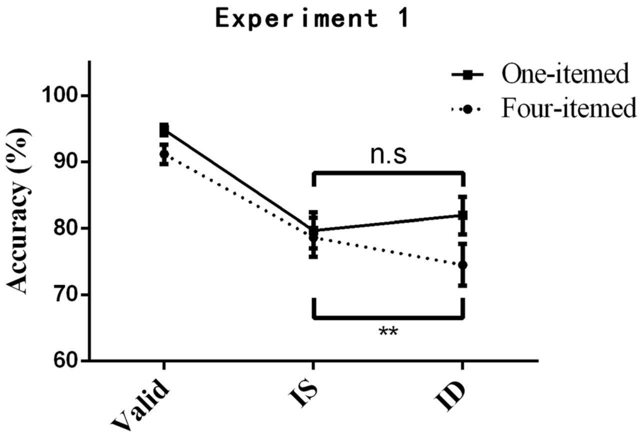

Fig. 2 Mean accuracy in Experiment 1 (standard errors indicated) for the valid, invalid same-object (IS), and invalid different-object (ID) conditions with different numbers of items in the mask. Note that "n.s" refers to $p > .05$, and ** indicates $p < .01$

78.1%], revealing no evidence of an object-based effect. Importantly, a significant interaction between object and mask was also observed [$F(1, 18) = 6.31$, $p = .022$, $\eta_p^2 = .26$], demonstrating the influence of sensory uncertainty on object-based attention. Specifically, the object-based effect under low sensory uncertainty (one-itemed mask) was not significant [$F(1.18) = 1.42$, $p > .05$; 79.6% vs. 81.9%], suggesting no indication of object-based attention. However, the object-based effect under high uncertainty (four-itemed mask) was significant [$F(1, 18) = 5.61$, $p = .029$, $\eta_p^2 = .238$; 78.5% vs. 74.4%], demonstrating object-based attention. No other significant main effect or interaction was observed ($p > .05$).

Discussion

Experiment 1 revealed that object-based attention is influenced by the sensory uncertainty induced by patterns of backward masking. Specifically, the object-based effect was more robust under high than under low sensory uncertainty. This observation challenges the attentional-spreading hypothesis, which lacks a mandatory object-based effect. Likewise, the observation also argues against the original view of attentional prioritization, which emphasizes positional uncertainty, since the object-based effects differ under equivalent high positional uncertainty of the targets. Importantly, the present findings support our hypothesis that attentional prioritization is modulated by sensory uncertainty.

First, the present results contradict the prediction of the attentional-spreading hypothesis. According to this hypothesis, the automatic attentional spreading from the cued location to the whole object (Richard et al., 2008) should result in an object-based effect regardless of our manipulation of sensory uncertainty. However, this prediction does not correspond with our observation that an object-based effect was absent in this task. Moreover, attentional spreading theoretically posits that the object-based effect should arise from the enhanced perceptual representation of a target in the attended object. Therefore, the object-based perceptual representation of targets should not be eliminated or weakened by masks following the targets. However, the masking patterns did modulate the object-based effect, and even eliminated the effect under low sensory uncertainty. Overall, attentional spreading cannot explain the present findings regarding object-based attention.

Moreover, the present findings are inconsistent with the idea of attentional prioritization that emphasizes positional uncertainty (Drummond & Shomstein, 2010; Shomstein & Yantis, 2002, 2004). According to this view, object-based attention exists as long as the position of the target is uncertain. In the present cueing task, the target position was fairly unpredictable regarding the same-object location and the different-object location. Thus, the object-based effect was predicted under both circumstances of sensory uncertainty. In this experiment, however, the object-based effect was observed only under high sensory uncertainty. Therefore, the present findings contradict the prediction of attentional prioritization that emphasizes the positional uncertainty of targets.

Importantly, the present findings are consistent with the idea that attentional selection is modulated by sensory uncertainty. That is, the object-based effect is larger under high than under low sensory uncertainty. This result implies that sensory uncertainty can influence perceptually selective prioritization and object-based attention; positional uncertainty is not sufficient in the object-based attentional prioritization model. Therefore, attentional prioritization seems to be modulated by uncertainty in a broad sense, including sensory uncertainty.

Experiment 2

Experiment 1 showed that object-based attention is dependent on sensory uncertainty. However, this observation may be confounded by task difficulty because the task was more difficult under high than under low sensory uncertainty. Since the object-based effect was observed under the more difficult (four-itemed mask) condition but disappeared under the less difficult (one-itemed mask) condition, it can be argued that the more difficult the task, the larger the object-based effect. Indeed, sensory uncertainty and task difficulty are dependent on each other (Bankó, Gál, Körtvélyes, Kovács, & Vidnyánszky, 2011). Therefore, we aimed to increase the overall task difficulty in order to resolve the confusion between task difficulty and sensory uncertainty in accounting for object-based attention. Two predictions were established on the basis of this argument regarding task difficulty: (1) increasing the overall task difficulty should enlarge the object-based effect that probably modifies the interaction between sensory uncertainty and object-based attention, and (2) conditions with equal difficulty should result in the same degree of object-based effect, regardless of sensory uncertainty. In Experiment 2, masks more similar to the target were applied in order to increase the overall task difficulty (Durlach et al., 2003; Kidd, Mason, & Arbogast, 2002).

Method

Participant Thirty right-handed college students with normal or corrected-to-normal vision participated in the experiment (16 females, 14 males; age = 20.8 ± 2.34 years old). Informed consent was obtained from all participants. They were naive to the task and were given monetary compensation for their participation.

Stimuli, design, and analysis Experiment 2 was similar to Experiment 1, except for the following differences.

The backward mask was generated with MATLAB rather than a simple "#" symbol. Each mask (1.06° × 1.06° of visual angle) consisted of five vertical lines and five horizontal lines, such that the mask and the target were more similar in their features (right angle and lines). Each line had a width of two pixels and a length randomized between six and 20 pixels.

The orientations of the rectangles were balanced between participants, because no difference related to orientation had been found in Experiment 1. Moreover, this design was intended to guarantee the number of correct trials by increasing the total number of trials in each combined condition, since the increase in task difficulty was expected to decrease the percentage of correct responses.

Following the analyses of Experiment 2, additional analyses were conducted to compare Experiment 1 and Experiment 2, so as to clarify the roles of task difficulty and sensory uncertainty in the object-based effect. To be brief, the data from horizontal and vertical rectangles were merged. A 3 (Validity) × 2 (Mask) × 2 (Difficulty) ANOVA and a 2 (Object) × 2 (Mask) × 2 (Difficulty) ANOVA were executed. In these analyses. difficulty was defined as the accuracy levels in Experiments 1 and 2. Finally, a comparison of the object-based effects was made between the one- and four-itemed mask conditions with similar performance. The criteria for data exclusion were the same as those in Experiment 1.

Results

Three participants were excluded from further analysis because of excessive errors following the data exclusion criteria. The remaining 27 participants (12 with the vertical orientation and 15 with the horizontal orientation) were incorporated into the following analysis.

Results of Experiment 2

The results of 3 (Validity: valid, invalid same-object, invalid different-object) × 2 (Mask: one-itemed, four-itemed) × 2 (Orientation: horizontal, vertical) ANOVA are as follows. A significant main effect of validity was observed [$F(2, 50) = 68.85, p < .001, \eta_p^2 = .73$; 90.3% in the valid condition, 72.3% in the invalid same-object condition, and 71.4% in the invalid same-object condition], and the main effect of mask was significant [$F(1, 25) = 25.11, p < .001, \eta_p^2 = .50$; 80.6% in the one-itemed mask condition and 75.4% in the four-itemed mask condition] as well. See Fig. 3 for a visualization. Importantly, a significant interaction between mask and validity was again observed [$F(2, 50) = 3.41, p = .041, \eta_p^2 = .12$]. This significant interaction effect indicates that the distinct masking patterns separately influenced the cueing effect. Additionally, the interaction between mask and orientation was significant [$F(1, 25) = 4.60, p = .042, \eta_p^2 = .16$]. No other main effect or interaction was significant ($p > .05$). The main findings in Experiment 1 thus were replicated.

Space-based attention The 2 (Space: valid, invalid same-object) × 2 (Mask: one-itemed, four-itemed) × 2 (Orientation: horizontal, vertical) ANOVA showed main effects of space [$F(1, 25) = 75, p < .001, \eta_p^2 = .74$; 90.3% vs. 72.3%] and mask [$F(1, 25) = 13.43, p < .001, \eta_p^2 = .34$; 83.2% vs. 79.5%]. A significant interaction between mask and orientation was observed [$F(1, 25) = 4.65, p = .041, \eta_p^2 = .16$]. In addition, the simple effect of mask was significant in the group with horizontal rectangles, indicating a difference between the effects of masking patterns with horizontal rectangles [$t(14) = 3.88, p < .001, d = 0.82$; 84.9% vs. 79%] and with vertical rectangles [$t(11) = 1.02\ p = .33$; 81.4% vs. 79.9%].

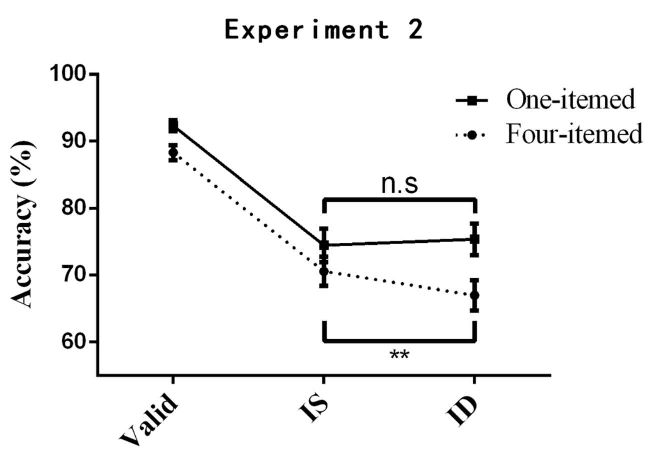

Fig. 3 Mean accuracy in Experiment 2 (standard errors indicated) as a function of cue validity (valid, invalid same-object [IS] and invalid different-object [ID]) and the posttarget mask. Note that "n.s" refers to $p > .05$, and ** indicates $p < .01$

Object-based effect The results of a 2 (Object: invalid same-object, invalid different-object) × 2 (Mask: one-itemed, four-itemed) × 2 (Orientation: horizontal, vertical) ANOVA are presented as follows. We found a main effect of mask [$F(1, 25) = 14.68$, $p = .001$, $\eta_p^2 = .37$; 74.8% vs. 69%]. However, the main effect of object was not significant [$F(1, 25) < 1$, $p > .05$; 72.3% vs. 71.4%], showing an absence of object-based attention. Notably, a significant interaction between mask and object was observed [$F(1, 25) = 6.10$, $p = .021$, $\eta_p^2 = .20$], indicating that object-based attention was influenced by the backward masking. A simple effect of object was reliably observed in the four-itemed mask condition [$F(1, 25) = 5.40$, $p = .029$, $\eta_p^2 = .18$; 70.6% vs. 67.4%], but not in the one-itemed mask condition [$F(1, 25) < 1$, $p > .05$; 74% vs. 75.5%]. Additionally, the interaction between orientation and object was also significant [$F(1, 25) = 8.81$, $p < .01$, $\eta_p^2 = .26$]. The simple effect of object was significant in displays with horizontal rectangles [$F(1, 25) = 7.38$, $p = .012$, $\eta_p^2 = .23$; 73.8% vs. 68.9%], but not with vertical rectangles [$F(1, 25) = 2.41$, $p > .05$; 70.9% vs. 74.0%]. No other significant main effect or interaction was observed ($p > .05$).

The main result of Experiment 1, that object-based attention is dependent on backward masking, was thus replicated.

Combined analysis of Experiment 1 and Experiment 2

The results of a 3 (Validity) × 2 (Mask) × 2 (Difficulty) ANOVA revealed main effects of both validity [$F(2, 88) = 94.35$, $p < .001$, $\eta_p^2 = .68$; 91.6% in the valid condition, 75.8% in the invalid same-object condition, and 74.7% in the invalid different-object condition] and mask [$F(1, 44) = 34.09$, $p < .001$, $\eta_p^2 = .44$; 78.3% in one-itemed mask condition and 83.0% in four-itemed mask condition]. The effect of difficulty between Experiment 1 and Experiment 2 [$F(1, 44) = 4.93$, $p = .03$, $\eta_p^2 = .10$; 83.4% vs. 78%] was statistically significant, with a higher accuracy in Experiment 1 than in Experiment 2. Importantly, the interaction between validity and mask was significant [$F(2, 88) = 6.63$, $p < .01$, $\eta_p^2 = 0.13$]. Specifically, the simple effects of validity were significant in both the one-itemed mask condition [$F(1, 43) = 52.20$, $p < .001$, $\eta_p^2 = .71$; 93.5%, 77%, and 78.6%] and the four-itemed mask condition [$F(1, 43) = 64.90$, $p < .001$, $\eta_p^2 = .75$; 89.6%, 74.5%, and 70.7%]. No other significant interaction was observed ($p > .05$).

The key results of a 2 (Object) × 2 (Mask) × 2 (Difficulty) ANOVA demonstrated significant main effects of mask [$F(1, 44) = 19.74$, $p < .001$, $\eta_p^2 = .31$; 77.8% vs. 72.6%] and difficulty [$F(1, 44) = 4.38$, $p = .04$, $\eta_p^2 = .09$; 78.6% vs. 71.8%]. Moreover, the interaction between mask and object was again significant [$F(1, 44) = 12.44$, $p = .001$, $\eta_p^2 = .22$], showing a simple effect of object only under high sensory uncertainty [$F(1, 44) = 35.90$, $p < .001$, $\eta_p^2 = .45$; 74.5% vs. 70.7%]. Importantly, the interaction between task difficulty and object was not significant ($p > .05$). No other main effect or interaction was significant ($p > .05$).

These results indicate that sensory uncertainty rather than task difficulty reliably influenced the object-based effect.

A comparison across sensory uncertainty with equal accuracy

The overall accuracies were 85.4% and 81.3% in Experiment 1 and 80.7% and 75.3% in Experiment 2 for the one- and four-itemed masks, respectively. Coincidentally, the accuracy in the four-itemed mask condition in Experiment 1 was similar to that in the one-itemed mask condition in Experiment 2. Thus, we examined the object-based effect under various sensory uncertainties with similar task difficulty. Note that the 2 (Object) × 2 (Mask) ANOVA was a post-mortem analysis that was not based on a well-controlled design.

This analysis showed a null main effect of mask ($p > .05$), indicating no difference in task difficulty between low and high sensory uncertainty. There was also no significant main effect of object ($p > .05$). Importantly, the interaction between mask and object was marginally significant [$F(1, 44) = 3.14$, $p = .08$, $\eta_p^2 = .07$]. In breaking down this interaction, we found a marginal object-based effect in the four-itemed mask condition [$F(1, 44) = 3.56$, $p = .06$, $\eta_p^2 = .08$; 78.5% vs. 74.4%], but no such effect in the one-itemed mask condition [$F(1, 44) < 0.1$, $p = .62$; 74.4% vs. 75.4%].

The marginal interaction implied that sensory uncertainty but not task difficulty accounted for the object-based effect. The combined findings most probably exclude the role of task difficulty in object-based attention in the present task.

Discussion

In Experiment 2, task difficulty was increased by utilizing masks that were similar to the target, and sensory uncertainty was still manipulated by masking patterns as in Experiment 1. The main results of Experiment 1 were replicated in the present task with increased difficulty. Importantly, the two predictions of the task difficulty argument were not supported by the results of this experiment. First, task difficulty is unlikely to have influenced object-based attention, because the main results of Experiment 1 and the overall object-based effect remained the same with a more difficult task. Second, the object-based effect was probably different (marginal significance) under similar task difficulties with various sensory uncertainties, even though the post-mortem analysis has some limitations. Therefore, the interaction between sensory uncertainty and object-based attention is largely due to sensory uncertainty and not to task difficulty. Additionally, the argument for a larger object-based effect with more difficult tasks conflicts with the observations in previous studies, which demonstrated more robust object-based effects (Ho & Atchley, 2009) and greater brain activation toward irrelevant features of an attended object (Sy et l., 2013) in less difficult tasks. Thus, the modulation of the object-based effect by different masking patterns seems to be attributable to sensory uncertainty rather than task difficulty.

Experiment 3

The experiments above were conducted with a data-limited manipulation in which accuracy was the primary index of behavioral measurement (Duncan, 1984; Ho, 2011; Luck et al., 1996; Shiu & Pashler, 1994). Besides accuracy, perceptual threshold is another measurement that is sensitive to probing perceptual processing in data-limited experiments (Stein & Peelen, 2015; Wildegger et al., 2015). Since the perceptual threshold of a stimulus has been reported to decrease with visual attention (Anobile et al., 2013; Dosher & Lu, 2000; Roesch et al., 2010; Solomon, 2004), it may also provide a sensitive measurement of object-based attention. Since a psychophysical method with the QUEST adaptive staircase procedure can be used to evaluate the minimum duration of a target at the perceptual threshold (Watson & Pelli, 1983), an object-based effect indexed by the perceptual threshold of duration is expected to change as a function of sensory uncertainty.

Method

Participants Eighteen participants (11 females, seven males; 22.05 ± 2.14 years) took part in the experiment. They were right-handed and had normal or corrected-to-normal vision. Informed consent was obtained from all participants, who were naive to the task and were provided with monetary compensation for their participation.

Stimuli, design, and analysis The procedure and stimuli in Experiment 3 were the same as those in Experiment 2, except for the target display duration, which was updated in light of the previous response using the psychophysical method. The psychometric function (PF) is a curve that represents the probability of a correct response along the continuum of increasing intensity of the target (Chen & Tyler, 2001; Lu & Dosher, 1998; Pelli, 1985; Wu & Chen, 2010) and follows a Weibull distribution. The parameters β, δ, and γ were chosen according to Watson and Pelli's (1983) recommendations for an alternative forced choice procedure: β controls the steepness of the PF (3.5), δ is the fraction of trials on which the observer presses at random (.05), and γ specifies the probability of success at zero intensity (.5). The *perceptual threshold* is the display duration that yields 75% correct responses in each condition. For each participant, six PFs were established with the QUEST threshold-seeking algorithm (Watson & Pelli, 1983) for each combined condition of validity and mask. The one-itemed mask and the four-itemed mask were arranged in separate sessions, and the orders were counterbalanced between participants. The two sessions consisted of 300 trials each, with 180 valid trials, 60 invalid trials for the same object, and 60 invalid trials for the different object.

The mean PFs were computed for each condition (the estimated cumulative Weibull distributions vary as a function of the probability and the duration of target display; see Fig. 4). The duration at which the correct response rate became greater than 75% was used as the independent variable. A 3 (Validity: valid, invalid same-object, invalid different-object) × 2 (Mask: one-itemed, four-itemed) ANOVA was conducted on the data. Then, two 2 × 2 ANOVAs were conducted to test the space-based attention effect and the object-based attention effect separately. The corrections for degrees of freedom and multiple comparisons were the same as in the experiments above.

Results

The data from one participant were excluded because he did not follow the instructions and made too many guesses. Since the perceptual thresholds of duration for the vertical rectangles (109 ms; nine participants) and for the horizontal rectangles (125 ms; eight participants) were not significantly different [$F(1, 15) = 2.10$, $p > .05$], the remaining analyses were collapsed across this factor.

The 3 (Validity: valid, invalid same-object, invalid different-object) × 2 (Mask: one-itemed, four-itemed) ANOVA yielded a significant main effect of validity [$F(2, 32) = 70.82$, $p < .001$, $\eta_p^2 = .83$; 64 ms in the valid condition, 140 ms in the invalid same-object condition, and 147 ms in the invalid different-object condition]. The interaction between validity and mask was significant [$F(2, 32) = 3.97$, $p = .03$, $\eta_p^2 = .21$], but the main effect of mask was not [$F(1, 16) < 1$, $p > .05$].

Space-based attention The 2 (Space: valid, invalid same-object) × 2 (Mask: one-itemed, four-itemed) ANOVA on thresholds demonstrated a significant main effect of space [$F(1, 16) = 66.38$, $p < .001$, $\eta_p^2 = .81$; 64 ms vs. 140 ms]. No other main effect or interaction was apparent ($p > .05$).

Object-based attention The 2 (Object: invalid same-object, invalid different-object) × 2 (Mask: one-itemed, four-itemed) ANOVA on thresholds showed a significant interaction between object and mask [$F(1, 16) = 11.21$, $p = .001$, $\eta_p^2 = .41$]. In breaking down this interaction, we found that the simple effect of object was not significant with the one-itemed mask [$F(1, 16) < 1$, $p > .05$; 142 vs. 137 ms] but was significant with the four-itemed mask [$F(1, 16) = 13.62$, $p = .002$, $\eta_p^2 = .46$; 135 vs. 155 ms]. Neither the main effect of

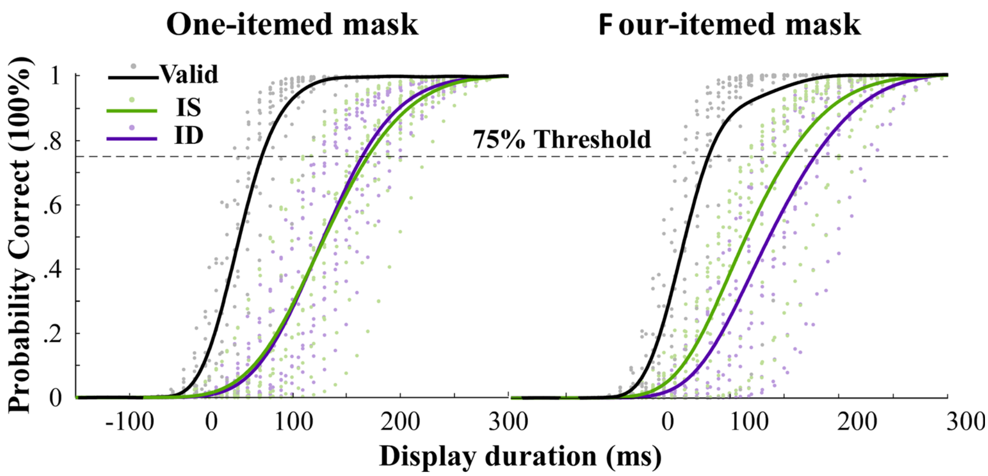

Fig. 4 Presentation of results for the psychometric method in Experiment 3. The dashed line displays the 75% threshold. The solid lines present the mean cumulative density functions of the participants' psychometric functions for the different experimental conditions

object [$F(1, 16) = 2.27$, $p > .05$; 140 vs. 147 ms] nor mask [$F(1, 16) < 1$, $p > .05$; 137 vs. 145 ms] was significant. The role of sensory uncertainty in object-based attention was replicated through the measurement of perceptual thresholds.

Discussion

With the perceptual threshold of duration as the psychophysical index, converging evidence that object-based effects varied as a function of sensory uncertainty were obtained. Specifically, the object-based effect, defined as a benefit in the perceptual threshold of duration for the invalid same-object target relative to the invalid different-object target in this experiment, was again larger under high than under low sensory uncertainty. This observation is consistent with the results of Experiments 1 and 2, in which accuracy was used as the primary index. Thus, the conclusion that sensory uncertainty affects object-based attention was supported by indices of both accuracy and perceptual threshold.

Perceptual threshold provides an important index for measuring object-based attention. First, the perceptual threshold is sensitive to perceptual processing, which can be modulated by visual attention (Stein & Peelen, 2015; Wildegger et al., 2015). Therefore, perceptual threshold can appropriately reflect the perceptual consequence of object-based attention. Second, perceptual threshold has been implemented to reveal object-based attention (Chou, Yeh, & Chen, 2014; Collegio et al., 2014; Han, Dosher, & Lu, 2003). For example, Chou, Yeh, and Chen demonstrated that the threshold of stimulus intensity was decreased for targets in attended as compared with unattended objects, suggesting that perceptual threshold provides a sensible measurement for object-based attention. In our experiment, the duration threshold was used to measure the object-based effect, which showed the same pattern of results as accuracy, regarding the role of sensory uncertainty in object-based effect. Third, the measurement of perceptual threshold can avoid the problem of task difficulty, since the accuracies were equal in every condition. Moreover, we found a modulation of perceptual threshold by a task-irrelevant object in the present study. This finding goes beyond our conventional understanding that the perceptual threshold decreases only for a task-relevant and attended stimulus (Cheal & Lyon, 1991; Mendoza, Schneiderman, Kaul, & Martinez-Trujillo, 2011; Seibold, Fiedler, & Rolke, 2010). Overall, the converging evidence from measuring perceptual thresholds further supports the observed dependence of object-based attention on sensory uncertainty.

Experiment 4

In the experiments above, sensory uncertainty was manipulated by backward masking. However, this manipulation of sensory uncertainty may be confounded with positional uncertainty. That is, the one-itemed mask at the same position as the target probably cued participants to the target position, whereas the four-itemed mask gave no indication of the position of a target. Thus, one might argue that positional uncertainty contributed to the present results. In Experiment 4, we aimed to resolve this contradiction by replacing the backward masks with circles. In this manipulation, the possible positional uncertainty was kept as in the above experiments, by presenting the one versus four circles. However, the circles reduced the possibility of sensory uncertainty because they lacked perceptual similarity to the targets. If the positional uncertainty provided by one- and four-itemed backward-masking stimuli is crucial for object-based attention, Experiment 4 should show the same pattern of results as Experiments 1–3. However, if sensory uncertainty is important for object-based attention, the reduction of sensory uncertainty with the circles in Experiment 4 should lead to diminished, or even disappeared, object-based attention in both the one- and four-itemed conditions.

Method

Participant Twenty-one right-handed college students with normal or corrected-to-normal vision participated in the experiment (14 males, seven females, age = 21.6 ± 2.22 years old). Informed consent was obtained from all participants, who were naive to the task and were given monetary compensation for their participation.

Stimuli, design, and analysis Experiment 4 was similar to Experiment 1, except for the following changes: The backward-masking stimuli were replaced by circles subtending 1.06° × 1.06° of visual angle. Also, the duration of the target was set at 59 ms after a preliminary experiment, such that the performance could be comparable to that in Experiments 1 and 2.

The criteria for data exclusion and the analyses were the same as those in Experiment 1.

Results

One participant with overall accuracy below 60% was excluded from the subsequent analyses, so the data from 19 participants contributed to the results.

Results of Experiment 4

The 3 (Validity: valid, invalid same-object, invalid different-object) × 2 (Circles: one-itemed, four-itemed) × 2 (Orientation: horizontal, vertical) ANOVA with a measurement of mean accuracy showed a significant main effect of validity [$F(2, 38) = 15.04$, $p < .001$, $\eta_p^2 = .44$; 90.1% in the valid condition, 83.9% in the invalid same-object condition, and 83.1% in the invalid different-object condition], as well as a marginal effect of circles [$F(1, 19) = 3.72$, $p = .069$, $\eta_p^2 = .16$; 86.6% and 84.8% for the one- and four-itemed circles, respectively]. See Fig. 5 for a visualization. The main effect of rectangle orientation was also significant [$F(1, 19) = 8.63$, $p = .008$, $\eta_p^2 = .31$; 83.7% and 87.7% for the horizontal and vertical rectangles, respectively]. A marginally significant interaction between these three factors was observed [$F(1, 19) = 2.83$, $p = .071$, $\eta_p^2 = .13$]. No other significant main effect or interaction was observed ($p > .05$).

Space-based effect This effect was examined by conducting a 2 (Space: valid, invalid same-object) × 2 (Circles: one-itemed, four-itemed) × 2 (Orientation: horizontal, vertical) ANOVA. We found a significant main effect of space [$F(1, 19) = 19.22$, $p < .001$, $\eta_p^2 = .50$; 90.1% vs. 83.9%] and a marginal main effect of circles [$F(1, 19) = 4.20$, $p = .055$, $\eta_p^2 = .18$; 87.9% vs. 86.1%]. Also, a main effect of orientation emerged [$F(1, 19) = 11.20$, $p = .003$, $\eta_p^2 = .37$; 84.7% vs. 89.2%]. No other main effect or interaction was significant ($p > .05$).

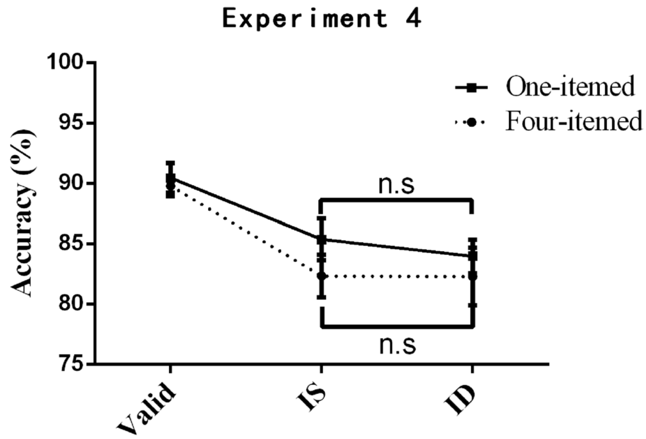

Fig. 5 Mean accuracy in Experiment 4 (standard errors indicated) as a function of cue validity (valid, invalid same-object [IS] and invalid different-object [ID]) and the number of backward-masking circles. Note that "n.s" refers to $p > .05$

Object-based effect The 2 (Object: invalid same-object, invalid different-object) × 2 (Circles: one-itemed, four-itemed) × 2 (Orientation: horizontal, vertical) ANOVA revealed a marginally significant main effect of circles [$F(1, 19) = 3.89$, $p = .063$, $\eta_p^2 = .17$; 80.7% vs. 76.5%] and a significant main effect of orientation [$F(1, 19) = 5.13$, $p = .035$, $\eta_p^2 = .21$; 81.6% vs. 85.4%]. However, there was no significant main effect of object [$F(1, 19) < 1$, $p > .05$; 84.7% vs. 82.3%], showing no evidence of an object-based effect. Importantly, no significant interaction between object and circle was observed, either [$F(1, 19) < 1$, $p > .05$], demonstrating that the positional information of the circles did not influence object-based attention. Additionally, no other significant main effect or interaction was observed ($p > .05$).

Combined analysis of Experiment 1 and Experiment 4

To determine the role of sensory uncertainty on object-based attention, we carried out a 2 (Object: invalid same-object, invalid different-object) × 2 (Backward-Masking Items: one-itemed stimuli, four-itemed stimuli) × 2 (Experiments: Exp. 1, Exp. 4) ANOVA. This analysis showed a main effect of backward-masking items [$F(1, 37) = 7.94$, $p = .008$, $\eta_p^2 = .18$], with higher accuracy in the one-itemed condition than in the four-itemed condition. The interaction between object and experiment was marginally significant [$F(1, 37) = 3.15$, $p = .08$, $\eta_p^2 = .08$]. Moreover, there was a significant three-way interaction [$F(1, 37) = 4.60$, $p = .039$, $\eta_p^2 = .11$]. When we broke up this interaction, the results showed an object-based effect only under the four-itemed condition in Experiment 1

[$F(1, 37) = 6.25$, $p = .017$, $\eta_p^2 = .15$]. Since the only difference between experiments was the manipulation of sensory uncertainty, these observations demonstrated again that sensory uncertainty contributed to the object-based effect. Additionally, we ran a 2 (Object: invalid same-object, invalid different-object) × 2 (Experiment: Exp. 1, Exp. 4) ANOVA, which directly compared the performance in the four-itemed conditions. Crucially, this analysis showed an interaction [$F(1, 37) = 4.25$, $p = .046$, $\eta_p^2 = .13$], with a stronger object-based effect in Experiment 1, under sensory uncertainty [$F(1, 37) = 6.14$, $p = .013$, $\eta_p^2 = .15$], than in Experiment 4, without sensory uncertainty [$F(1, 37) < 1$, $p > .1$]. This result confirmed the role of the sensory uncertainty on object-based attention.

Discussion

The results of Experiment 4 showed a different pattern of interaction between object-based attention and the backward-masking stimuli than in Experiments 1–3. In Experiment 4, the patterns of backward-masking stimuli with regard to positional uncertainty were similar, but the results with regard to sensory uncertainty were dissimilar from those in the other experiments. In particular, the backward-masking stimuli no longer affected object-based attention as those in the previous experiments had. This distinction must have been induced by the effects of the backward-masking stimuli—that is, sensory uncertainty exerts an influence through perceptual similarity (Hawkins et al., 1990). Specifically, when the target is similar to the irrelevant masking stimulus, such as with the masks in Experiments 1–3, there is a greater possibility that the participant will take the mask for a target. In contrast, if the target is distinct from the masking stimulus, as with the circles in Experiment 4, the possibility of confounding the following stimuli with the targets is greatly reduced. Additionally, the results of the combined analysis are rather clear. Specifically, the backward-masking stimuli modulated object-based attention in Experiments 1–3, which featured sensory uncertainty, whereas they did not affect object-based attention in Experiment 4, without sensory uncertainty. Therefore, the sensory uncertainty elicited by backward-masking stimuli affects object-based attention. Notably, the positional arrangement of the following stimuli was the same across all experiments—that is, the one-itemed stimulus at the location of the target, and the four-itemed stimuli at all candidate locations for the target. Thus, the object-based effect induced by backward-masking stimuli is unlikely to be accounted for by so-called positional uncertainty. Besides, the concept of positional uncertainty, according to previous studies, refers to the prior probability of the positions of targets. In a number of studies, positional uncertainty has modulated selection of the incoming stimuli (Chen & Cave, 2006; Drummond & Shomstein, 2010; Ho, 2011; Shomstein & Yantis, 2002, 2004). In this respect, in our experiments the prior probability of positional information was equally controlled under both low and high sensory uncertainty. Altogether, our Experiment 4 provided compelling evidence that sensory uncertainty rather than positional uncertainty modulated object-based attention in this study.

General discussion

In this study, sensory uncertainty was manipulated to assess two competitive hypotheses of object-based attention—that is, the attentional spreading hypothesis and the attentional prioritization hypothesis. The results from four experiments using accuracy and perceptual threshold as indexes consistently showed that sensory uncertainty modulated the object-based effect. Specifically, an object-based effect was more obvious under high than low sensory uncertainty. Thus, this modulation contradicts the attentional spreading hypothesis, which predicts an automatic object-based effect independent of sensory uncertainty. Moreover, such modulation also challenges the sufficiency of positional uncertainty in the attentional prioritization hypothesis, since targets with high positional uncertainty do not always induce object-based attention. Overall, these findings suggest that attentional prioritization emphasizing positional uncertainty cannot sufficiently account for object-based attention and that the important role of sensory uncertainty needs to be considered.

Our finding suggests that sensory uncertainty influences object-based attention. In this study, sensory uncertainty is achieved by briefly displaying a target with backward masking, as in previous studies (Luck et al., 1996; Shiu & Pashler, 1994). Since sensory information is accumulated over time (Cisek et al., 2009; Heekeren et al., 2008), the mask can somehow be integrated with the target and affect the sensory ambiguity of the target (Durlach et al., 2003; Kidd et al., 2002). Since a one-itemed mask appeared certainly at a target position, the target can be distinguished from the background that reduces sensory uncertainty by decreasing the possibility of taking the target as noise (Shiu & Pashler, 1994). In contrast, a four-itemed mask distributed at every candidate position, which enhanced sensory uncertainty of the target and by making it obscured and unremarkable among the masking noise. In this study, it's obvious that sensory uncertainty had affected the perceptual selection following the rule of uncertainty (Dosher & Lu, 2000; Lu et al., 2002; Shiu & Pashler, 1994). Specifically, the selective attention preferred the target with low sensory uncertainty to override the influence from the attended object; in contrast, the perceptual selection was easily guided by the attended object under high sensory uncertainty that resulted in an object-based effect. Moreover, the influence of sensory uncertainty on object-based attention was further confirmed by excluding the possible confounding variable of task difficulty in a more difficult task (Exp. 2) and by obtaining converging evidence from the measurement of perceptual threshold (Exp. 3). Moreover, there was no such interaction when sensory uncertainty was eliminated by replacing the masks with perceptually distinct stimuli (Exp. 4), providing compelling evidence for sensory uncertainty and against the possible explanation of positional uncertainty. Note that the null effects of OBA under low sensory uncertainty in all experiments might be due to insensitive task or measurement, as statistically insignificant results can always be argued in this way; however, the consistent findings of a significant interaction between levels of sensory uncertainty and object-related factors strongly confirm our view that sensory uncertainty influences object-based attention.

The attentional spreading hypothesis was unable to explain the present finding in two aspects. First, the attentional spreading hypothesis proposes that an automatic attentional distribution in attended objects enhances their perceptual representation (Goldsmith & Yeari, 2003; Moore, Yantis, & Vaughan, 1998; Richard et al., 2008). Thus the object-based perceptual enhancement should be present regardless of low and high sensory uncertainty. However, the object-based effect was absent in the low sensory uncertainty condition and was merely observed under high sensory uncertainty condition. Moreover, this hypothesis suggests that the object-based perceptual enhancement is originated from the spatial cue. Therefore, the object-based effect should not differ before presenting the one- and four-itemed backward masking, because sensory inputs at an early stage of target perception were virtually identical under low and high sensory uncertainty. Additionally, the object-based interference induced by masking patterns should be identical at the late stage of target perception as well, since the masking stimuli for targets were equiprobable located in attended objects under low and high sensory uncertainty. For the above reasons, the object-based effect should be independent of sensory uncertainty. However, these predictions contradict the present results that show the influence of sensory uncertainty on object-based attention. Overall, the attentional spreading hypothesis cannot adequately account for the present observations of the object-based effect.

On the other hand, we suggest that positional uncertainty cannot sufficiently explain the present results of object-based attention. According to attentional prioritization emphasizing positional uncertainty, the cued object is prioritized for selective attention as long as the position of the target is uncertain, manifesting object-based attention. Otherwise, the target with a certain position is prioritized, resulting in the absence of object-based attention (Drummond & Shomstein, 2010; Shomstein, 2012; Shomstein & Yantis, 2002). In the present study, the position of the target was unpredictable and always uncertain; accordingly, the object-based effect should be present regardless of low and high sensory uncertainty. However, this prediction was not supported because object-based attention was absent under low sensory uncertainty. Moreover, we also provide evidence against the explanation of positional uncertainty induced by backward-masking stimuli. That is, the manipulation of backward masking in this task may also modulate positional uncertainty because the one-itemed mask might indicate the location of a target and reduced its positional uncertainty. However, this possibility is refuted by results of Experiment 4, which shows no modulation of object-based attention when the masking stimuli no longer induced sensory uncertainty, as in Experiments 1–3. Thus, the present finding of object-based attention is unlikely due to positional uncertainty.

Note that the effect of sensory uncertainty on object-based attention is consistent with the view that attention prefers certain information (Bach & Dolan, 2012; Yu & Dayan, 2005). An amount of studies have demonstrated that the content of certain information can be prioritized by selective attention (Dosher & Lu, 2000; Lu et al., 2002; Shiu & Pashler, 1994). For example, when targets were abrupt from the other stimuli and perfectly perceived without uncertainty, a spatial cue does not affect the discrimination of targets (Shiu & Pashler, 1994). Thus, information of certainty overrides the cueing effect, making a conclusion of attention preferring certainty. As was proposed by Shomstein and her colleagues (Drummond & Shomstein, 2010; Shomstein & Yantis, 2002), a target with a certain position is prioritized, which eliminates or reduces an influence from the attended object. In contrast, when the target is of high positional uncertainty, the attended object will be prioritized and induce object-based attention. In the present study, sensory uncertainty showed a similar pattern to the modulation of object-based attention by positional uncertainty The pattern revealed an absence of object-based attention under low sensory uncertainty and a presence of object-based attention under high sensory uncertainty. The lack of object-based attention was supposed to be a prioritization to the target of low sensory uncertainty as a consequence of sensory reinforcement (Bach & Dolan, 2012; Orbán & Wolpert, 2011). Meanwhile, the presence of object-based attention was due to prioritization of the attended object under high uncertainty. Thus, this prioritization is determined by uncertainty that adjusts the order of selective attention. In consequence, selection was equally good for targets in both the attended and unattended objects under low sensory uncertainty, whereas selection was much worse for targets in the unattended relative to the attended object under high sensory uncertainty. Likewise, there was poor selection and the worst performance for targets in the unattended object under high sensory uncertainty, which attributed to the interaction between sensory uncertainty and object-based attention in our experiments. Thus, positional uncertainty alone cannot sufficiently account for the object-based attention; both positional uncertainty and sensory uncertainty can modulate the content to be prioritized, determining object-based attention. Overall, attentional prioritization seems to be driven by information with low uncertainty, and uncertainty can be broadly defined to include at least positional and sensory uncertainty.

The view that attentional prioritization is modulated by uncertainty in a broad sense deepens our understanding of object-based attention. First, attentional prioritization is dominated by the rule that attention prefers certain information (Bach & Dolan, 2012; Yu & Dayan, 2002, 2005). Thus, various forms of uncertainty, besides positional uncertainty (Chen & Cave, 2006; Drummond & Shomstein, 2010; Shomstein & Yantis, 2002, 2004) and sensory uncertainty, can modulate the context to be prioritized. Indeed, nonspatial uncertainty has recently been reported in studies to affect object-based attention (Carter & Shomstein, 2014; Collegio et al., 2014). Besides, other sources of uncertainty, such as certain features (e.g., frequency and motion) of the stimuli, the contextual environment, and the response rules have also been reported to modulate selective prioritization (Ball & Sekuler, 1981; Davis et al., 1983). Therefore, it is probably inappropriate to consider only one form of uncertainty in a task. For instance, Chen and Cave (2006) demonstrated an object-based effect in a task with constant target position. In that experiment, the contextual environment of visual configuration varied across trials unpredictably that added contextual uncertainty. Thus, contextual uncertainty may have an influence on and contribute to the object-based effect even in a task with constant target position. In short, we propose that there are broad connections between various forms of uncertainty and object-based attention, and that this indicates the importance of extending the concept of uncertainty itself to increasing understanding of object-based attention.

In summary, sensory uncertainty affects object-based attention for targets with high positional uncertainty, as indicated by both accuracy and perceptual threshold measurements. This argument conflicts with the attentional-spreading hypothesis, because the automatic object-based attention proposed by the latter is not supported by the observation of a dependence of object-based attention on sensory uncertainty. More importantly, attentional prioritization based solely on positional uncertainty cannot sufficiently account for the present results of a modulation of object-based attention by sensory uncertainty. Hence, the concept of uncertainty in the attentional-prioritization hypothesis needs to be expanded to embrace uncertainty in a broad sense, or at least to include sensory uncertainty, as confirmed by this study. This revised attentional-prioritization hypothesis suggests that object-based attention may arise under circumstances of various forms of uncertainty.

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