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Attention can operate on object representations in visual sensory memory

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Abstract

Numerous studies have shown that attention can be allocated to various types of objects, such as low-level objects developed by perceptual organization and high-level objects developed by semantic associations. However, little is known about whether attention can also be affected solely by object representations in the brain, after the disappearance of physical objects. Here, we used a modified double-rectangle paradigm to investigate how attention is affected by object representation in visual sensory memory when the physical objects disappear for a short period of time before the target onset. By manipulating the interstimulus interval (ISI) between the offset of the objects and the onset of the target, an object-based attention effect, with shorter reaction times (RTs) for within-object relative to between-object conditions, was observed in the short-ISI (within 500 ms in Experiments 1a, 1b, 2, and 3) conditions while disappearing in the long-ISI (800 ms in Experiment 4) conditions. This result demonstrated that the mere presence of object representation in visual sensory memory, or the sensory memory-maintained object, can serve as an object unit that attention can operate on. This provides evidence for the relationship between object-based attention and visual sensory memory: object representation in visual sensory memory could affect attentional allocation, or attention can operate on a sensory memory-maintained object.

Keywords Object-based attention · Object representation · Sensory memory · Vision

Introduction

Object-based attention (OBA) refers to the phenomenon wherein attention can operate on an object, and once an object is selected, the processing of all its features is facilitated (Duncan, 1984; Egly et al., 1994). Duncan provided the first piece of evidence for OBA by demonstrating that participants' accuracy was higher for reporting two features of a single object relative to reporting two features belonging to two separate objects when the two objects spatially overlapped. Following this study, numerous studies provided further evidence for OBA through other paradigms, including the double-rectangle cueing paradigm (Egly et al., 1994), flanker paradigm (Kramer & Jacobson, 1991; Shomstein & Yantis, 2002), and temporal order judgment paradigm (Donovan et al., 2017). For example, in an influential study using the double-rectangle paradigm, Egly et al. (1994) found that participants' reaction times (RTs) were shorter for a target requiring a within-object shift of attention relative to a between-object shift of attention. This within-object advantage can be considered a pure object-based effect without contaminations of any space-based effect because the spatial distances between the cued and target occurring locations were kept the same for the within- and between-object conditions. So far, several theories have been proposed to account for the OBA effect, including sensory enhancement (Chen & Cave, 2006, 2008; Richard et al., 2008), attentional prioritization (Shomstein & Behrmann, 2008; Shomstein & Yantis, 2004), attentional shifting (Lamy & Egeth, 2002), and uncertainty reduction (Drummond & Shomstein, 2010) (see also Chen, 2012, for a review).

A critical question in the field of object-based attention is, what is an "object" that attention can operate on?

The perceptual object (i.e., the object perceived by visual perception or an object one could be aware of, such as the geometrical shape or closed outline) is probably the first kind of object to come to one's mind. In Duncan's original study, the objects were a long or short box outline with a gap on

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either its right or left side and a line with solid or dashed texture, tiling right or left (Duncan, 1984). This definition, which can be considered a kind of perceptual object, was widely used in early studies of object-based attention, such as the two rectangles in the influential double-rectangle paradigm (Egly et al., 1994) and other subsequent studies (Drummond & Shomstein, 2010; He et al., 2004; Lamy & Egeth, 2002; Mccarley et al., 2002; Pratt & Sekuler, 2001). Importantly, the perceptual object is not necessarily a real and intact object such as an intact geometrical shape or line. The object can also be defined by Gestalt laws of grouping. That is, perceptual organization based on properties like similarity (Baylis & Driver, 1992; Kramer & Jacobson, 1991), proximity (Marrara & Moore, 2003), continuation (Moore et al., 1998), collinearity (Lavie & Driver, 1996), or common fate (Behrmann et al., 2000).

Moreover, a top-down object can also affect object-based attention. Using Chinese characters as stimuli, researchers found that if two adjacent Chinese characters could form a meaningful word, this word could be perceived as an object and exerted an OBA effect, while two meaning-irrelevant Chinese characters could not (Li & Logan, 2008). Using the radicals (the structures that make up the Chinese character) of a Chinese character as stimuli, the OBA effect was only found when the two radicals could form a legitimate Chinese character (Yuan & Fu, 2014). By training participants to familiarize themselves with a pair of shapes that originally had a meaningless relationship, researchers found that this binding of two shapes could also be perceived as an object and showed the OBA effect (Zhao et al., 2014). Furthermore, two hands performing a handshake, which is endowed with social interaction information, could also be perceived as an object and produced the OBA effect (Yin et al., 2018). These findings suggest that the "object" in the OBA can be extended to high-level or top-down objects, such as semantic objects and experience-dependent objects.

Although the objects mentioned above might be developed from different associations, they are visible, or the participants could be aware of them. However, the "object" in the OBA is not limited to the visible object. Several types of research have found the OBA effect in invisible objects, such as objects under the perceptual threshold (Chou & Yeh, 2012;Norman et al., 2013 ; Zhang & Fang, 2012). For example, using the continuous flash suppression (CFS) paradigm, researchers made the double rectangles invisible for the participants and achieved the subliminal manipulation of the object. Under these circumstances, the OBA effect was still observed even though the participants were unaware of the objects (Chou & Yeh, 2012). The same finding was obtained using the alternation of a Gabor patch and objects with low contrast and a short exposure time to make objects invisible to the participants (Norman et al., 2013; Zhang & Fang, 2012). This evidence indicated that a visible object is not a prerequisite for the OBA, and an invisible object could also exert an influence on attention allocation, as long as the object representation is captured by the visual system, even without awareness of it. Interestingly, a recent study demonstrated that attention could operate on the object created by attention (Ongchoco & Scholl, 2019). In this study, participants were presented with a blank grid and were asked to imagine the grid in different shapes (two parallel lines or a letter "H") according to the instructions. Their task was to judge whether two probes, which appeared in the same or different imagined objects, had the same length or not. The results showed that when participants were asked to imagine two parallel lines, their accuracy would be higher in the condition of two probes appearing in the same line than in the condition of two probes appearing in different lines, and there was no difference observed in the two conditions when participants were asked to imagine the letter "H." This same-object advantage further confirmed that the OBA could be observed via created imagery, without the existence of a real object.

Different from the visible or invisible objects mentioned above, some objects first appear and then disappear. Although they vanish in our view, their representations, which are stored in memory, can also elicit the OBA effect. Most previous studies focused on whether the OBA effect could be found in visual short-term memory (VSTM) or visual working memory (VWM) (Bao et al., 2007; Griffin & Nobre, 2003; Matsukura et al., 2007; Ohyama & Watanabe, 2010). In Bao et al.'s research, participants were required to process two features continuously in mind and reported the final state of these features. They found that the response was faster when two features belonged to the same object than to different objects. This result verified that an object in VWM can manifest a processing advantage (Bao et al., 2007). In Griffin's research, four objects (colored or texture shape) were presented for 100 ms and disappeared. After a 100-ms cue and 500- to 1,000-ms blank, the target appeared. Participants were asked to judge whether the target object had shown up among the previous four objects or not. The results showed that if the target appeared at the cued location, the accuracy was better than that at the non-cued location (Griffin & Nobre, 2003). This finding also suggested that there is a benefit to orienting attention toward selective objects of internal representations that are stored in VSTM (Griffin & Nobre, 2003; Matsukura et al., 2007). Likewise, in the modified overlaid-stimuli paradigm, when participants were asked to report the object's features and remember the object's colors, the object selection was interfered by object memory, suggesting the OBA could operate during VSTM or VWM maintenance (Fischer et al., 2020; Matsukura & Vecera, 2009, 2011, 2015).

Since the object benefit could be elicited in the VSTM or VWM, it is natural to ask whether the object representation could be maintained in other memory systems (e.g., sensory memory), and strong enough to induce the OBA. Following this logic, we ask whether the object representation maintained in visual sensory memory, the previous stage of VSTM or VWM, could also guide attention and elicit the OBA effect.

Although they are different memory mechanisms, visual sensory memory is easily confused with VSTM. Visual sensory memory, also termed iconic memory (Neisser, 2014) or the sensory register (Shiffrin & Atkinson, 1969), is the visual system that exhibits a persistence effect in the form of a rapidly decaying image or icon following the termination of a brief stimulus (Long, 1980). Environmental stimuli are first input to sensory memory, and most information will decay quickly; only the attended-to information can be initially processed and transferred to VSTM for ongoing cognitive tasks (Luck, 2007). Thus, VSTM is thought to be the visual component of the VWM system (Luck, 2007). Moreover, unless transferred into long-term memory with further control processes (e.g., rehearsal), the information in short-term storage will also decay and be discarded in about 30 s or less (Sakai, 2017; Shiffrin & Atkinson, 1969). Generally, the life-span of visual sensory memory has been found to be in hundreds of milliseconds (e.g., approximately 1,000 ms (Graziano & Sigman, 2008), less than 1 s (Sperling, 1960), longer than 130–200 ms (Averbach & Coriell, 1961), or approximately 200–500 ms (Sakai, 2017)). The life-span of visual sensory memory is affected by the luminance (Haber & Standing, 1970), duration (Irwin & Yeomans, 1986; Sperling, 1960), geometric composition, shape, and spatial form of the stimulus (Graziano & Sigman, 2008; see also Coltheart, 1980, and Long, 1980, for a review). In contrast, VSTM has a longer life-span (e.g., about 30 s or less (Shiffrin & Atkinson, 1969), deteriorating greatly within 10–20 s (Phillips, 1974), or lasting for up to a minute (Sakai, 2017)). Aside from the difference in time or process stage between visual sensory memory and VSTM or VWM, their most obvious distinction is that objects could enter sensory memory as long as they were seen, while VSTM and VWM require manipulation of information temporarily (Shiffrin & Atkinson, 1969). That is, study of VSTM or VWM is involved in cognitive processes such as memory tasks, while sensory memory is not.

In line with the aforementioned findings, visual sensory memory, as well as other mechanisms such as VWM (Bao et al., 2007), VSTM (Griffin & Nobre, 2003; Matsukura et al., 2007), and visual imagery (Ongchoco & Scholl, 2019), provides another good mechanism for maintaining the representation of a physically disappeared object momentarily. We propose that the physically disappeared object representation can be maintained in the visual sensory memory for a short duration, and attention can operate on this object representation and elicit the OBA effect. Accordingly, as the representation in sensory memory decays over time, the OBA effect induced by that object representation in visual sensory memory will also decay over time.

Note that the object representation left by the disappeared object was different from the imperfect or impoverished stimuli, such as objects grouped by Gestalt laws (Avrahami, 1999; Marino & Scholl, 2005; Moore et al., 1998). Although these two kinds of objects were from low-level stimuli input without the cognitive process, they are still different because the imperfect or impoverished object was grouped by the current visual information. In contrast, disappeared object representation is left by the previous visual object.

After the disappearance of objects, the OBA effect was still observed in a modified double-rectangle paradigm (Nah et al., 2018) in which objects disappeared at the same time as the target onset. Notably, when the participants responded to the target, the rectangles were no longer present on the screen, suggesting that the attentional allocation only might be influenced object representation in sensory memory. However, with similar manipulation to the presentation of objects and target, no OBA effect was observed in another study (Ho & Yeh, 2009). Given these opposite results, it is still unknown whether the OBA could be found after the disappearance of objects.

For this issue, we hypothesized that the representation of disappeared objects could be maintained by visual sensory memory for a short period. During this short period, the object representation would still be active and strong enough to affect attention allocation. Specifically, we adopted Egly's double-rectangle paradigm and manipulated the interstimulus interval (ISI) between the object (the two rectangles) offset and the target onset. Under this manipulation, we predicted that there would be a significant OBA effect, and this effect would vary with the ISI. Under a short ISI, the representation of the physically disappeared object might still be maintained in mind, and thus, an OBA effect would be observed. However, if the ISI was further increased and exceeded the range of visual sensory memory, the object representation would decay, and the OBA effect was also expected to decline or even disappear.

Experiment 1a

In Experiment 1a, the task was the same as the classic double-rectangles paradigm, except that the two rectangles were sustained for another 100 ms after the cue and then disappeared (see Fig. 1). The target could appear immediately (0-ms ISI condition) or following a 100-ms blank interval (100-ms ISI condition). If the two rectangles still existed in sensory memory and influenced the attention allocation, the OBA effect would be observed in both the 0- and 100-ms ISI conditions.

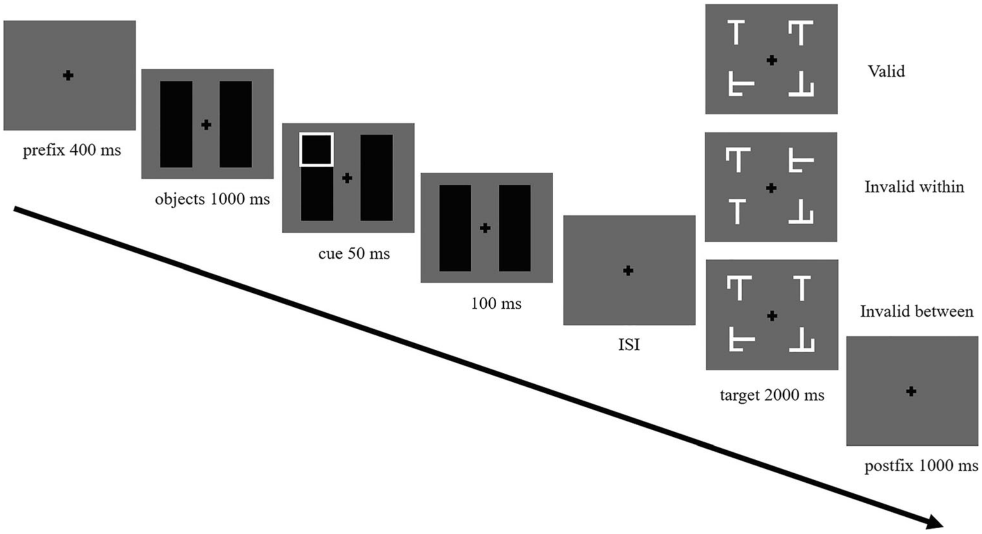

Fig. 1 Illustration of the procedure of the present study. The trial illustrated is an example of vertical rectangles with a cue in the upper left end, with the target being the letter "T." Note that the rectangles disappeared before the target array onset for a certain amount of time, as determined by interstimulus interval (ISI) in different experiments. The 500-ms feedback of a red cross would occur only in the incorrect or no response conditions

Method

Participants

The presumptive sample size for all experiments of the present study was calculated with the G*Power 3.1 program (Faul, Erdfelder, Lang, & Buchner, 2007). By setting the α as 0.05, using the middle effect size (0.25) of $\eta_p{}^2$, and adopting a test force (1-β) of 0.8, the power analysis revealed a sample size of n = 24. If we adopted a stricter statistical test force (1-β) of 0.9, this sample size was 30. According to this calculation and the possible participant loss (unusual data or technical issues), our actual sample size (varied from 25 to 30) slightly exceeded the estimated one (24) to make sure we could achieve the actual power.

Twenty-five participants (21 female, average age of 19.8 ± 1.3 years) from Guangzhou University were recruited for Experiment 1a. All participants were right-handed, had normal or corrected-to-normal vision, and were naive about the purpose of the experiment. Participants were recruited from Guangzhou University, in exchange for a payment of 30 Yuan (about US$4.6) per hour or course credit. Each participant voluntarily enrolled and signed an informed consent form prior to the experiments. The research protocol of this study was approved by the local institutional review board at the Department of Psychology of School of Education at Guangzhou University.

Apparatus and stimulus

The participants were seated in a sound-attenuated chamber approximately 60 cm away from a CRT monitor (resolution: 1,024 × 768 pixels, refresh rate: 85 Hz), and their eyes were positioned at the same height as the center of the monitor. All stimuli were presented on a gray background. Both rectangles subtended 17.5° × 2.7° and were rendered in black and positioned 7.4° from the central fixation point. The targets, distracters, fixation, and cue were all rendered in white. The target, subtended 2.5° × 2.5°, was the letter "T" or "L" and the distractors, subtended 2.5° × 2.5°, were hybrids of the letters of "T" and "L" with random orientation; the fixation, subtended 0.5° × 0.5°, was a cross, and the cue, subtended 2.5° × 2.5°, was a hollow square. Stimulus presentation and manual response measurements were controlled by E-Prime 2.0 software (Psychological Software Tools, Inc., Pittsburgh, PA, USA).

Design and procedure

A 3 (cue type: valid, invalid within-object, and invalid between-object) × 2 (ISI: 0 and 100 ms) within-subject factorial design was deployed. The three cue types were defined by the target appearing on the cued location, the other end of the cued rectangle, and the near end of the uncued rectangle, respectively. These three cue types constituted 75%, 12.5%, and 12.5% of all trials, respectively. The target never appeared diagonally across from the cue. To make it unified, participants were explicitly informed that the target would most likely appear in the cue location and would never appear diagonal to the cue, but the exact proportion was not disclosed.

The rectangle orientation and target letter were counterbalanced across trials, and the ISI was counterbalanced across blocks. The cue appeared with equal frequency in each of the four rectangle corners. We combined the three types of cues (valid, invalid within-object, and invalid between-object) with two target letters ("T" and "L"), two rectangle orientations (vertical and horizontal), four cue locations (upper left, lower left, upper right, and lower right corner), and two ISIs (0 and 100 ms). This combination resulted in an overall 1,024 trials (768 valid, 128 invalid within-object, and 128 invalid between-object; 512 trials of ISI at 0 ms and 512 trials of ISI at 100 ms). In the formal test, the 1,024 trials were subdivided into 16 blocks.

Participants were asked to keep their eyes on the central fixation during the whole experiment and identify the target letter by pressing a button on the keyboard ("F" for the letter "T" and "J" for the letter "L") as rapidly and accurately as possible. Both speed and accuracy were emphasized.

Before the formal test, participants were asked to complete two practice sessions. In the first session, they were asked to identify the target letter ("T" or "L") in the center of the screen to make them familiar with the target letter and its corresponding button. The second session was identical to the formal test, and the formal test started only after participants made more than 20 correct responses successively. The whole experiment lasted approximately 90 minutes, and a compulsive rest was taken after the first eight blocks.

At the beginning of each trial, a central fixation was presented. After 400 ms, two identical rectangles appeared vertically or horizontally for 1,000 ms, and then a 50-ms cue flashed in one corner of the two rectangles randomly. The rectangles were sustained for another 100 ms before their disappearance. Then, the target and three distractors appeared simultaneously in four corners of rectangles after a fixation with an ISI of 0 or 100 ms and lasted either 2,000 ms or until response. If the wrong response or non-response was detected, a red cross feedback would be presented for 500 ms. The trial ended with another fixation of 1,000 ms.

Statistical analysis

The data of one subject was excluded from analysis because the subject couldn't finish the experiment successfully. The mean accuracy of the remaining participants was 95.5%, and only data of reaction times (RTs) were used for analysis. Trials with errors and RTs shorter than 250 ms (4.5% of all experimental trials) were discarded, and RTs beyond two SDs[1] in each condition of the remaining trials (4.1% of all experimental trials) were excluded from the analysis. This meant 8.6% of all experimental trials were discarded.

To examine the space-based attention (SBA), we coalesced invalid within- and between-object conditions as an invalid condition. A 2 × 2 repeated-measures analysis of variance (ANOVA) was conducted on the RT with spatial validity (valid and invalid) and ISI (0 and 100 ms) as within-subject factors.

For the OBA analysis, a 2 × 2 ANOVA was conducted on the RT, with cue type (invalid within-object and invalid between-object condition) and ISI (0 and 100 ms) as within-subject factors.

Results

For the SBA analysis, the main effect of validity was significant, $F(1, 23) = 149.1, p < 0.001, {\eta_p}^2 = 0.87$, with a shorter RT in the spatially valid condition (519 ± 14 ms) (mean RT ± one standard error, the following data were the same) relative to the spatially invalid condition (666 ± 16 ms). The main effect of ISI was significant, $F(1, 23) = 34.6, p < 0.001, {\eta_p}^2 = 0.60$, with a shorter RT in the 100-ms condition (577 ± 14 ms) relative to the 0-ms ISI condition (608 ± 16 ms). There was no significant interaction between spatial validity and ISI, $F(1, 23) = 0.10, p = 0.752$.

The OBA effect is shown in Fig. 2. For the OBA analysis, the main effect of cue type was significant, $F(1, 23) = 14.2, p < 0.001, {\eta_p}^2 = 0.38$, with a shorter RT in the within-object condition (660 ± 16 ms) relative to that in the between-object condition (672 ± 17 ms). The main effect of ISI was significant, $F(1, 23) = 15.2, p < 0.001, {\eta_p}^2 = 0.40$, with a shorter RT in the 100-ms condition (651 ± 16 ms) relative to the 0-ms ISI condition (681 ± 17 ms). The interaction was not significant, $F(1, 23) = 0.33, p = 0.573$.

Discussion

A typical spatial attention effect (Posner et al., 1980) was observed in this experiment, indicating that the cue attracted attention successfully.

Importantly, the attentional shift was faster within-object than between-object, even when the two objects had no longer been present on-screen for 100 ms. This suggested that although the object disappeared from the screen, its representation in sensory memory could still be active in mind and selected by attention, which made it advantageous for processing the target occurring in the same object. Therefore, this experiment clearly showed that attention could operate on the "object" defined by object representation in visual sensory memory.

Moreover, the interaction between cue type and ISI was not significant, indicating that the OBA effect was still as strong as that in the 0-ms condition. This may be due to the representations of two rectangles still being active in the mind within 100 ms and being strong enough for attention to operate on.

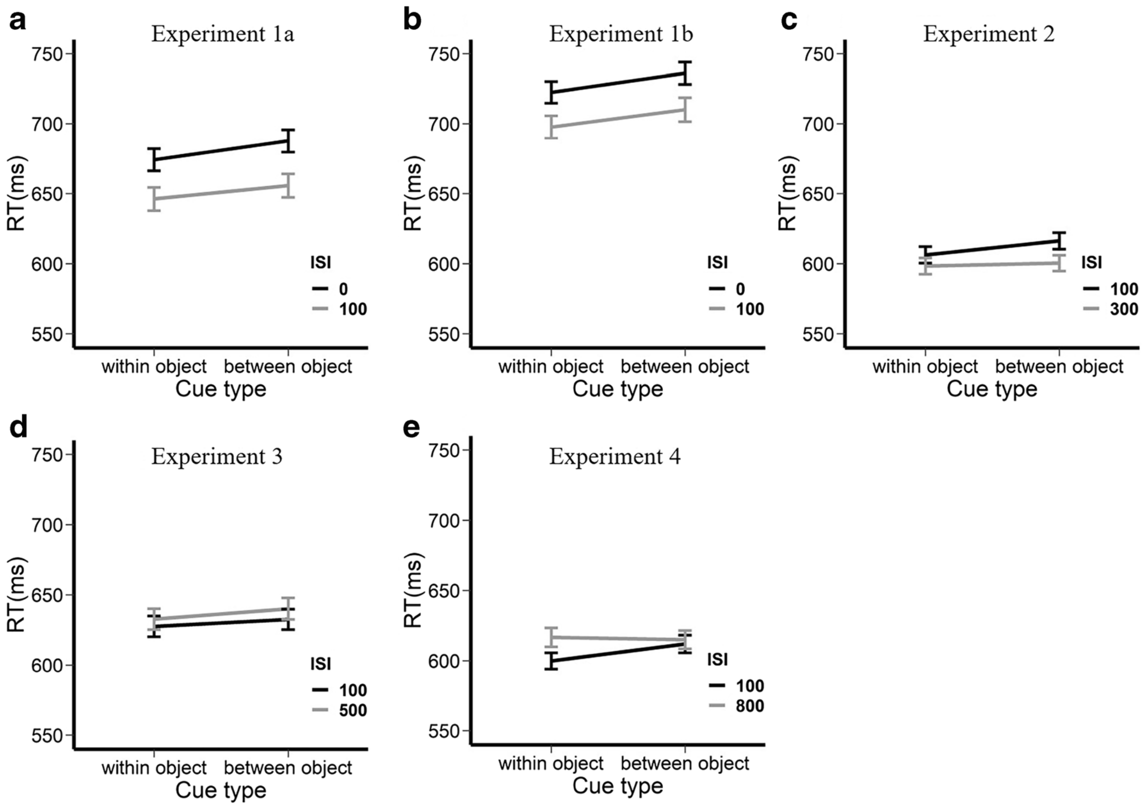

Fig. 2 Reaction times (RTs) (with one Loftus and Masson within-subjects error bars, SE) of two invalid (within- and between-object) conditions in all experiments. A to E correspond to Experiment 1a to Experiment 4 respectively. The main effect of OBA was observed in all experiments; however, the interaction between interstimulus interval (ISI) and cue type (within- and between-object) was significant only in Experiment 4, indicating that the OBA effect was maintained in 100-ms ISI condition but disappeared in the 800-ms ISI condition

Experiment 1b

Experiment 1b was designed to verify whether the result obtained from Experiment 1a was repeatable when the blocked ISI was changed to a mixed ISI condition.

Method

Participants

Twenty-seven participants (18 female, average age of 20.7 ± 2.2 years) from Guangzhou University were recruited for Experiment 1b. All participants were right-handed, had normal or corrected-to-normal vision, and were naive about the purpose of the experiment.

Design and procedure

Experiment 1b was exactly the same as Experiment 1a except that the ISI was random intra-bock (i.e., the ISI was completely mixed in blocks).

Statistical analysis

The data of all participants were used for analysis, with a mean accuracy of 98.1%. Trials with errors and RTs shorter than 250 ms (1.9% of all experimental trials) were discarded, and RTs beyond two SDs in each condition of the remaining trials (4.4% of all experimental trials) were excluded from the analysis. This meant 6.3% of all experimental trials were discarded. The same analysis procedure was used for Experiment 1b as for Experiment 1a.

Results

For the SBA, the main effect of validity was significant, $F(1, 26) = 166.6$, $p < 0.001$, $\eta_p^2 = 0.86$, with a shorter RT in the spatially valid condition (529 ± 19 ms) relative to the spatially invalid condition (717 ± 16 ms). The main effect of ISI was significant, $F(1, 26) = 178.8$, $p < 0.001$, $\eta_p^2 = 0.87$, with a shorter RT in the 100-ms condition (608 ± 19 ms) relative to the 0 ms ISI condition (637 ± 16 ms). There was no significant interaction between spatial validity and ISI, $F(1, 26) = 2.50$, $p = 0.126$.

The OBA effect is shown in Fig. 2. For the OBA, there was a significant main effect of cue type, $F(1, 26) = 16.3$, $p < 0.001$, $\eta_p^2 = 0.39$, with a shorter RT in the within-object condition (710 ± 16 ms) relative to the between-object condition (723 ± 17 ms). The main effect of ISI was significant, $F(1, 26) = 67.1$, $p < 0.001$, $\eta_p^2 = 0.72$, with a shorter RT in the 100-ms (704 ± 16 ms) relative to the 0-ms condition (729 ± 17 ms). There was no significant interaction between cue type and ISI, $F(1, 26) = 0.03$, $p = 0.866$.

Discussion

The results of Experiment 1b basically replicated the findings of Experiment 1a, even though the two ISI conditions were mixed across the whole experiment. Again, the OBA effect was observed steadily at 0 and 100 ms after the disappearance of the object. This finding further supports our hypothesis that attention can operate on the object representation maintained in visual sensory memory, given that the time for attention allocation does not exceed the duration of visual sensory memory.

Experiment 2

Experiments 1a and 1b both demonstrated that the OBA effect could be observed when the object disappeared, but its representation was still maintained in visual sensory memory after its 100-ms offset. However, the ISI in Experiments 1a and 1b was short (0 and 100 ms), and the information in sensory memory could last for about 500–1,000 ms (Sperling, 1960). Therefore, in Experiment 2, we used longer ISIs (100 and 300 ms) to examine whether the OBA effect could last for a longer ISI. If the object representation fades quickly with the decay of visual sensory memory, the OBA effect may be absent for a longer ISI between the object (two rectangles) offset and target onset. In contrast, if the object representation can still be kept in visual sensory memory, the OBA effect should be present.

Method

Participants

Twenty-seven participants (14 male, average age of 19.3 ± 1.8 years) from Guangzhou University were recruited for Experiment 2. All participants were right-handed, had normal or corrected-to-normal vision, and were naive about the purpose of the experiment.

Design and procedure

The stimuli and procedure of Experiment 2 were completely identical to the Experiment 1b, except that the ISI was changed from 0 ms and 100 ms to 100 ms and 300 ms.

Statistical analysis

The data of all participants were used for analysis, with a mean accuracy of 95.6%. Trials with errors and RTs shorter than 250 ms (4.4% of all experimental trials) were discarded, and RTs beyond two SDs in each condition of the remaining trials (4.1% of all experimental trials) were excluded from the analysis. This meant 8.5% of all experimental trials were discarded. The same data analysis procedure used for Experiment 1 was used for Experiment 2.

Results

For the SBA analysis, the main effect of validity was significant, $F(1, 26) = 92.0$, $p < 0.001$, $\eta_p^2 = 0.78$, with a shorter RT in the spatially valid condition (500 ± 12 ms) relative to the spatially invalid condition (605 ± 11 ms). The main effect of ISI was significant, $F(1, 26) = 21.0$, $p < 0.001$, $\eta_p^2 = 0.45$, with a shorter RT in the 300-ms ISI condition (546 ± 12 ms) relative to the 100-ms ISI condition (559 ± 11 ms). There was no significant interaction between ISI and spatial validity, $F(1, 26) = 0.13$, $p = 0.72$.

The OBA effect was shown in Fig. 2. For the OBA analysis, the main effect of cue type was marginally significant, $F(1, 26) = 4.06$, $p = 0.054$, $\eta_p^2 = 0.14$, with a shorter RT in the within-object condition (602 ± 12 ms) relative to the between-object condition (608 ± 12 ms). The main effect of ISI was significant, $F(1, 26) = 7.56$, $p = 0.011$, $\eta_p^2 = 0.23$, with a shorter RT in the 300-ms ISI condition (599 ± 12 ms) relative to the 100-ms ISI condition (611 ± 12 ms). There was no significant interaction between ISI and cue type, $F(1 ,26) = 1.93$, $p = 0.177$.

Discussion

The main effect of the OBA was marginally significant in this experiment, suggesting that the object representation in sensory memory, even with longer ISIs of 100 and 300 ms, could still influence attention allocation effectively.

The marginally significant OBA effect was probably due to the following reasons. First, the mix of two ISI conditions may affect the phenomenological experience of the participants (Behrmann et al., 2000). For example, the independent variable blocked presentation could enhance the task focus, while its mixed presentation required extra resources for intra-task and inter-task processing (Jaswal & Logie, 2006). Thus, we would use the blocked design in Experiments 3 and 4 to avoid this potential interference. Second, the long and humdrum experiment duration (about 90 min in total) may have induced a fatigue effect and affected the stability of the data (e.g., several participants in Experiments 1a, 1b, and 2 had self-reported that the experiment was lengthy and made them a bit drowsy). To minimize this potential fatigue effect, the proportion of cue validity in the following experiments was reduced to shorten the experimental duration.

The non-significant interaction between ISI and cue type could be due to the ISI of 300 ms not being long enough for the decay of the sensory memory-maintained object.

Experiment 3

Since a marginally significant OBA effect was observed but no significant interaction between ISI (100, 300 ms) and cue type was found in Experiment 2, the ISI was further prolonged to 500 ms in Experiment 3 to explore whether the OBA effect would vanish, as the sensory memory-maintained object representation decayed with a longer ISI. In addition, to avoid the possible interference of mixing two ISI conditions in each block, the 100- and 500-ms ISI conditions were blocked separately in Experiment 3.

Method

Participants

Twenty-seven participants (six male, average age of 18.9 ± 1.2 years) from Guangzhou University were recruited for Experiment 3. All participants were right-handed, had normal or corrected-to-normal vision, and were naive about the purpose of the experiment.

Design and procedure

Experiment 3 was the same as Experiment 1a except for the following changes. First, the ISI was changed from 0 and 100 ms to 100 and 500 ms. Second, the proportion of the cue validity was changed from 6:1:1 to 3:1:1, which significantly cut down the trial number (640 trials in total, 384 valid trials, 128 invalid-within and invalid-between trials). This cue validity has been used in some previous studies and been shown to be valid for the OBA effect (Hecht & Vecera, 2007; Hein et al., 2017; Lee & Vecera, 2005; Mccarley et al., 2002; Nah et al., 2018). The two practice sessions remained the same, and the whole experiment duration was about 1 hour.

Statistical analysis

The data of all participants were used for analysis, with a mean accuracy of 95.4%. Trials with errors and RTs shorter than 250 ms (4.6% of all experimental trials) were discarded, and RTs beyond two SDs in each condition of the remaining trials (4.0% of all experimental trials) were excluded from the analysis. This meant that 8.6% of all experimental trials were discarded. The same analysis procedure as in Experiments 1a, 1b, and 2 was conducted in Experiment 3.

Results

For the SBA analysis, the main effect of validity was significant, $F(1, 26) = 47.2, p < 0.001, \eta_p^2 = 0.64$, with a shorter RT in the spatially valid condition (543 ± 14 ms) relative to the spatially invalid condition (633 ± 15 ms). The main effect of ISI was significant, $F(1, 26) = 8.0, p = 0.004, \eta_p^2 = 0.27$, with a shorter RT in the 100-ms ISI condition (583 ± 15 ms) relative to the 500-ms ISI condition (594 ± 14 ms). There was no significant interaction between ISI and spatial validity, $F(1, 26) = 1.56, p = 0.22$.

The OBA effect is shown in Fig. 2. For the OBA analysis, the main effect of cue type was significant, $F(1, 26) = 4.48, p = 0.044, \eta_p^2 = 0.15$, with a shorter RT in the within-object condition (630 ± 15 ms) relative to the between-object condition (636 ± 15 ms). The main effect of ISI was not significant, $F(1, 26) = 1.85, p = 0.186$. There was no significant interaction between ISI and cue type, $F(1, 26) = 0.47, p = 0.524$.

Discussion

Both the SBA and OBA effects were observed in Experiment 2, indicating that the proportion change of the cue validity had little influence on the results.

The OBA main effect was significant, which suggested that the sensory representation of the object was still active enough to produce the OBA even at a time of 500 ms after its offset. The object representation in sensory memory may still be present within 500 ms.

An ANOVA with the experiment (1a, 1b, 2, or 3) as a factor to examine the OBA effect indicated that there was no significant difference in the OBA effect across experiments, $F(1, 3) = 1.413, p = 0.243$. However, it should be noted that in terms of descriptive data, the OBA effects were relatively small (6 ms) in Experiments 2 and 3 compared with those in Experiment 1. This might be due to the longer ISI (300 and 500 ms) we used, because the sensory memory-based object decays over time. To verify this assumption, we used an even longer ISI (800 ms) between the offset of the objects and the onset of the target array to identify a significant interaction between two ISI conditions.

Experiment 4

Sensory memory usually decays within 1 s (Neisser, 2014). If the OBA effect we observed was indeed caused by object representation in sensory memory, there must be a point in time at which the OBA effect would vanish. Thus, the ISI was further prolonged to 800 ms in Experiment 4.

Method

Participants

Thirty participants (seven male, average age of 18.9 ± 1.2 years) from Guangzhou University were recruited for Experiment 4. All participants were right-handed, had normal or corrected-to-normal vision, and were naive about the purpose of the experiment.

Design and procedure

Experiment 4 was identical to Experiment 3 except for the ISI, which were changed from 100 and 500 ms to 100 and 800 ms.

Statistical analysis

Two participants were excluded because of their RTs were slow and exceeded 2 SDs of the mean RT. The data of the remaining 28 participants were used for analysis, with a mean accuracy of 96.1%. Trials with errors and RTs shorter than 250 ms (3.9% of all experimental trials) were discarded, and RTs beyond two SDs) in each condition of the remaining trials (4.3% of all experimental trials) were excluded from the analysis. In total, 8.2% of all experimental trials were discarded.

Results

In the SBA analysis, the main effect of validity was significant, $F(1, 27) = 54.4$, $p < 0.001$, $\eta_p^2 = 0.67$, with a shorter RT in the spatially valid condition (534 ± 11 ms) relative to the spatially invalid condition (611 ± 13 ms). The main effect of ISI was significant, $F(1, 27) = 6.96$, $p = 0.014$, $\eta_p^2 = 0.20$, with a shorter RT in the 100-ms ISI condition (567 ± 13 ms) relative to the 800-ms ISI condition (578 ± 11 ms). There was no significant interaction between ISI and cue type, $F(1, 27) = 0.13$, $p = 0.73$.

The OBA effect is shown in Fig. 2. For the OBA analysis, the main effect of cue type was significant, $F(1, 27) = 5.87$, $p = 0.022$, $\eta_p^2 = 0.18$, with a shorter RT in the within-object condition (608 ± 13 ms) relative to the between-object condition (614 ± 13 ms). The main effect of ISI was marginally significant, $F(1, 27) = 3{,}78$, $p = 0.062$, $\eta_p^2 = 0.12$, with a shorter RT in the 100-ms ISI condition (606 ± 13 ms) relative to the 800-ms ISI condition (616 ± 13 ms). Importantly, the interaction between ISI and cue type was significant, $F(1, 27) = 5.61$, $p = 0.032$, $\eta_p^2 = 0.16$, suggesting that the OBA effect was more pronounced for the 100-ms relative to the 800-ms ISI condition (12 and –2 ms, respectively) .

A post hoc test was conducted for the OBA effect in the 100-ms and 800-ms ISI conditions. In the 100-ms ISI condition, RT was shorter in the within-object condition (600 ± 12 ms) than in the between-object condition (612 ± 13 ms), $t(27) = –3.35$, $p = 0.002$, Cohen's d = –0.633. In the 800-ms ISI condition, there was no significant difference in RT between the within-object (617 ± 14 ms) and between-object conditions (615 ± 13 ms), $t(27) = 0.44$, $p = 0.667$, Cohen's d = –0.082.

Discussion

A significant interaction between the OBA and ISI was found in Experiment 4. By analyzing the OBA effect in two ISI conditions separately, we observed a significant OBA effect only in the 100-ms ISI condition. This result indicated that the OBA effect was present at 100 ms after object offset, but not after 800 ms. This is consistent with our hypothesis that the object representation in sensory memory might decay and vanish after a long duration. Since attention was still attracted by the cue effectively in the 800-ms ISI condition (as shown by the significant spatial effect), the absence of OBA in the 800-ms condition was most likely due to the decay of sensory representation.

One notable phenomenon was that the overall RTs showed a U-shape dependency on the ISI (i.e., the RT decreased first and then increased along with the prolonging of the ISI). This tendency was also found in a study of inhibition of return (IOR, Zhao & Heinke, 2014), in which the overall RT also decreased first and then increased along with the increase of ISI between the cue and the target. This phenomenon can be explained in terms of varying the alertness of participants, or the foreperiod effect (Hughes, 1984; Niemi & Näätänen, 1981).

Analysis across all experiments

The results of the OBA effect in all experiments are illustrated in Fig. 2 and shown in Table 1. To test whether the OBA effect with a 100-ms ISI was different, we conducted a one-way ANOVA with the experiment (1a, 1b, 2, 3, or 4) as a factor.

Table 1 Summary of the space-based attention (SBA), object-based attention (OBA) main effects, and OBA effect in each condition in all experiments

Experiment	1a (Blocked ISI)		1b (Mixed ISI)		2 (Mixed ISI)		3 (Blocked ISI)		4 (Blocked ISI)	
ISI (ms)	0, 100		0, 100		100, 300 ms		100, 500 ms		100, 800 ms	
SBA effect (ms)	147		188		105		90		77	
P	< 0.001		< 0.001		< 0.001		< 0.001		< 0.001	
OBA effect (ms)	12		13		6		6		6	
P	< 0.001		< 0.001		0.054		0.044		0.022	
Interaction (ISI and OBA)	0.573		0.866		0.177		0.524		0.032	
ISI (separate)	0	100	0	100	100	300	100	500	100	800
OBA effect (ms)	14	10	12	13	10	2	5	7	12	-2
P	0.008	0.046	0.011	0.015	0.018	0.630	0.190	0.029	0.002	0.666

ISI interstimulus interval

We found that the OBA effect in the 100-ms ISI condition had no significant difference across the experiments, $F(1, 4) = 0.53$, $p = 0.716$.

In null hypothesis significance testing (NHST), a *p*-value less than 0.05 only can provide support for the H_1 hypothesis of an existing difference among conditions. In contrast, a *p*-value larger than 0.05 cannot provide support for the H_0 hypothesis of a null-existing difference among conditions (Dienes, 2014). To address this issue, we further conducted a Bayesian ANOVA in JASP (JASP Team, 2020) for the condition of 100-ms ISIs across experiments, which could provide better support for the H_0 hypothesis (Rouder et al., 2009; Wagenmakers et al., 2011).

The results showed that $BF_{01} = 17.965$, in favor of the null hypothesis (specifically, the probability of H_0 being true is 17.965 times that of H_1 being true). This result indicated that the OBA effect in the 100-ms ISI condition was stable across all experiments. To test the OBA effect of each ISI condition, a unary linear regression analysis was conducted. The result showed that the ISI was negatively associated with the OBA effect ($B = -0.017$, $SE = 0.005$, $p = 0.002$, adjusted $R^2 = 0.031$). The regression diagram was shown in Fig. 3a. This result indicated that the OBA effect declined with the increase of the ISI and vanished when the ISI was 800 ms. This trend of the OBA effect was similar to the decline of information in sensory memory (Neisser, 2014), consistent with the idea that the OBA effect in our experiments was derived from the object representation in sensory memory and vanished with the decay of that object representation in sensory memory.

The linear regression conducted above included different participants and conditions, such that putting those ISI conditions together might be a little inappropriate. Therefore, we conduct another two linear regressions on the basis of the presentation condition of ISI (mixed or blocked). The linear regression was conducted on the ISI mixed (Experiments 1b and 2) and blocked (Experiments 1a, 3, and 4) groups separately, and the 100-ms ISI condition was removed, such that the data were more comparable in each graph. In the mixed ISI group (Fig. 3b), the ISI was negatively associated with the OBA effect ($B = -0.043$, $SE = 0.020$, $p = 0.034$, adjusted $R^2 = 0.066$). In the blocked ISI group, the ISI was also negatively associated with the OBA effect ($B = -0.016$, $SE = 0.007$, $p = 0.032$, adjusted $R^2 = 0.046$), as shown in Fig. 3c. Note that those linear regressions were merely aimed at describing the trend of the decline of the OBA effect instead of drawing an inferential conclusion. Nevertheless, these results clearly illustrated that the OBA effect declined with the increase of ISI, as predicted by the sensory memory-maintained object hypothesis.

A previous study indicated that the information in sensory memory decays at an exponential rate (Graziano & Sigman, 2008). Hence, we also conducted exponential fittings for our data, but we failed to find any function that reached a significant level. This may be due to (1) only having five ISI conditions, and (2) the OBA effect being relatively small, likely preventing us from fitting an exponential curve well. Nevertheless, the purpose of our study was to demonstrate that the OBA effect would decline rapidly within the lifespan of sensory memory. The precise rate at which it decays is not the crucial issue of our study and could not be resolved here.

General discussion

In the research on object-based attention, it has been proposed that attention can operate on an "object" defined broadly, including Gestalt principle-based objects (Egly et al., 1994; Marrara & Moore, 2003), semantic objects (Li & Logan, 2008; Yuan & Fu, 2014), and experience-based objects (Zhao et al., 2014). Furthermore, the OBA effect could be elicited not merely by a physically presented object but also

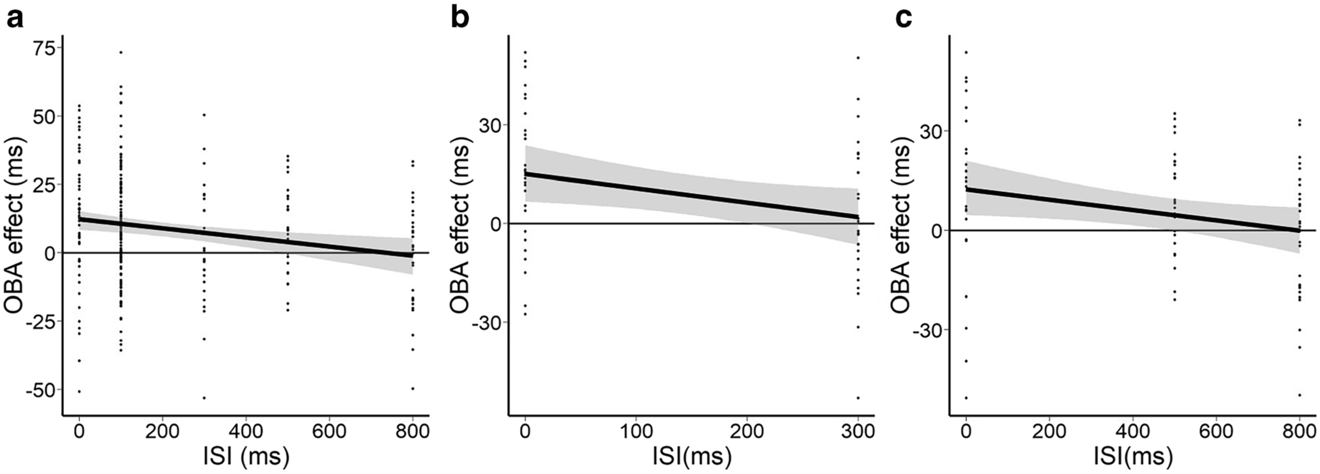

Fig. 3 The linear regression results of the object-based attention (OBA) effect as a function of interstimulus interval (ISI). The dark line was the linear fitting of these OBA effects and the ISI conditions. The gray area was the 95% confidence interval of the fitted line. **a** was the regression of ISI conditions in all experiments. **b** was the regression of mixed group (0- and 300-ms ISI conditions). **c** was the regression of block group (0-, 500- and 800-ms ISI conditions). The data of 100-ms ISI condition were not included in (**b**) and (**c**), because this was taken as the baseline of mixture for all other ISI conditions

by an object representation stored in VSTM or VWM (Bao et al., 2007; Griffin & Nobre, 2003; Matsukura et al., 2007). However, although several studies had implied that there was OBA might relate to sensory memory (Matsukura & Vecera, 2009; Woodman et al., 2003), no previous studies had concentrated on this question and shown clear evidence that object representation in visual sensory memory could affect the allocation of visual attention.

The present study provides evidence that the maintenance of object representation in visual sensory memory could effectively elicit the OBA effect. This sensory memory-maintained object extends our knowledge of what type of object is involved in the OBA effect.

Visual sensory memory as the likely mechanism for the present OBA effect

Research has shown that not only visual stimuli but also information about them can be maintained in our brain after the physical offset of visual stimuli (Irwin & Thomas, 2008). Thus, it is reasonable to infer that within the duration of visual sensory memory, the physically disappeared objects would be maintained in visual sensory memory, and these sensory memory-maintained object representations could be operated on by attention and elicit the OBA effect.

This study addressed this issue by adapting the double-rectangle paradigm (Egly et al., 1994) and manipulating the ISI between the object offset and target onset, such that the objects disappeared for a short period (0 or 100 ms in Experiments 1a and 1b, 100, or 300 ms in Experiment 2, 100, or 500 ms in Experiment 3, and 100 or 800 ms in Experiment 4) before the target onset, leaving no physical objects available for attentional operation. Because visual sensory memory can usually be maintained within hundreds of milliseconds (Neisser, 2014; Sakai, 2017), we hypothesized that within a certain time range, the representation of these objects might still be maintained in visual sensory memory and allow for attentional selection. Our hypothesis was confirmed in this study. In Experiment 1a and 1b, the OBA effect was observed for ISIs of both 0 and 100 ms in the blocked and mixed ISI conditions, indicating that object representation in visual sensory memory could affect the allocation of attention and produce the OBA effect. The OBA effect was replicated in Experiment 2 with a 300-ms ISI condition (marginally) and in Experiment 3 with a 500-ms ISI condition. These results indicated that within the range of visual sensory memory, the object representation could be maintained and elicit the OBA effect. In Experiment 4, the OBA effect was only observed in the 100-ms ISI condition but not in the 800-ms ISI condition, suggesting that the OBA effect faded away with the decay of visual sensory memory after a long period of time (800 ms).

Notice that some ISIs in our experiment had entered the range of VSTM or VWM, which might be confused with sensory memory of our study. Given that there was much evidence indicated that object-based selection could operate within VSTM or VWM (Matsukura & Vecera, 2009; Matsukura & Vecera, 2011; Woodman et al., 2003), as manifested by higher memory accuracy to the same object feature, one might argue that the OBA observed in short ISIs and the absence of OBA in 800 ms might not be caused by the object representation in sensory memory, but by the influence of VSTM or VWM. However, there is one primary reason that the object in the present study was more likely stored in visual sensory memory instead of VSTM or VWM.

That is, visual sensory memory decays within hundreds of milliseconds, while the persistence of VSTM or VWM is usually longer than one second. The ISIs (100, 300, 500, 800 ms) in our study were within the temporal range of visual sensory memory. Even though the 800 ms might be beyond the range of sensory memory and enter the VSTM or VWM, the information in sensory memory is not necessary to be transferred into VSTM or VWM after the life-span of sensory memory has ended, because only the attended information could be initially processed and transferred to VSTM (Luck, 2007). Those studies that demonstrated OBA could operate in VSTM or VWM usually asked participants to memorize some features of objects, that is, the object is usually task-relevant. In contrast, the object in the present study was task-irrelevant, and there was no need for the participants to memorize them and to transfer it into VSTM or VWM for further processing. Presumably, the object representation in the present study was only maintained in visual sensory memory, instead of being transferred to VSTM or VWM.

Nevertheless, although we gave the reason that sensory memory instead of VSTM or VWM may account for our result of the longer ISI condition (500 and 800 ms), this inference was drawn without empirical evidence. Therefore, we can only tentatively draw our conclusion that sensory memory was the more likely explanation of our results. That is, the absence of the OBA in 800 ms was more likely explained by the decays of object representation in sensory memory, rather than decays in VSTM or VWM.

In addition, there was a study indicating the information was transferred from iconic memory into VWM in an object-based manner (Woodman et al., 2003), which might question the novelty of our study. In their Experiment 3, six items were arranged within a two-rectangle-like structure, and participants were asked to remember their color for the following task. When a post-cue (50 ms after the offset of items) appeared, those items grouped with this cued item (grouped by proximity, correspond to the items in the within-object condition) had higher accuracy than those not grouped together (correspond to the items in the between-object condition). Although this study aimed to demonstrate that Gestalt grouped items directly influence VWM storage, their Experiment 3 might lead to misunderstandings that the OBA could operate within the range of sensory memory. However, as we mentioned earlier, participants in their study were required to memorize those items. This manipulation suggested those items were stored in VWM instead of sensory memory. Moreover, their response array started 1,000 ms after the offset of items. In comparison, our result showed that the OBA could not be elicited 800 ms after the object's offset. Thus, the grouping effect (OBA) observed in their study more likely reflected the object in VWM storage rather than the sensory memory. In short, although those results implied that the OBA might relate to the object maintained in sensory memory, they didn't provide direct evidence that object representation in sensory memory could elicit the OBA, because WM had played its role in maintaining object representation. In contrast, our study systematically explored whether the object solely stored in sensory memory (without contaminations from WM) could elicit the OBA and how long such an effect could last.

Role of object representation in object-based attention

Object representation is a crucial factor that affects the OBA effect (Shomstein & Behrmann, 2008; Zhao et al., 2015). Generally, the OBA effect is influenced by the degree to which object representation is established (Reppa et al., 2012). In our study, the OBA effect was significant in the 100-ms ISI condition but not in the 800-ms ISI condition, showing that this effect declines with the ISI. This tendency might be due to the elapse of object representation in sensory memory.

Previous studies demonstrated that the OBA is a subtle but pervasive visual phenomenon. The objects that exert the object benefit are not limited to Gestalt principle-based objects (Lavie & Driver, 1996; Marrara & Moore, 2003; Moore et al., 1998) but also include top-down objects such as Chinese words (Li & Logan, 2008; Yuan & Fu, 2014) and objects endowed with special meaning (Yin et al., 2018; Zhao et al., 2014). Further evidence indicated that once object representation is established, the OBA effect can be observed without the physically presented object. This object representation could be maintained in VWM or VSTM (Bao et al., 2007; Griffin & Nobre, 2003). Even an invisible object (Chou & Yeh, 2012;Norman et al., 2013 ; Zhang & Fang, 2012) or imaginary object (Ongchoco & Scholl, 2019) could produce the OBA effect. The mechanisms for the OBA may be different from visual imagery (Ongchoco & Scholl, 2019) or subliminal perception (Norman et al., 2013; Zhang & Fang, 2012), but they are consistent in maintaining the representation of objects. Compared to subliminal or imagery representation, the sensory memory mechanism provides another new perspective for the study of the OBA effect, specifically that sensory memory also could maintain object representation for attention to operate on.

Relationship with Nah et al. (2018) and Ho and Yeh (2009)

As far as we know, two previous studies using the double-rectangle paradigm showed conflicting results regarding the OBA effect occurring after object offset (0-ms ISI condition). So far, no study has used an ISI greater than 0-ms ISI to identify whether there is a visual sensory memory-maintained object that allows attentional selection.

In a modified version of the double-rectangle paradigm, Nah et al. (2018) observed a significant OBA effect when the target followed the disappearance of an object. Using a "double-trapezoid paradigm" (Experiment 3b), they observed a significant OBA effect when the trapezoids were offset at the onset of the search array. Although the objects they used were not classical rectangles, their experimental design was similar to ours. Moreover, we adopted the same cue-target onset asynchrony (CTOA), task type, and color of stimuli as they did. This design allowed our experiment to be as similar as possible to theirs while approaching the problem from the perspective of object representation in visual sensory memory.

However, in Ho and Yeh's (2009) study, when the two rectangles disappeared at the time of target onset in a double-rectangle paradigm, no significant OBA effect was observed. In their study, two rectangles appeared first and then were replaced by a new object or a blank. They called this new object an instantaneous object and argued that the OBA effect was guided by the instantaneous object, which was absent when the target appeared. Although the cue directed attentional resources to the rectangle, these resources might quickly be "released" when the rectangles disappeared (Ho & Yeh, 2009).

The different results obtained by Ho and Yeh (2009) and our Experiments 1a and 1b may be attributed to several aspects of experimental design.

First, in their experiment, participants were asked to detect the target, but in our experiment, a discrimination task was employed. The absence of the OBA effect might result from the detection task being highly sensitive to shifts in participants' decision criteria (Chen, 1998), which could lead to a difference in response criteria that would override the subtle OBA effect. Furthermore, the discrimination task, relative to the detection task, might maximize the potential effect by increasing the task difficulty (Carrasco, 2011). That is, a larger OBA effect is observed in the discrimination task relative to the detection task, as shown by the descriptive data of several previous studies (Nah et al., 2018; Pilz et al., 2012; Shomstein & Behrmann, 2008). Second, previous studies have found that the orientation of rectangles has no influence on the OBA effect (Brown & Denney, 2007; Egly et al., 1994) or have shown an advantage of horizontal transfer (Al-Janabi & Greenberg, 2016; Hein et al., 2017; Pilz et al., 2012). If attention is indeed more accessible across the horizontal plane, the use of only vertical rectangles in Ho and Yeh's experiment may have diminished the OBA effect. Third, in their experiments, the rectangles did not disappear in every trial but disappeared with a certain probability (two rectangles disappeared in 80% and 20% of all trials in their Experiments 1A and B, respectively). In both experiments, no significant OBA effect was observed in the absent rectangles trial. This manipulation of probability could have a great impact on the process of attention allocation; for example, regardless of the probability of the rectangles disappearing, participants might invest fewer attention resources into the rectangles, or deploy their attention only in rectangle-present trials. These kinds of top-down strategies might lead to the absence of the OBA effect (Lee et al., 2012; Lee & Vecera, 2005).

In short, these two studies had a similar manipulation of objects (disappeared the object before the target) with ours. The design of Ho and Yeh (2009) was more different from ours, so there might be other factors that explain the absence of OBA in their object-absence trials. In contrast, the design of Nah et al. (2018) was more comparable with ours, so we replicated the OBA in the 0 ms offset of objects.

To sum up, our study not only replicated the OBA effect of Nah et al.'s (2018) Experiment 3b in the 0-ms ISI condition but went beyond that study by extending this OBA effect to several longer ISI conditions. This excluded the possibility that the OBA effect was the result of the synchronism of object offset and target onset, leaving the sensory memory-maintained object the most likely candidate for affecting the allocation of attention. Moreover, Experiment 4 replicated the OBA effect in the 100-ms ISI condition but found no OBA effect in the 800-ms ISI condition, suggesting that the object representation would decay and no longer be strong enough to affect attention allocation after such a long delay. This decay of object representation over time is very similar to the information decay in sensory memory, leaving visual sensory memory the likely mechanism for the OBA effect.

Object-based inhibition of return (IOR)

It may be argued that in Experiment 4, the vanishment of the OBA effect in the 800-ms ISI condition may have been caused not by the decay of object representation in sensory memory but by the object-based IOR (Tipper, 1991) because the ISI we adopted in Experiment 4 was likely to fall within the time range of object-based IOR.

Previous research demonstrated that the IOR could be object-based (Tipper, 1991). Later studies confirmed that by using the double-rectangle cuing paradigm, this phenomenon could also be observed (Jordan & Tipper, 1999; List & Robertson, 2007; Reppa & Leek, 2003). In those studies, long ISIs (greater than 1,000 ms) between the cue and the target were adopted, and the RTs became longer in the within-object condition than in the between-object condition, showing a reversed pattern of the OBA effect.

However, the object-based IOR could not explain the results of our Experiment 4. First, in the aforementioned studies that observed the object-based IOR, there was a central-reorienting cue employed in the double-rectangle paradigm, which aimed at drawing attention away from the peripheral region (Jordan & Tipper, 1999) and probably made a significant difference in the object-based IOR (List & Robertson, 2007). However, no central-reorienting cue was used in Experiment 4. Second, the spatial IOR effect was also found in the aforementioned studies showing the object-based IOR, and the space-based IOR usually appeared earlier than the object-based IOR (List & Robertson, 2007). Because space-based IOR may be more sensitive to time than object-based IOR, it could be observed first. However, there was no spatial IOR effect in our Experiment 4, indicating that the object-based IOR was not likely to appear in our task. Third, the ISIs that gave rise to the object-based IOR were longer than 1,000 ms in the aforementioned studies (Hecht & Vecera, 2007; List & Robertson, 2007), while the ISI in our Experiment 4 was only 800 ms.

One might argue that our study did not exhibit a spatial IOR. This is likely because the spatial cue was informative. In contrast, the object cue, which was uninformative, might have exhibited IOR. Notice that the cue included both spatial and object information, but it was differently informative to the target in these two dimensions in our study. The cue for the spatial dimension was task-relevant, while the cue for the object dimension was completely task-irrelevant. This difference might affect the space-based and object-based IOR effects, but it might not be the critical factor to determine the appearance of the IOR effect because both the space-based and object-based IOR effects have been observed in some studies using the double-rectangle paradigm with an uninformative spatial cue (Jordan & Tipper, 1999; List & Robertson, 2007; Leek, Reppa, & Tipper, 2003). Therefore, we admit that different informative cues might influence the IOR effect but not determine the appearance of the IOR.

In sum, the disappearance of the OBA effect in the 800-ms ISI condition might not be caused by the object-based IOR. It is more likely caused by the decay of object representation in visual sensory memory.

Limitations

First, one plausible explanation for the present OBA effect is that it was not caused by the object representation in visual sensory memory but by the attentional capture of the object offset – that is, the sudden offset of the two rectangles (objects) in the display attracted participants' attention. However, this seems unlikely because offset does not necessarily attract attention when it is irrelevant to the goal (Donaldson & Yamamoto, 2016), and the simultaneous offset of the two objects cannot fully account for the OBA effect that is specific to one object only. Nevertheless, future experiments could be run to directly manipulate the level of offset, such that the effect of object offset on the OBA effect can be evaluated.

Second, there might be other explanations for the present findings. Some studies have used the rectangle or circle outline (a precue) to guide attention to this region and facilitate the information processing in this region (Greenwood et al., 1997; Parasuraman et al., 2000). The results indicated that the target within this rectangle region was detected faster or with higher accuracy than that on the outside. These studies revealed that attention may have spread over a region. Indeed, the object (rectangles) in our study could be regarded as a part of the region, which constrained the region for attentional bias. Alternatively, the region that facilitated the attention was defined by a rectangle or circle outline. The rectangle or circle outline also could be regarded as an object. Moreover, the space-based effect (SBA) reported in our study also supported that attention could spread over regions, which is related to but different from OBA. In short, our study might be in line with the idea that attention spreads over a region and only provided evidence that this region could be constrained by object representation stored in sensory memory.

Conclusion

This study showed an object-based attention effect after the disappearance of physical objects, demonstrating that the object representation stored in visual sensory memory can play a role in allocating attention before fading away. The maintenance of object representation in visual sensory memory has an active but time-limited influence on attention allocation. Within 500 ms after the offset of the object, the object representation was still present in sensory memory, and attention could operate on it. After an 800 ms delay, however, the object representation faded away with the decay of visual sensory memory, such that the OBA effect disappeared. Therefore, attention is likely to operate on the short-lived object representation maintained in sensory memory and enjoys the same processing advantage as the physical object presented in front of our eyes. In short, attention can operate on a sensory memory-maintained object.

Appendix

Table 2 Reaction times (RTs) for the exclusion criteria of three standard deviations in all experiments

Experiment	1a (Blocked ISI)		1b (Mixed ISI)		2 (Mixed ISI)		3 (Blocked ISI)		4 (Blocked ISI)	
ISI	0, 100 ms		0, 100 ms		100, 300 ms		100, 500 ms		100, 800 ms	
SBA Main effect (ms)	153		192		103		92		78	
p	< 0.001		< 0.001		< 0.001		< 0.001		0.010	
OBA Main effect (ms)	13		14		8		7		5	
p	0.001		0.002		0.013		0.043		< 0.001	
Interaction (ISI and OBA)	0.566		0.551		0.614		0.670		0.068	
ISI (separate)	0	100	0	100	100	300	100	500	100	800
OBA effect (ms)	16	11	11	16	9	6	6	8	10	0
p	0.010	0.043	0.035	0.017	0.037	0.194	0.141	0.087	0.002	0.900

SBA space-based attention, *OBA* object-based attention, *ISI* interstimulus interval

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Author Note 1. We also analyzed the RT data apart from three SDs for each experiment, as shown in Appendix Table 2. Similar results and tendencies were observed as that using two SD rejection criteria. There was a p-value changes from 0.068 to 0.032 between using these two standards, for the interaction between ISI and OBA effect in Experiment 4. This suggests that this interaction may not be robust and the data may include RTs beyond 2 SD and affected the significance. However, we believe that the 2 SD standard is more stringent and thus reported the corresponding results to this standard.

2. All data, stimulus materials and code for experiment and data analysis have been made publicly available via the Open Science Framework and can be accessed at https://osf.io/jr4ks/?view_only=60197bddf25445b5a93e85c6bd314bf2.

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