

# Different temporal dynamics of object-based attentional allocation for reward and non-reward objects

**Fangxing Song**

School of Psychology, Shaanxi Normal University,  
Xi'an, China  
Shaanxi Provincial Key Laboratory of Behavior and  
Cognitive Neuroscience, Xi'an, China



**Sicen Zhou**

School of Psychology, Shaanxi Normal University,  
Xi'an, China  
Shaanxi Provincial Key Laboratory of Behavior and  
Cognitive Neuroscience, Xi'an, China



**Yunfei Gao**

School of Psychology, Shaanxi Normal University,  
Xi'an, China  
Shaanxi Provincial Key Laboratory of Behavior and  
Cognitive Neuroscience, Xi'an, China



**Saisai Hu**

School of Psychology, Shaanxi Normal University,  
Xi'an, China  
Shaanxi Provincial Key Laboratory of Behavior and  
Cognitive Neuroscience, Xi'an, China



**Feng Kong**

School of Psychology, Shaanxi Normal University,  
Xi'an, China  
Shaanxi Provincial Key Laboratory of Behavior and  
Cognitive Neuroscience, Xi'an, China



**Jingjing Zhao**

School of Psychology, Shaanxi Normal University,  
Xi'an, China  
Shaanxi Provincial Key Laboratory of Behavior and  
Cognitive Neuroscience, Xi'an, China



Previous studies have confirmed that both non-reward objects (such as rectangles) and reward objects (such as banknotes) can guide the allocation of our attention; however, it is unclear whether the allocation mode of attention for reward objects is the same as for non-reward objects. This study aims to evaluate different modes of object-based attentional selection elicited by two types of objects: reward objects and non-reward objects. In our analysis, we used a two-rectangle paradigm in which two objects were presented visually. In a series of four experiments, we found a constant object-based effect with non-reward

objects, such as rectangles and umbrellas, as stimuli in all of the stimulus onset asynchrony (SOA) conditions (**Experiments 1 and 4**), but the object-based effect disappeared only at longer SOA with reward objects such as monetary and food objects as stimuli (**Experiments 2 and 3**). Moreover, we found that monetary and food objects induced similar object-based effects. These results suggest that the temporal dynamics of object-based attentional allocation are different with respect to reward and non-reward objects, and different types of reward objects can guide attentional allocation in a similar way.

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## Introduction

The external world contains many non-reward objects (such as leaflets and rectangles) and reward objects (such as banknotes), and an individual's attention can be guided by those objects (Dodd & Pratt, 2005; Malcolm & Shomstein, 2015; Zhao, Song, Zhou, Hu, Liu, Wang, & Kong, 2020). However, further research is needed on whether the allocation mode of attention for reward objects is the same as for non-reward objects. Consider, for example, the scenario of walking down a cluttered street—you may well ignore the scattered promotional leaflets on the ground but would probably notice a dropped banknote. This may imply that objects with reward properties (i.e., reward objects) can capture attention through a different and perhaps stronger mechanism than that which operates for non-reward objects. Therefore, this study explores different modes of object-based attentional allocation for reward and non-reward objects, aiming to enrich understanding of how reward interacts with objects in guiding attention and how attention operates for different kinds of objects.

Attentional allocation guided by an object is referred to as object-based attention, which entails improved perceptual processing for features defined as belonging to a whole object (Duncan, 1984; Egly, Driver, & Rafal, 1994; Richard, Lee, & Vecera, 2008; Scotti, Collegio, & Shomstein, 2019). Many prior studies on object-based attention have been carried out using the *two-rectangle paradigm* initially introduced by Egly et al. (1994). In the classical paradigm, two parallel rectangles are first presented to participants, and a cue then appears randomly at any of the four ends of two rectangles. After the cue, the target appears in the same location as the cue (valid condition), at the opposite end of the cued rectangle (invalid same-object condition), or on the uncued rectangle (invalid different-object condition), with an equal cue-to-target distance between the invalid conditions. It has been found that there is a same-object advantage, in that a participant's response to the invalid same-object condition is faster than that to the invalid different-object condition (i.e., an *object-based effect*). Traditional studies on object-based attention have used non-reward objects (e.g., rectangles, chairs) as stimuli and found an object-based effect (Dodd & Pratt, 2005; Malcolm & Shomstein, 2015; Moore, Yantis, & Vaughan, 1998; Scotti, Malcolm, Peterson, & Shomstein, 2016). In addition to non-reward objects, however, there are also real-life objects that have reward properties, such as food and money. Recent research has found that the object-based effect can be elicited by monetary objects with reward properties (Zhao et al., 2020).

However, a critical and unresolved issue is whether the allocation mode of object-based attention is the

same for reward objects as for non-reward objects. Based on prior studies, the temporal dynamics of object-based attentional allocation may differ between them. Overall, reward properties may impact object-based attention by influencing cognitive control, with the impact potentially depending on the amount of time, whereas the object-based effect triggered by non-reward objects is stable and does not change over time. On the one hand, rewards have been studied in the context of cognitive control (for a review, see Botvinick & Braver, 2015). For example, previous research has found more post-error slowing (i.e., following an erroneous trial, the participant's response will slow down) in the high-reward condition than in the low-reward condition, which suggests that high-reward-induced motivation can improve an individual's ability in cognitive control (Bucker & Theeuwes, 2014). More importantly, it has also been demonstrated that rewards strongly influence selective attention by influencing cognitive control (for a review, see Failing & Theeuwes, 2018). For example, participants have shown higher detection sensitivity in the reward blocks (Engelmann, Damaraju, Padmala, & Pessoa, 2009; Engelmann & Pessoa, 2007; Milstein & Dorris, 2007) and have been able to strategically search for the stimuli associated with reward; that is, they have more easily selected targets whose selection has led to rewarding outcomes and more easily discarded distractors that have been ignored with higher gains (Della Libera & Chelazzi, 2006; Della Libera & Chelazzi, 2009; Kiss, Driver, & Eimer, 2009; Sawaki, Luck, & Raymond, 2015). In these studies, participants whose reward incentive was activated subjectively allocated attentional resources according to the reward strategy to pursue higher rewards.

On the other hand, cognitive control can affect object-based attention (Drummond & Shomstein, 2010; Shomstein & Yantis, 2004). For example, Shomstein and Yantis (2004) found that the probability of a target appearing in an uncued location could affect the object-based effect. In the shorter stimulus onset asynchrony (SOA) condition, the same-object and probability effects were concomitant; however, in the longer SOA condition, the same-object effect disappeared, and reaction times were entirely dependent on the location probability. Likewise, Drummond and Shomstein (2010) found that, when the certainty of the upcoming target location was 100%, the object-based effect only appeared at shorter SOA and disappeared at longer SOA. Therefore, we speculate that when reward objects are used as the stimuli, the reward properties of those objects will impact object-based attention by influencing cognitive control. Reward properties may enhance individuals' motivation to distribute attention subjectively to pursue rewards, which may lead to the disappearance of the object-based effect. In addition, because the influences of cognitive control

on object-based attention occur only at longer SOA (Drummond & Shomstein, 2010; Shomstein & Yantis, 2004), the impact of reward properties on object-based attention might depend on the amount of time; that is, the object-based effect will appear at shorter SOA and disappear at longer SOA. Also, some studies have found that even at longer SOA, the object-based effect triggered by rectangles is stable and does not disappear or reverse without a central cue (List & Robertson, 2007; for a review, see Reppa, Schmidt, & Leek, 2012). In light of these findings, we hypothesize that the temporal dynamics of object-based attentional allocation differs between reward and non-reward objects.

The second key issue to address is the potential impact of reward types on the interaction between reward and attention. Rewards are divided into two categories: primary rewards (e.g., food) and secondary rewards (e.g., money). It is controversial whether the underlying mechanisms of primary and secondary rewards are the same (Kim, Shimojo, & O’Doherty, 2011; Sescousse, Caldú, Segura, & Dreher, 2013; Simon et al., 2014). Therefore, it is unclear whether different kinds of reward objects can guide object-based attention in the same pattern. The common neural currency theory has been established in the field of decision neuroscience (Levy & Glimcher, 2012; Sugrue, Corrado, & Newsome, 2005; for a review, see Bartra, McGuire, & Kable, 2013). The concept of a common currency implies that different types of reward values are represented in a unique set of brain regions (ventral striatum and ventromedial prefrontal cortex) and that their values are computed on a single scale (Clithero & Rangel, 2013; Hare, Camerer, & Rangel, 2009; Peters & Buchel, 2009). More importantly, prior research has shown that even when no decision is needed, different reward values are still represented in the brain as a mechanism of common currency, and the reward value signal after representation may serve as an input to influence behavior accordingly (Sescousse, Li, & Dreher, 2015). Based on this common currency theory, we speculate that, for different types of reward objects, there is a general mechanism for guiding object-based attention.

To summarize, the issues explored in this paper are whether the temporal dynamics of object-based attentional allocation are the same for reward objects as for non-reward objects and whether different kinds of reward objects guide object-based attention in a similar way. To explore these issues, this study conducted four experiments using the modified two-rectangle paradigm (Egly et al., 1994). In Experiment 1, rectangles were used as non-reward stimuli to explore whether the object-based effect changes under different SOA conditions. Based on previous research in which the object-based effect triggered by rectangles was stable and did not disappear or reverse without a

central cue (List & Robertson, 2007; for a review, see Reppa et al., 2012), we predicted that the object-based effect would not change. In Experiment 2, pictures of banknotes were used as reward stimuli to explore whether the reward properties of objects can impact object-based attention. We postulated that reward properties can impact the object-based effect and that the effect would disappear only at longer SOA. In Experiment 3, pictures of bread were used as stimuli to explore whether there are similar temporal dynamics of object-based attentional allocation for food and monetary objects. We postulated that the temporal dynamics of object-based attentional allocation are similar for food and monetary objects. In Experiment 4, non-rewarding real-world objects (umbrellas and doors) were used as stimuli to demonstrate that the influence of reward objects on attentional allocation was not due to their “realness” or semantic properties rather than their reward properties. If the influence of reward objects on object-based attention is due to their reward properties rather than their realness or semantic properties, then the object-based effect would not be affected by SOA, just as we predicted for the rectangles condition.

## Experiment 1

### Method

#### Participants

Twenty-five undergraduates were paid to participate in Experiment 1. Participants’ ages ranged between 17 and 20 years old (mean age = 18 years,  $SD = 1.05$ ). All participants had normal or corrected-to-normal vision and were unaware of the purpose of the study. The sample size was determined by a priori power analysis using G\*Power (Faul, Erdfelder, Buchner, & Lang, 2009); with the alpha level set at 0.05, 22 observers would provide 0.95 power to find a medium-sized effect ( $f = 0.25$ ) (Cohen, 1992) for the interaction in a  $3 \times 3$  within-subjects analysis of variance (ANOVA). On this basis, we recruited 25 undergraduates to participate in the experiment. This study received the signed and informed consent of the participants and was approved by the Ethics Committee on Human Research Protection of the School of Psychology of Shaanxi Normal University.

#### Apparatus and stimuli

Stimuli were shown on a 19-inch color display with a resolution of  $1280 \times 1024$  pixels and a refresh rate of 60 Hz. Participants were seated approximately 25 inches from the monitor. The fixation point was a central  $0.48^\circ \times 0.48^\circ$  plus sign flanked by two rectangles oriented

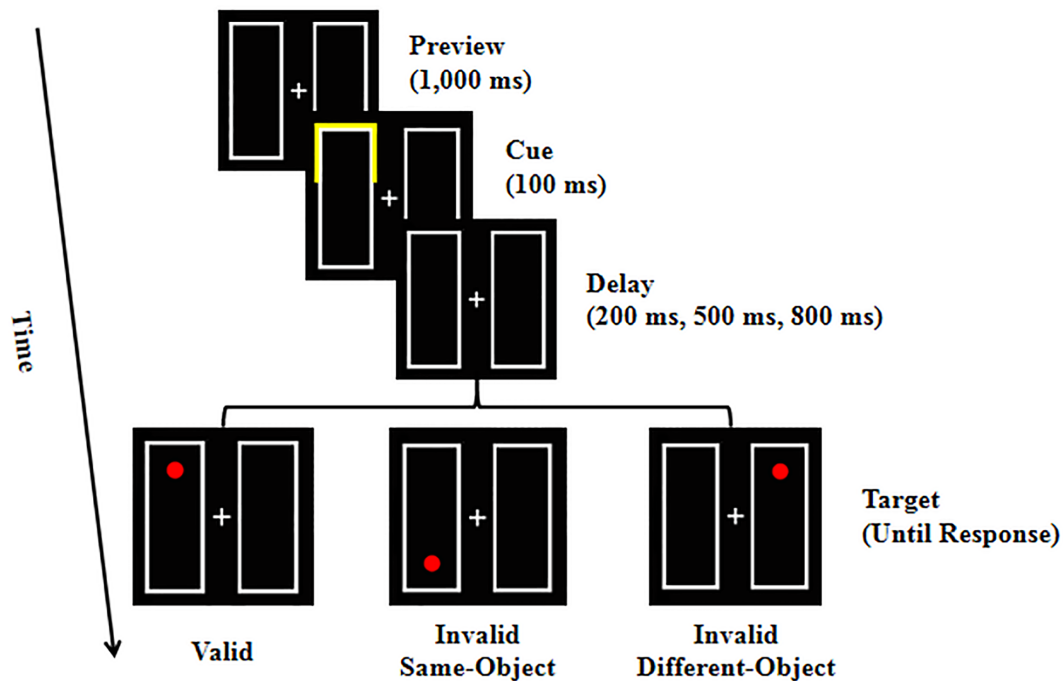


Figure 1. Sequences of events in [Experiment 1](#). In the valid condition trial, the target was at the same location as the cue. In the invalid same-object trial, the target was at the opposite end of the cued rectangle. In the invalid different-object trial, the target was on the uncued rectangle.

either horizontally or vertically and appearing on a black background. Each rectangle subtended  $2^\circ \times 4.9^\circ$ , and the separation between them was  $0.9^\circ$  of the visual angles. A yellow outline served as the cue, and a red dot ( $0.48^\circ \times 0.48^\circ$ ) was taken as the target.

### Design and procedure

In [Experiment 1](#), we used a 3 (cue validity: valid, invalid same-object, invalid different-object)  $\times$  3 (SOA: 300 ms, 600 ms, 900 ms) within-subjects factorial design. There were 600 trials in total, with 450 target-present trials and 150 catch trials without the target. Within the target-present trials, there were 270 (60%) trials for the valid condition and 90 (20%) trials for each of the two invalid conditions. Rectangle orientation (vertical or horizontal) was randomized across the trials. Each trial began with a display containing the fixation cross and two rectangles. After 1000 ms, a cue appeared randomly at any of the four ends of two rectangles for 100 ms. After an interstimulus interval of 200, 500, or 800 ms, the target (or nothing, in the catch trials) appeared and remained in view for 1500 ms or until the participant pressed the “M” key (see [Figure 1](#)). The next trial began after a 500-ms intertrial interval, during which the screen was blank. The participants were instructed to stare at the centric plus sign throughout the trial and to press the “M” key as quickly as possible when a target was detected. The entire experiment was comprised of

five blocks, each containing 120 trials, with a breathing space between each block. Participants undertook a practice block of 20 trials ahead of the formal test and entered the formal experiment only when the correct rate reached 90%.

### Results and discussion

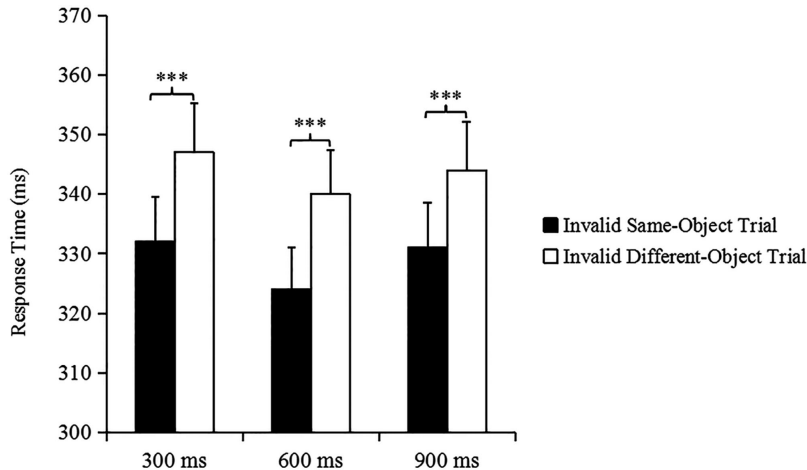
Response times (RTs) faster than 150 ms and slower than three standard deviations from the participant’s mean for every condition were removed (1.3%). Incorrect responses were also discarded (0.1%) for the RT analyses. Results of a one-sample Kolmogorov–Smirnov test suggest that the data of [Experiment 1](#) were normally distributed. The accuracy and RT data were submitted to a 3  $\times$  3 ANOVA with SOA and cue validity as the within-subjects factors. Analysis of accuracy did not show any significant main effects or interactions involving SOA or cue validity (all  $F_s < 2$ ,  $p_s > 0.2$ ) ([Table 1](#)). Analysis of RTs revealed no significant main effect of SOA,  $F(2, 48) = 2.14$ ,  $p = 0.13$ ,  $\eta_p^2 = 0.08$ , but the main effect of cue validity was significant,  $F(2, 48) = 33.36$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.58$ . More importantly, there was a significant interaction between SOA and cue validity,  $F(4, 96) = 5.56$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.19$  ([Table 2](#)).



SOA	Accuracy (SE)		
	Valid	Invalid same-object	Invalid different-object
300 ms	99.88 (0.09)	99.88 (0.12)	99.88 (0.12)
600 ms	99.96 (0.04)	99.88 (0.12)	100.00 (0.00)
900 ms	99.88 (0.07)	99.88 (0.12)	100.00 (0.00)

Table 1. Mean accuracy for each condition in [Experiment 1](#).

SOA	Response time (SE)		
	Valid	Invalid same-object	Invalid different-object
300 ms	333 (6.95)	332 (7.50)	347 (8.19)
600 ms	336 (7.29)	324 (7.05)	340 (7.34)
900 ms	344 (7.91)	331 (7.61)	344 (8.20)

Table 2. Mean response time (ms) for each condition in [Experiment 1](#).Figure 2. Mean RTs from [Experiment 1](#) as a function of cue validity (invalid same-object; invalid different-object) and SOA (300 ms, 600 ms, 900 ms). Bars represent the standard error. \*\*\*  $p < 0.001$ .

To explore the impact of SOA on object-based attention, we carried out a  $3 \times 2$  ANOVA with SOA and cue validity (invalid same-object, invalid different-object) as the within-subjects factors ([Figure 2](#)). The main effect of SOA was found to be significant,  $F(2, 48) = 3.26$ ,  $p = 0.05$ ,  $\eta_p^2 = 0.12$ . Post hoc tests with LSD correction revealed that RTs were slower for the 300-ms SOA condition ( $M = 340$  ms,  $SD = 39$ ) than for the 600-ms SOA condition ( $M = 332$  ms,  $SD = 35$ ),  $t(24) = 2.85$ ,  $p = 0.009$ , Cohen's  $d = 0.57$ , 95% confidence interval (CI) = 2–13. Moreover, the main effect of cue validity was also significant,  $F(1, 24) = 78.27$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.77$ , and RTs were faster for the invalid same-object condition ( $M = 329$  ms,  $SD = 35$ ) than for the invalid different-object condition ( $M = 344$  ms,  $SD = 38$ ), indicating a significant

object-based effect. Interestingly, the analysis did not find a significant interaction between SOA and cue validity,  $F(2, 48) = 0.31$ ,  $p = 0.74$ ,  $\eta_p^2 = 0.01$ , indicating that the object-based effect was not affected by SOA.

## Experiment 2

[Experiment 1](#) found that the object-based effect triggered by rectangles was not affected by SOA. In addition to these non-reward objects, however, in real life there are also reward objects (e.g., money). It is unclear whether the temporal dynamics of object-based attentional allocation for reward objects is the same as that for non-reward objects. Previous



Figure 3. Examples of the stimulus displays used in Experiments 2.

research has found that reward-induced motivation can improve an individual's cognitive control ability (Bucker & Theeuwes, 2014) and that volitional control can affect the object-based effect depending on the amount of time given (Drummond & Shomstein, 2010; Shomstein & Yantis, 2004). Hence, we posited that the reward properties of the reward objects may affect the object-based effect, and this influence could be mediated by SOA. Accordingly, in Experiment 2, pictures of banknotes were used as stimuli to explore this issue. We postulated that the reward properties can impact the object-based effect and the effect would disappear only at longer SOA.

## Method

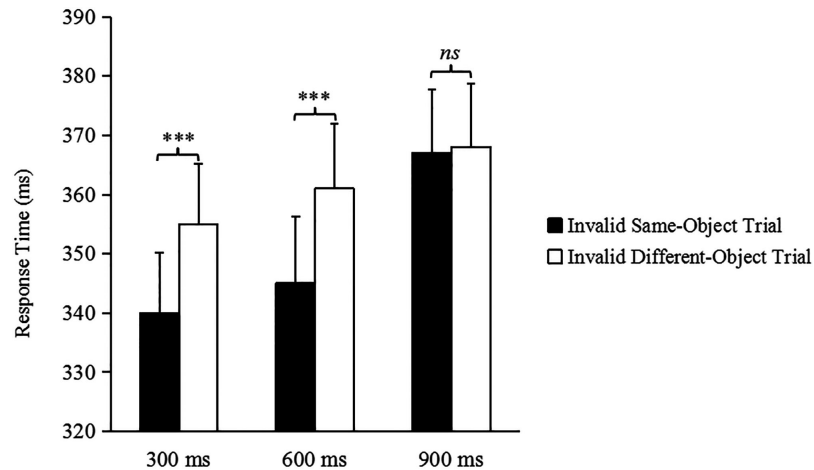
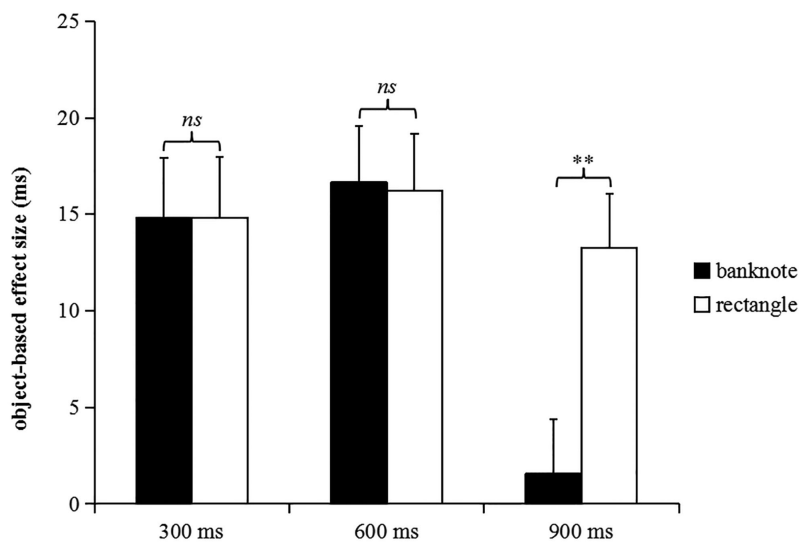
Twenty-five undergraduates were paid to participate in Experiment 2. Participants' ages ranged between 17 and 23 years old (mean age = 19 years,  $SD = 1.84$ ). The stimuli and procedure for Experiment 2 were the same as those of Experiment 1, except that two images of money that were the same as those used in the Zhao et al. (2020) study were presented to participants and the color of the target was changed to black (see Figure 3). The orientation (vertical or horizontal) of the notes, the position of faces on the notes, and the direction of the faces' gaze were counterbalanced across trials. Likewise, Experiment 2 used a 3 (cue validity: valid, invalid same-object, invalid different-object)  $\times$  3 (SOA: 300 ms, 600 ms, 900 ms) within-subjects factorial design.

## Results and discussion

Data processing was the same as in Experiment 1, with 2.3% of data discarded. The results of the Kolmogorov–Smirnov test suggest that the data of Experiment 2 were normally distributed. The RTs and accuracy were submitted to a 3  $\times$  3 ANOVA with SOA and cue validity as the within-subjects factors. In an ANOVA conducted on RTs, the main effect of SOA was found to be significant,  $F(2, 48) = 20.24$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.46$ . In addition, the main effect of cue validity was also significant,  $F(2, 48) = 14.49$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.38$ . More importantly, there was a significant interaction between SOA and cue validity,  $F(4, 96) = 4.84$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.17$  (Table 3).

To explore the impact of SOA on object-based attention, we carried out a 3  $\times$  2 ANOVA with SOA and cue validity (invalid same-object, invalid different-object) as the within-subjects factors (Figure 4). The main effect of SOA was found to be significant,  $F(2, 48) = 15.93$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.40$ . Post hoc tests revealed that RTs were slower for the 900-ms SOA condition ( $M = 368$  ms,  $SD = 53$ ) than for both the 300-ms condition ( $M = 347$  ms,  $SD = 50$ ),  $t(24) = 4.71$ ,  $p < 0.001$ , Cohen's  $d = 0.94$ , 95% CI = 11–29, and the 600-ms SOA condition ( $M = 353$  ms,  $SD = 55$ ),  $t(24) = 5.05$ ,  $p < 0.001$ , Cohen's  $d = 1.01$ , 95% CI = 9–20. Moreover, the main effect of cue validity was also significant,  $F(1, 24) = 28.11$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.54$ , and RTs were faster for the invalid same-object condition ( $M = 351$  ms,  $SD = 52$ ) than for the invalid different-object condition ( $M = 362$  ms,  $SD = 51$ ), indicating a significant object-based effect. More importantly, there was a significant interaction between SOA and cue validity,  $F(2, 48) = 7.92$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.25$ . The simple effect analysis found that the object-based effect was significant in the 300-ms SOA condition,  $F(1, 24) = 18.93$ ,  $p < 0.001$ , and in the 600-ms SOA condition,  $F(1, 24) = 24.11$ ,  $p < 0.001$ , but not significant in the 900-ms SOA condition,  $F(1, 24) = 0.35$ ,  $p = 0.56$ . More importantly, the object-based effect was smaller for the 900-ms SOA condition ( $M = 1.55$  ms,  $SD = 13.20$ ) than for the 300-ms condition ( $M = 14.80$  ms,  $SD = 17.01$ ),  $t(24) = -2.94$ ,  $p = 0.007$ , Cohen's  $d = 0.59$ , 95% CI = -23 to -4, and the 600-ms SOA condition ( $M = 16.65$  ms,  $SD = 16.95$ ),  $t(24) = -4.50$ ,  $p < 0.001$ , Cohen's  $d = 0.90$ , 95% CI = -22 to -8. Furthermore, to explore whether the temporal dynamics of object-based attentional allocation on rectangle and monetary object are consistent, we performed an inter-experimental comparison. The object-based effect sizes (RT differences between the invalid different-object and invalid same-object conditions) were submitted to a 2 (object type: rectangle, banknote)  $\times$  3 (SOA: 300 ms, 600 ms, 900 ms) factorial design with SOA as the within-subjects

SOA	Response time (SE)		
	Valid	Invalid same-object	Invalid different-object
300 ms	340 (9.83)	340 (10.13)	355 (10.12)
600 ms	350 (9.12)	345 (11.26)	361 (10.88)
900 ms	365 (9.65)	367 (10.75)	368 (10.68)

Table 3. Mean response time (ms) for each condition in [Experiment 2](#).Figure 4. Mean RTs from [Experiment 2](#) as a function of cue validity (invalid same-object, invalid different-object) and SOA (300 ms, 600 ms, 900 ms). Bars represent the standard error. ns,  $p > 0.05$ ; \*\*\*  $p < 0.001$ .Figure 5. Object-based effect sizes as a function of object type (rectangle, banknote) and SOA (300 ms, 600 ms, 900 ms). Bars represent the standard error. ns,  $p > 0.05$ ; \*\*  $p < 0.01$ .

factor and object type as the between-subjects factor ([Figure 5](#)). The results found that the main effect of object type was not significant,  $F(1, 48) = 2.01$ ,  $p = 0.16$ ,  $\eta_p^2 = 0.04$ , but the main effect of SOA was

significant,  $F(2, 96) = 5.90$ ,  $p = 0.004$ ,  $\eta_p^2 = 0.11$ . Post hoc tests revealed that object-based effect sizes were smaller for the 900-ms SOA condition ( $M = 7.41$ ,  $SD = 15.09$ ) than for the 300-ms SOA condition

SOA	Accuracy (SE)		
	Valid	Invalid same-object	Invalid different-object
300 ms	99.88 (0.07)	99.88 (0.12)	99.76 (0.17)
600 ms	99.84 (0.13)	100.00 (0.00)	99.24 (0.34)
900 ms	99.92 (0.06)	100.00 (0.00)	99.88 (0.12)

Table 4. Mean accuracy for each condition in [Experiment 2](#).

( $M = 14.82$ ,  $SD = 15.53$ ),  $t(49) = -2.38$ ,  $p = 0.02$ , Cohen's  $d = 0.35$ , 95% CI =  $-13.50$  to  $-1.31$ , or the 600-ms SOA condition ( $M = 16.45$ ,  $SD = 14.57$ ),  $t(49) = -3.54$ ,  $p < 0.001$ , Cohen's  $d = 0.50$ , 95% CI =  $-13.92$  to  $-4.15$ . More importantly, there was a significant interaction between object type and SOA,  $F(2, 96) = 3.00$ ,  $p = 0.05$ ,  $\eta_p^2 = 0.06$ . The simple effect analysis revealed that for the 900-ms SOA condition, object-based effect sizes for the rectangle ( $M = 13.27$ ,  $SD = 14.81$ ) were significantly larger than those for the banknote ( $M = 1.55$ ,  $SD = 13.20$ ),  $F(1, 48) = 8.71$ ,  $p = 0.005$ ; however, for the 300-ms and 600-ms SOA conditions, there were no significant differences in object-based effect sizes between the two types of objects.

In an ANOVA conducted on accuracy, the main effect of SOA was found to be significant,  $F(2, 48) = 4.15$ ,  $p = 0.02$ ,  $\eta_p^2 = 0.15$ . Post hoc tests revealed that accuracy was higher for the 900-ms SOA condition ( $M = 99.93$ ,  $SD = 0.22$ ) than for the 600-ms SOA condition ( $M = 99.69$ ,  $SD = 0.75$ ),  $t(24) = 2.15$ ,  $p = 0.04$ , Cohen's  $d = 0.43$ , 95% CI =  $0.01$ – $0.47$ . Moreover, the main effect of cue validity was significant,  $F(2, 48) = 3.94$ ,  $p = 0.03$ ,  $\eta_p^2 = 0.14$ . Post hoc tests revealed that accuracy was higher for the invalid same-object condition ( $M = 99.96$ ,  $SD = 0.20$ ) than for the invalid different-object condition ( $M = 99.63$ ,  $SD = 0.96$ ),  $t(24) = 2.09$ ,  $p = 0.05$ , Cohen's  $d = 0.42$ , 95% CI =  $0.00$ – $0.66$ . Importantly, the interaction between SOA and cue validity was also significant,  $F(4, 96) = 3.29$ ,  $p = 0.01$ ,  $\eta_p^2 = 0.12$ . The simple effect analysis revealed that the cue validity effect was significant in the 600-ms SOA condition,  $F(2, 48) = 4.90$ ,  $p = 0.01$ , but it was not significant in the 300-ms SOA condition or the 900-ms SOA condition. Post hoc tests revealed that, for the 600-ms SOA condition, accuracy in the invalid different-object condition ( $M = 99.24$ ,  $SD = 1.71$ ) was lower than that in the valid condition ( $M = 99.84$ ,  $SD = 0.62$ ),  $t(24) = -2.38$ ,  $p = 0.03$ , Cohen's  $d = -0.48$ , 95% CI =  $-1.12$  to  $-0.08$ , and the invalid same-object condition ( $M = 100.00$ ,  $SD = 0.00$ ),  $t(24) = -2.22$ ,  $p = 0.04$ , Cohen's  $d = -0.44$ , 95% CI =  $-1.47$  to  $-0.05$  (Table 4).

In [Experiment 2](#), when monetary objects were used as stimuli, the object-based effect appeared in the 300-ms and 600-ms SOA conditions but disappeared in the 900-ms SOA condition. This result suggests

that the object-based effect is affected by SOA. This finding is inconsistent with the result of [Experiment 1](#) (in which the object-based effect was not found to be affected by SOA). More importantly, we performed an inter-experimental comparison and found that, for the 900-ms SOA condition, the object-based effect of rectangles was significantly larger than that of monetary object. These results suggest that the temporal dynamics of object-based attentional allocation for monetary objects differ from those for rectangles, and the reward properties of monetary objects can impact attentional allocation in the 900-ms SOA condition, leading to the disappearance of the object-based effect.

## Experiment 3

The results of [Experiment 2](#) indicate that the reward properties of monetary objects could affect object-based attentional allocation; however, in addition to monetary rewards (i.e., secondary rewards), a reward may also be food (i.e., a primary reward) (for a review, see [Schultz, 2015](#)). Yet, it is unclear whether food objects will have the same influence as monetary objects on object-based attentional allocation—that is, whether there is a general processing mechanism for reward objects guiding attentional allocation. Accordingly, in [Experiment 3](#), images of bread were used as stimuli to explore this issue. If there is a general processing mechanism, then the object-based effect elicited by food objects would also disappear at longer SOA.

## Method

Twenty-five undergraduates were paid to participate in [Experiment 3](#). Participants' ages ranged between 17 and 21 years old (mean age = 19 years,  $SD = 0.89$ ). The stimuli and procedure for [Experiment 3](#) were the same as those of [Experiment 2](#) except that two images of bread were presented to participants ([Figure 6](#)). Likewise, [Experiment 3](#) used a 3 (cue validity: valid, invalid same-object, invalid different-object)  $\times$  3 (SOA: 300 ms, 600 ms, 900 ms) within-subjects factorial design.



SOA	Accuracy (SE)		
	Valid	Invalid same-object	Invalid different-object
300 ms	99.96 (0.04)	100.00 (0.00)	99.88 (0.12)
600 ms	99.96 (0.04)	100.00 (0.00)	100.00 (0.00)
900 ms	99.92 (0.06)	100.00 (0.00)	99.88 (0.12)

Table 5. Mean accuracy for each condition in [Experiment 3](#)

SOA	Response time (SE)		
	Valid	Invalid same-object	Invalid different-object
300 ms	343 (8.89)	346 (8.61)	359 (10.14)
600 ms	343 (7.82)	343 (8.78)	352 (8.01)
900 ms	359 (7.20)	357 (7.74)	359 (7.29)

Table 6. Mean response time (ms) for each condition in [Experiment 3](#).Figure 6. Examples of the stimulus displays used in [Experiments 3](#).

## Results and discussion

Data processing was the same as that in the first two experiments, with 2.4% of the data removed. The results of the Kolmogorov–Smirnov test suggest that the data of [Experiment 3](#) were normally distributed. The accuracy and RTs were submitted to a  $3 \times 3$  ANOVA with SOA and cue validity as the within-subjects factors. Analysis of accuracy did not show any significant main effects or interactions involving SOA or cue validity (all  $F_s < 2$ ,  $p_s > 0.3$ ) ([Table 5](#)). Analysis of RTs revealed that the main effect of SOA was significant,

$F(2, 48) = 5.30$ ,  $p = 0.008$ ,  $\eta_p^2 = 0.18$ . Moreover, the main effect of cue validity was also significant,  $F(2, 48) = 11.84$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.33$ . More importantly, analysis revealed a significant interaction between SOA and cue validity,  $F(4, 96) = 4.33$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.15$  ([Table 6](#)).

To explore the influence of SOA on object-based attention, we carried out a  $3 \times 2$  ANOVA with SOA and cue validity (invalid same-object, invalid different-object) as the within-subjects factors ([Figure 7](#)). The main effect of SOA was found to be significant,  $F(2, 48) = 3.13$ ,  $p = 0.05$ ,  $\eta_p^2 = 0.12$ . Post hoc tests revealed that RTs were faster for the 600-ms SOA condition ( $M = 347$  ms,  $SD = 41$ ) than for the 900-ms SOA condition ( $M = 358$  ms,  $SD = 37$ ),  $t(24) = -3.03$ ,  $p = 0.006$ , Cohen's  $d = 0.60$ , 95% CI =  $-18$  to  $-3$ . Moreover, the main effect of cue validity was also significant,  $F(1, 24) = 15.86$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.40$ , and RTs were faster for the invalid same-object condition ( $M = 349$  ms,  $SE = 40$ ) than for the invalid different-object condition ( $M = 357$  ms,  $SD = 40$ ). More importantly, there was a significant interaction between SOA and cue validity,  $F(2, 58) = 3.47$ ,  $p = 0.04$ ,  $\eta_p^2 = 0.13$ . The simple effect analysis revealed that the object-based effect was significant in the 300-ms SOA condition,  $F(1, 24) = 14.09$ ,  $p = 0.001$ , and the 600-ms SOA condition,  $F(1, 24) = 7.53$ ,  $p = 0.01$ , but not significant in the 900-ms SOA condition,  $F(1, 24) = 0.46$ ,  $p = 0.50$ . More importantly, the object-based effect was larger for the 300-ms SOA condition ( $M = 13.63$  ms,  $SD = 18.16$ ) than for the 900-ms SOA condition ( $M = 1.99$  ms,  $SD = 14.71$ ),  $t(24) = 2.74$ ,  $p = 0.01$ , Cohen's  $d = 0.55$ , 95% CI =  $3$ – $20$ .

Moreover, to explore whether the temporal dynamics of object-based attentional allocation on food and

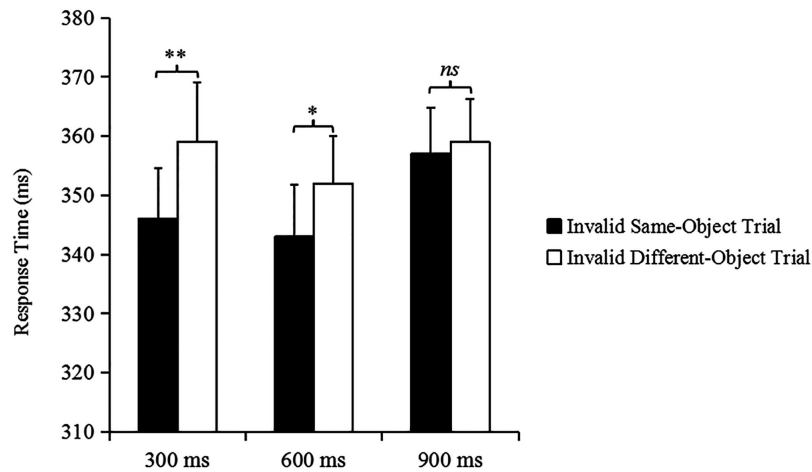


Figure 7. Mean RTs in [Experiment 3](#) as a function of cue validity (invalid same-object, invalid different-object) and SOA (300 ms, 600 ms, 900 ms). Bars represent the standard error. ns,  $p > 0.05$ ; \*  $p < 0.05$ ; \*\*  $p < 0.01$ .

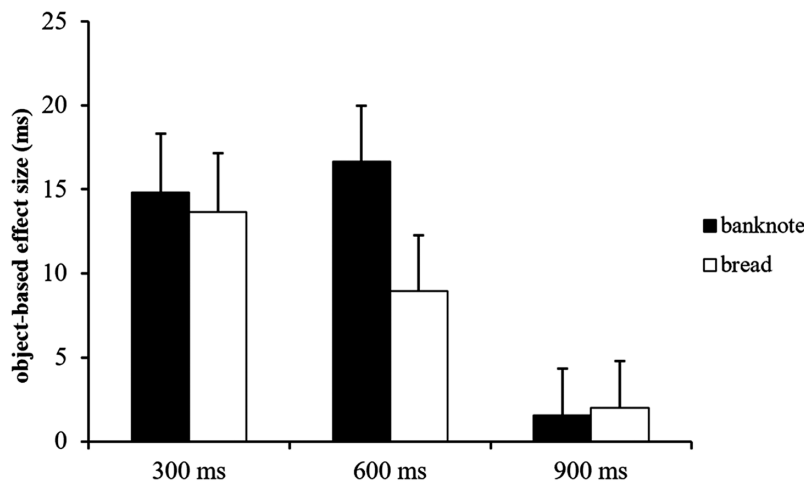


Figure 8. Object-based effect sizes as a function of object type (bread, banknote) and SOA (300 ms, 600 ms, 900 ms). Bars represent the standard error.

monetary object are consistent, we performed an inter-experimental comparison. The object-based effect sizes were submitted to a 2 (object type: bread, banknote)  $\times$  3 (SOA: 300 ms, 600 ms, 900 ms) factorial design with SOA as the within-subjects factor and object type as the between-subjects factor ([Figure 8](#)). The results found that the main effect of object type was not significant,  $F(1, 48) = 0.93$ ,  $p = 0.34$ ,  $\eta_p^2 = 0.02$ , but the main effect of SOA was significant,  $F(2, 96) = 10.06$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.17$ . Post hoc tests revealed that object-based effect sizes were smaller for the 900-ms SOA condition ( $M = 1.77$ ,  $SD = 13.84$ ) than those for the 300-ms SOA condition ( $M = 14.22$ ,  $SD = 17.43$ ),  $t(49) = -4.06$ ,  $p < 0.001$ , Cohen's  $d = 0.57$ , 95% CI =  $-18.61$  to  $-6.28$ , and for the 600-ms SOA condition ( $M = 12.80$ ,  $SD = 16.91$ ),  $t(49) = -4.13$ ,  $p < 0.001$ , Cohen's  $d = 0.58$ , 95% CI =  $-16.39$  to  $-5.66$ . Importantly, the

analysis did not find a significant interaction between SOA and object type,  $F(2, 96) = 1.01$ ,  $p = 0.37$ ,  $\eta_p^2 = 0.02$ .

Overall, [Experiment 3](#) repeated the results of [Experiment 2](#), and indicated that food and monetary objects have a similar influence on object-based attention. This suggests there is a general processing mechanism for reward objects guiding object-based attentional allocation, unaffected by reward type.

## Experiment 4

[Experiments 1](#) to [3](#) demonstrated that the temporal dynamics of object-based attentional allocation for



Figure 9. Examples of the stimulus displays used in Experiments 4.

reward objects is different from that in relation to rectangles; however, a possible explanation for these results is that the impact of reward objects may be due to their realness or semantic properties rather than their reward properties (Malcolm, Rattinger, & Shomstein, 2016; Scotti et al., 2016). Therefore, in Experiment 4, non-rewarding real-world objects (umbrellas and doors) were used as stimuli to eliminate the interference of realness or semantic properties. If the influence of reward objects on object-based attentional allocation is due to their reward properties rather than the realness or semantic properties, then the object-based effect elicited by umbrellas and doors should not be affected by SOA.

## Method

Twenty-five undergraduates were paid to participate in Experiment 4. Participants' ages ranged between 18 and 20 years old (mean age = 19 years,  $SD = 0.63$ ). The stimuli and procedure were the same as those of Experiment 2 except that two images of real umbrellas or doors were presented to participants (Figure 9). All participants got both stimuli, and both stimuli randomly appeared from trial to trial. We rated the participant's familiarity with umbrella, door, bread, and banknote on a 7-point scale from 1 (very unfamiliar) to 7 (very familiar). The results revealed similarly high familiarity among participants for umbrella ( $M = 6.58$ ,  $SD = 0.65$ ), door ( $M = 6.42$ ,  $SD = 1.05$ ), bread ( $M = 6.58$ ,  $SD = 0.65$ ), and banknote ( $M = 6.71$ ,  $SD = 0.65$ ),  $F(3, 69) = 0.96$ ,  $p = 0.42$ ,  $\eta_p^2 = 0.04$ . Likewise, Experiment 4 used a 3 (cue validity: valid, invalid same-object, invalid different-object)  $\times$  3 (SOA: 300 ms, 600 ms, 900 ms) within-subjects factorial design.

## Results and discussion

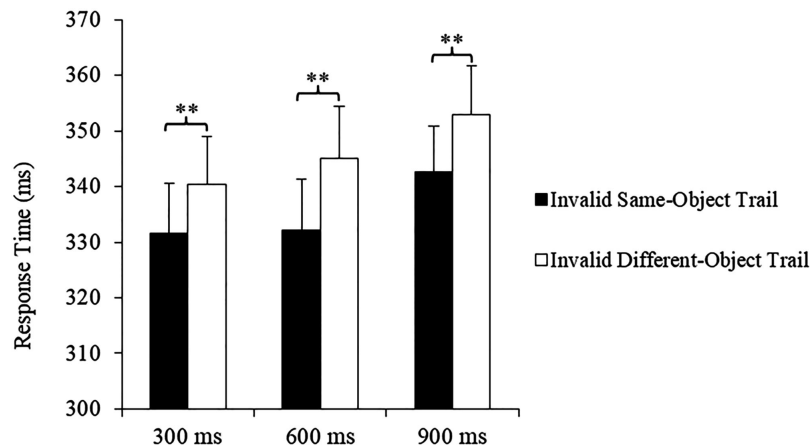
Data processing was the same as with the first three experiments, with 2.5% of the data discarded. The results of the Kolmogorov–Smirnov test suggest that the data of Experiment 4 were normally distributed. Preliminary analysis indicated no difference between the two types of objects (umbrellas and doors). The accuracy and RTs were submitted to a  $3 \times 3$  ANOVA with SOA and cue validity as the within-subjects factors. Analysis of accuracy did not show any significant main effects or interactions involving SOA or cue validity (all  $F_s < 3$ ,  $p_s > 0.07$ ) (Table 7). In an ANOVA conducted on RTs, the main effect of SOA was found to be significant,  $F(2, 48) = 13.45$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.36$ . In addition, the main effect of cue validity was also significant,  $F(2, 48) = 27.10$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.53$ . Importantly, the analysis did not find a significant interaction between SOA and cue validity,  $F(4, 96) = 0.71$ ,  $p = 0.59$ ,  $\eta_p^2 = 0.03$  (Table 8).

To explore the influence of SOA on object-based attention, we carried out a  $3 \times 2$  ANOVA with SOA and cue validity (invalid same-object, invalid different-object) as the within-subjects factors (Figure 10). The main effect of SOA was found to be significant,  $F(2, 48) = 13.60$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.36$ . Post-hoc tests showed that RTs were slower for the 900-ms SOA condition ( $M = 348$  ms,  $SD = 42$ ) than for the 300-ms SOA condition ( $M = 336$  ms,  $SD = 43$ ),  $t(24) = 4.79$ ,  $p < 0.001$ , Cohen's  $d = 0.96$ , 95% CI = 7–17, and the 600-ms SOA condition ( $M = 339$  ms,  $SD = 46$ ),  $t(24) = 4.02$ ,  $p < 0.001$ , Cohen's  $d = 0.80$ , 95% CI = 5–14. In addition, the main effect of cue validity was also significant,  $F(1, 24) = 31.13$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.57$ , and RTs were faster for the invalid same-object condition ( $M = 335$  ms,  $SD = 43$ ) than for the invalid different-object condition ( $M = 346$  ms,  $SD = 44$ ), indicating a significant

SOA	Accuracy (SE)		
	Valid	Invalid same-object	Invalid different-object
300 ms	99.43 (0.35)	100.00 (0.00)	99.89 (0.11)
600 ms	99.54 (0.21)	99.64 (0.27)	99.79 (0.15)
900 ms	99.61 (0.25)	99.54 (0.28)	99.79 (0.15)

Table 7. Mean accuracy for each condition in [Experiment 4](#).

SOA	Response time (SE)		
	Valid	Invalid same-object	Invalid different-object
300 ms	329 (8.34)	332 (8.97)	340 (8.59)
600 ms	327 (9.27)	332 (9.29)	345 (9.48)
900 ms	340 (8.25)	343 (8.18)	353 (8.74)

Table 8. Mean response time (ms) for each condition in [Experiment 4](#).Figure 10. Mean RTs from [Experiment 4](#) as a function of cue validity (invalid same-object, invalid different-object) and SOA (300 ms, 600 ms, 900 ms). Bars represent the standard error. \*\*  $p < 0.01$ .

object-based effect. Importantly, the analysis did not find a significant interaction between SOA and cue validity,  $F(2, 48) = 0.48$ ,  $p = 0.62$ ,  $\eta_p^2 = 0.02$ , suggesting that the SOA did not affect the object-based effect.

Moreover, to explore whether the temporal dynamics of object-based attentional allocation on rectangle and non-rewarding real-world object is consistent, we performed an inter-experimental comparison. The object-based effect sizes were submitted to a 2 (object type: rectangle, non-rewarding real-world object)  $\times$  3 (SOA: 300 ms, 600 ms, 900 ms) factorial design with SOA as the within-subjects factor and object type as the between-subjects factor ([Figure 11](#)). The results found that no main effects or interactions involving SOA or object type were significant (all  $F_s < 3$ ,  $p_s > 0.1$ ). [Experiment 4](#) repeated the results of [Experiment 1](#), finding that the object-based effect was

not affected by SOA. This indicates that the impact of reward objects on object-based attention is due to their reward properties rather than their realness or semantic properties.

Furthermore, to explore whether the temporal dynamics of object-based attentional allocation on reward and non-reward objects is consistent, we performed an inter-experimental comparison. We combined rectangle and non-rewarding real-world object into the non-reward objects and the food and monetary objects into the reward objects. The object-based effect sizes were submitted to a 2 (object type: non-reward object, reward object)  $\times$  3 (SOA: 300 ms, 600 ms, 900 ms) factorial design with SOA as the within-subjects factor and object type as the between-subjects factor ([Figure 12](#)). The results found that the main effect of object type was not significant,



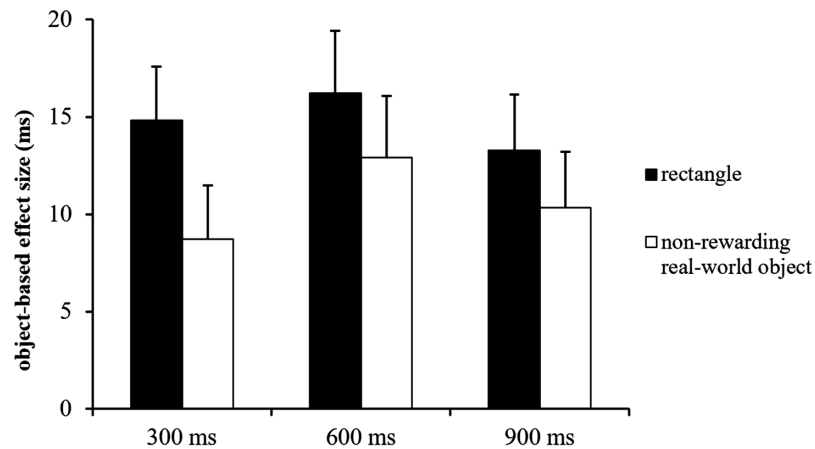


Figure 11. Object-based effect sizes as a function of object type (rectangle, non-rewarding real-world object) and SOA (300 ms, 600 ms, 900 ms). Bars represent the standard error.

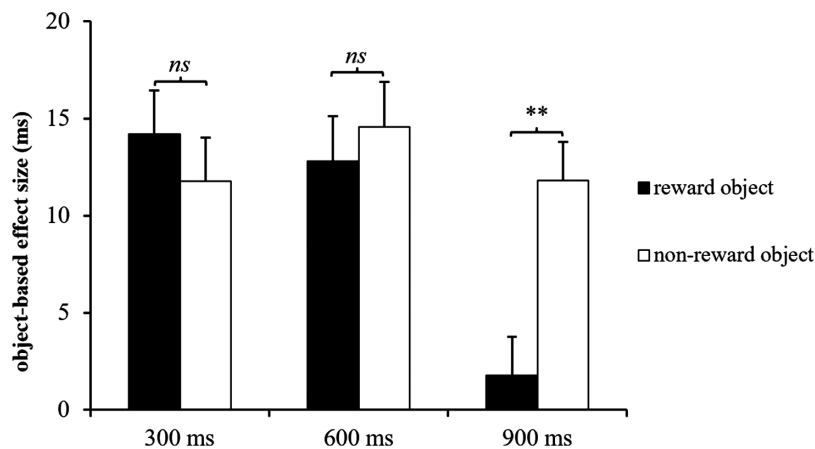


Figure 12. Object-based effect sizes as a function of object type (non-reward object, reward object) and SOA (300 ms, 600 ms, 900 ms). Bars represent the standard error. ns,  $p > 0.05$ ; \*\*  $p < 0.01$ .

$F(1, 98) = 2.56$ ,  $p = 0.11$ ,  $\eta_p^2 = 0.03$ , but the main effect of SOA was significant,  $F(2, 196) = 6.68$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.06$ . Post hoc tests revealed that object-based effect sizes were smaller for the 900-ms SOA condition ( $M = 6.79$ ,  $SD = 14.89$ ) than for the 300-ms SOA condition ( $M = 13.00$ ,  $SD = 15.75$ ),  $t(99) = -2.90$ ,  $p = 0.003$ , Cohen's  $d = 0.29$ , 95% CI =  $-10.46$  to  $-1.96$ , or the 600-ms SOA condition ( $M = 13.68$ ,  $SD = 16.35$ ),  $t(99) = -3.32$ ,  $p = 0.001$ , Cohen's  $d = 0.33$ , 95% CI =  $-11.02$  to  $-2.77$ . More importantly, there was a significant interaction between object type and SOA,  $F(2, 196) = 4.65$ ,  $p = 0.01$ ,  $\eta_p^2 = 0.05$ . The simple effect analysis revealed that, for the 900-ms SOA condition, object-based effect sizes for non-reward objects ( $M = 11.80$ ,  $SD = 14.33$ ) were significantly larger than those for reward objects ( $M = 1.77$ ,  $SD = 13.84$ ),  $F(1, 98) =$

$12.67$ ,  $p = 0.001$ ; however, for the 300-ms and 600-ms SOA conditions, there were no significant differences in object-based effect sizes between the two types of objects.

## General discussion

Our study aimed to test whether the temporal dynamics of object-based attentional allocation for reward objects are the same as those for non-reward objects and whether reward objects guide object-based attentional allocation in a general processing mechanism. In [Experiment 1](#), rectangles were used as stimuli, and the results obtained suggest that

the object-based effect was not affected by SOA. In [Experiment 2](#), banknotes were used as stimuli, and it was found that the object-based effect appeared in the 300-ms and 600-ms SOA conditions but disappeared in the 900-ms SOA condition. In [Experiment 3](#), pictures of bread were used as stimuli, and the temporal dynamics of object-based attentional allocation were the same as those obtained in [Experiment 2](#). In [Experiment 4](#), real umbrellas and doors were used as stimuli, and the results suggested that, as in [Experiment 1](#), the object-based effect was not affected by SOA.

Overall, our results suggest that the temporal dynamics of object-based attentional allocation differ between reward and non-reward objects, as the object-based effect was unaffected by SOA with non-reward objects as stimuli but disappeared only at 900-ms SOA with reward objects as stimuli. This may be because reward properties of the reward objects enhance our motivation to distribute attention equally across potential target locations despite unreliable information provided by cues and object context. Previous research has found that reward-induced motivation can improve an individual's cognitive control ability ([Bucker & Theeuwes, 2014](#)). Moreover, some studies have revealed that rewards can strongly influence selective attention by influencing cognitive control (for a review, see [Failing & Theeuwes, 2018](#)). More importantly, prior studies have suggested that cognitive control can affect the allocation of object-based attention ([Drummond & Shomstein, 2010](#); [Shomstein & Yantis, 2004](#)). In these studies, observers could subjectively allocate attention according to contextual strategies (e.g., the probability of the target appearing in the uncued location), and this effect was mediated by the duration of the task or activity (such effect appears only at longer SOA). Further evidence that additional time is required in order to allocate attention subjectively comes from [Van Zoest, Donk, and Theeuwes \(2004\)](#), who found that goal-driven control could influence visual selection at longer SOA. In other words, being given more time to process top-down strategies before the target appears allows those strategies to affect visual search patterns more effectively. Accordingly, we believe that in the 900-ms SOA condition, the observer exclusively allocates attention according to the corresponding reward properties to pursue rewards and is not restricted by the boundaries of objects. Furthermore, because the invalid same-object location and the invalid different-object location had the same reward properties in our study, there was no difference in reaction times between the two locations, which led to the disappearance of the object-based effect. Remarkably, these results somewhat support the attentional prioritization theory. As a classical theory of object-based attention, it suggests that object-based selection may reflect an object-specific attentional prioritization strategy, whereby invalid same-object location is processed ahead of invalid

different-object location ([Drummond & Shomstein, 2010](#); [Shomstein & Yantis, 2002](#)). In our study, the participants' strategy of seeking reward stimuli may have overcome the object-specific attentional prioritization strategy, leading attention allocation to be guided only by reward properties. Our results are also partly consistent with previous research reporting that monetary objects can elicit and affect the object-based effect. For example, [Zhao et al. \(2020\)](#) manipulated the value differences between objects and found that the high-value object could automatically capture attention. Our study, by contrast, used objects with the same reward properties as stimuli and found that observers could strategically allocate attention according to the reward properties in the 900-ms SOA condition. These findings indicate that reward objects can influence attentional allocation in bottom-up (automatically) and top-down (strategically) ways, depending on the difference in reward properties between the objects and the amount of time taken.

Our results indicate that reward properties can affect the allocation of object-based attention only at longer SOA, which is partly consistent with previous studies reporting that the influences of contextual strategies on object-based attention were mediated by the duration of the task or activity (such effect appears only at 600-ms SOA rather than 200-ms or 400-ms SOAs) ([Drummond & Shomstein, 2010](#); [Shomstein & Yantis, 2004](#)). However, in contrast to these findings, we found that reward properties affected the object-based effect only at 900-ms SOA rather than 600-ms SOA. One possible reason is that the reward objects we used in the current study were real-world objects. Compared with the geometric objects, the real-world objects are more complex and have more information, so the processing of the real-world objects requires more time (e.g., [Malcolm & Shomstein, 2015](#)). This may be the reason why reward properties affected object-based attention only in 900-ms SOA condition. Future research could further explore the temporal dynamics of reward properties affecting object-based attention.

Moreover, our results suggest that food and monetary objects have the same influence on object-based attention. Prior research has found that monetary objects can elicit and influence the object-based effect ([Zhao et al., 2020](#)). However, money is often considered as a secondary reward, whereas food, for example, is a primary reward. In the current study, we separately used food and monetary objects as stimuli and found a consistent allocation mode of object-based attention. This suggests that reward objects can influence object-based attention via a general mechanism. This result seems to be consistent with the common currency theory, which implies that different types of reward values are represented in a unique set of brain regions (ventral striatum and ventromedial prefrontal cortex) and that their values should be computed on a single scale ([Levy & Glimcher, 2012](#); [Sescousse et al., 2013](#);

Sugrue et al., 2005). Furthermore, our results reveal that different types of reward values consistently affect object-based attention, suggesting that reward values may also be represented in the brain by a common currency mechanism in the field of attention.

Furthermore, we ruled out the possibility that the realness or semantic properties of reward objects led to the disappearance of the object-based effect in the 900-ms SOA condition. In addition to their different reward properties, reward objects and rectangles also differ with respect to their relative “realness.” Furthermore, previous studies have found that the semantic information of real-world objects can also affect the object-based effect (Malcolm et al., 2016; Scotti et al., 2016). Therefore, the impact of reward properties on object-based attention may be intertwined with realness and semantic interference. Accordingly, in Experiment 4, we used real umbrellas and doors as stimuli and found that the object-based effect was not affected by SOA, suggesting that the impact of reward objects on the participants’ object-based attention was due to their reward properties, rather than their realness or semantic properties. This result is partly consistent with the earlier findings that the object-based effect for geometric objects is stable and not affected by SOA (List & Robertson, 2007; for a review, see Reppa et al., 2012). Importantly, we extended this finding to a real-world object, indicating that the object-based effect triggered by the non-rewarding object (whether geometric or real world) is not affected by SOA.

To conclude, this study found that the temporal dynamics of object-based attentional allocation differed between reward and non-reward objects and that food and monetary objects had the same influence on object-based attention. These findings imply that reward values may also be represented in the brain by a common currency mechanism in the field of attention, and the object-based attentional selection is not completely automatic and is influenced by top-down strategies.

*Keywords:* object-based attention, reward, attentional allocation, temporal dynamic, common currency

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Corresponding authors: Feng Kong; Jingjing Zhao.  
Email: kongfeng87@126.com;  
zhaojingjing\_31@126.com.

Address: School of Psychology, Shaanxi Normal University, Xi’an, China.

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