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Learned Reward Association Improves Visual Working Memory

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Statistical regularities in the natural environment play a central role in adaptive behavior. Among other regularities, reward association is potentially the most prominent factor that influences our daily life. Recent studies have suggested that pre-established reward association yields strong influence on the spatial allocation of attention. Here we show that reward association can also improve visual working memory (VWM) performance when the reward-associated feature is task-irrelevant. We established the reward association during a visual search training session, and investigated the representation of reward-associated features in VWM by the application of a change detection task before and after the training. The results showed that the improvement in VWM was significantly greater for items in the color associated with high reward than for those in low reward-associated or nonrewarded colors. In particular, the results from control experiments demonstrate that the observed reward effect in VWM could not be sufficiently accounted for by attentional capture toward the high reward-associated item. This was further confirmed when the effect of attentional capture was minimized by presenting the items in the sample and test displays of the change detection task with the same color. The results showed significantly larger improvement in VWM performance when the items in a display were in the high reward-associated color than those in the low reward-associated or nonrewarded colors. Our findings suggest that, apart from inducing space-based attentional capture, the learned reward association could also facilitate the perceptual representation of high reward-associated items through feature-based attentional modulation.

Keywords: reward, working memory, attention, visual, learning

The rapid detection of items of value in a dynamic environment is challenging because such items are often accompanied by other distractors. Value-orientated actions can be optimized by the recognition of a few diagnostic features that are linked with potential reward through past experience. Previous studies have suggested that the learned association of an item with a reward can enhance motivation and benefit goal-directed behavior (Pavlov, 1927; Rescorla & Wagner, 1972). Such association has been shown to modulate the allocation of selective attention to items that have been associated with reward previously (Anderson, Laurent, & Yantis, 2011; Della Libera & Chelazzi, 2006, 2009; Hickey, Chelazzi, & Theeuwes, 2010, 2011; Hickey & van Zoest, 2012; Peck, Jangraw, Suzuki, Efem, & Gottlieb, 2009; Raymond & O'Brien, 2009). It is important to note that it has been suggested that the reward association influences attentional allocation in a way that differs from other forms of selective attention (Awh, Belopolsky, & Theeuwes, 2012). Under certain task contexts, the reward-induced attentional allocation is driven neither by task-relevant goals nor by stimulus' physical salience (Anderson et al., 2011; Della Libera & Chelazzi, 2009; Hickey et al., 2010). Particularly, the reward association is established before the examination of its impact on attentional allocation, and the reward-induced selection bias can be obtained even when it contradicts with current goals.

Generally, learning an association between a reward and a specific item leaves behind memory traces that guide attention for future tasks. This form of reward-induced attentional allocation could be viewed as a consequence of automatic matching of a reward-associated item with its stored representation in the memory system. This raises a question of whether the reported reward effects were accompanied by the improvement of memory performance for the reward-associated items. Previous studies have demonstrated that reward can improve memory consolidation that manifests gradually and lasts for a persistent period of time (Abe et al., 2011; Bunzeck, Doeller, Fuentemilla, Dolan, & Duzel, 2009). However, these studies were performed to emphasize the functional link between task-related reward signal and memory performance without considering the attentional factors. Therefore, how the previously learned reward association influences the memory performance, particularly the visual working memory (VWM), remains less well understood.

It is well known that VWM shares common mechanisms and interacts extensively with attention (Awh, Vogel, & Oh, 2006; Gazzaley & Nobre, 2012; Zanto, Rubens, Thangavel, & Gazzaley, 2011). An examination of the reward association effect on VWM performance is, therefore, critical for fully understanding the role of the reward association on perceptual processing. Investigations on this issue could also provide further experimental evidence on how pre-

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vious reward history influences the competition for limited perceptual resources. Recent studies (Anderson et al., 2011; Della Libera & Chelazzi, 2009) have shown that the item with the pre-established reward-associated feature can capture attention although at the cost of impairing visual search performance. These findings raise the possibility that the reward association may influence the VWM performance by biasing attentional allocation toward the reward-associated items. This "attentional capture hypothesis" is supported by other studies showing similar biasing effects (Della Libera & Chelazzi, 2006, 2009; Hickey et al., 2010, 2011). Meanwhile, reward may also exhibit attentional modulation effect through improved early perceptual processing (Hickey & van Zoest, 2012; O'Brien & Raymond, 2012) or enhanced retention of memorized items (Kawasaki & Yamaguchi, 2013). This alternative "attentional modulation hypothesis" could also lead to enhanced representation in VWM for the reward-associated items.

In the present study, we examined the effect of learned reward association on VWM and attempted to answer two questions. First, whether the reward-associated feature can improve VWM performance when it is task-irrelevant. Second, what is the role that attention plays (capture vs. modulation) concerning the improvement in VWM if it is observed. We designed a set of three experiments to address these questions. In Experiment 1, we adopted a change detection paradigm that measures VWM (Pashler, 1988), and examined whether the learned reward association can improve VWM performance. After establishing the reward associations during a visual search training session, we investigated the performance improvement in the change detection task for the item in the high reward-associated, low reward-associated, and nonrewarded colors. We also measured the VWM performance of a physically salient but not reward-associated item in a separate block. This additional measurement on physical salience was included to serve as a reference condition given its close relationship to attentional capture effect. To anticipate, the results showed larger VWM improvement for the high reward-associated target than the low reward-associated and nonrewarded targets in the change detection task but no advantage for the physically salient target over nonsalient targets. In Experiment 2, we replaced the incentive monetary rewards with on-screen feedback on the correctness of the observers' responses, while the other procedures were identical to Experiment 1. In addition, in Experiment 3 we minimized the effect of attentional capture by presenting the items in the sample and test displays of the change detection task with the same color. The "attentional capture hypothesis" predicted two possible phenomena: (1) the impaired performance when high reward-associated color served as a distractor, and (2) the vanished VWM performance improvement for the high reward-associated item when attentional capture was blocked. Alternatively, the "attentional modulation hypothesis" predicted the reserved reward effect on VWM performance even after eliminating the possibility of the capture effect.

Experiment 1

Method

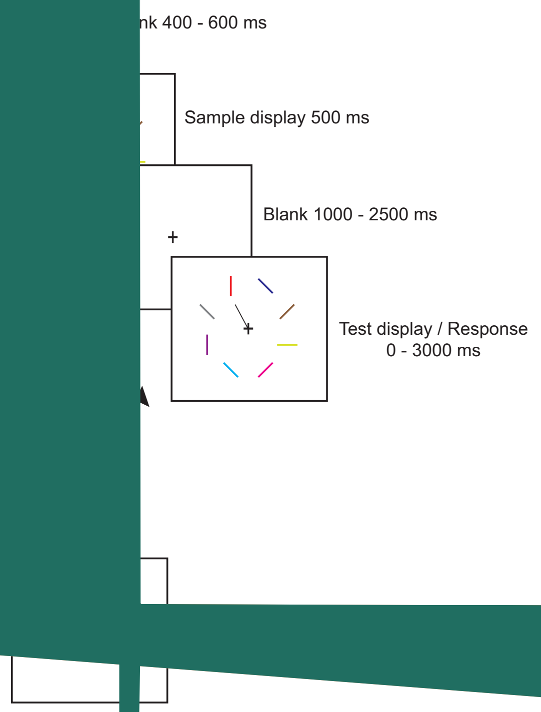
Participants. Fourteen observers (6 males; mean age 21.8 years) participated in Experiment 1. All participants were students from Peking University, had normal or corrected-to-normal vision, and gave written informed consent. The experiment was approved by the local ethics committee.

Stimuli. Stimuli were displayed on the black background of a CRT monitor (refresh rate: 100 Hz). We selected 10 colors (including red and green) for the experiments, and they were adjusted to be physically equiluminant (15 cd/m^2).

Procedure. The experiment comprised three sessions on three successive days: (1) a pretest session that involved the change detection task, (2) a training session on the visual search task, and (3) a posttest session that involved the change detection task (see Figure 1). The observers were paid ¥35 (¥ [Yuan] is the unit of Chinese currency, ¥1≈16¢) for their participation in the pre- and posttest sessions. The payment for participation in the training session was based on the performance of individual observers (mean: ¥22.07 ± 1.49).

In the pretest session, we adopted a change detection paradigm with eight items and a post-delay cue to ensure that capacity-limited VWM was measured (Sligte, Scholte, & Lamme, 2008). Each observer performed 20 practice trials before the pretest. Each trial began with the presentation of a central fixation cross (0.6° × 0.6°) for a random duration of 400–600 ms, and this was followed by a sample display. The sample display comprised eight colored bars (1.6° × 0.1°) at equal eccentricities (6°) from the central fixation point and was shown for 500 ms. The orientation of the bars was randomly assigned to be horizontal, vertical, or 45° to the horizontal and vertical. Each orientation appeared at least once in a display. Then, the test display appeared after a blank fixation period of a random duration of 1,000–2,500 ms to minimize the residual traces from iconic memory and avoid ceiling or floor effects in memory performance. In addition to the eight colored bars, the test display contained a white probe line (0.9° × 0.1°), which pointed to one of the bars. The observer was asked to determine whether the probed bar had rotated by 90° between the sample and the test displays by pressing one of two keys (left and right arrow key on the keyboard) using index and middle fingers of the right hand. They were told explicitly that the only change that can occur between the sample and test displays was the change of orientation for one of the eight bars. There was no change of color between the sample and test displays. The pretest consisted of 432 trials, half of which involved a red bar and the other half involved a green bar. Red and green bars did not appear in the same trial. The colors of the other seven bars were randomly selected from the remaining eight available colors. There were no two bars in the same color in a display. The probability that the red or green bar served as the target was the same as that for the other seven bars (12.5%). Accuracy was computed separately for three groups of trials, namely those in which red, green, or another color served as the target. Observers continued to participate in the experiment only if their accuracies for the three color categories (red, green, and other colors) during the pretest varied by less than 10% (i.e., the highest accuracy minus the lowest accuracy). This selection criterion was required to exclude participants with strong individual biases in color perception that could hamper the experimental manipulation.

In the training session, we established a task-irrelevant reward-color association with a training session on the visual search task (Anderson et al., 2011). During the visual search task, each trial started with the presentation of a central fixation cross (0.6° × 0.6°) for a random duration of 400–600 ms. A search display was then presented for 500 ms. The search display was composed of eight white bars (1.3° × 0.1°) that were located inside colored circles (2.6° × 2.6°) at equal eccentricities (6°) around the central fixation point. The search target was a bar with horizontal (0°) or


nk 400 - 600 ms
Sample display 500 ms
Blank 1000 - 2500 ms
+
Test display / Response
0 - 3000 ms

Total: 42

vertical orientation (90°). The other seven bars were tilted by 45° either to the left or to the right. The target bar appeared only inside a red or a green circle, with equal probability (50%). The observer was instructed to identify the target bar and press a button to indicate its orientation. Immediately after a correct response, on-screen feedback was provided that showed the reward for the current trial and the total reward accumulated. For half of the observers, the red and green circles were associated with a high probability (80%) of a high reward (¥0.5) and a low reward (¥0.1), respectively. The color–reward association was reversed for the other observers. Incorrect responses were followed by a blank screen. Notably, the observers' choice was made independently of the color of the target circle. They were not informed about the regularity of the reward–color association. However, the observers were informed that the amount of payment that they would receive was one-tenth of their final accumulated monetary reward (up to ¥24). The training session for each observer consisted of 800 trials, and the trial order was randomized across conditions.

The posttest comprised two runs. The order of the two runs was randomized across observers. One of the two runs was the same as the pretest change detection task, whereas the other (the physical salience run; 384 trials) differed from the pretest in two aspects. First, red and green colors were excluded from the physical salience run. Second, each display contained a bar that was four times thicker (1.6° × 0.4°; the salient item) than the other bars. The observers were informed that the probability that the thicker bar would be probed was the same as that of the other seven bars (12.5%). The performance of physical salient item in VWM was measured to serve as a reference condition that could be used to compare with the reward-induced effect on VWM.

Results and Discussion

Visual search training. We measured the behavioral performance of the observers during training on the visual search task. The performance of the observers improved over the course of training for the two conditions, in which the color of the circle that surround the target bar was associated with high reward and low reward, but as indicated by a paired *t* test, there were no significant differences in relation to either accuracy, $t(13) = 0.12$, $p = .91$ or reaction time (RT), $t(13) = 0.33$, $p = .75$ between the two conditions (Figure 2A). To further check the possible difference that occurred during the learning period between the high-reward and low-reward conditions, we analyzed observers' visual search performance in the last 100 trials of the training session. We found no significant differences in either accuracy, $t(13) = 0.52$, $p = .61$ or RT, $t(13) = 0.82$, $p = .42$ between the two conditions (high reward-associated color vs. low reward-associated color).

Change detection task. For the change detection tasks, we calculated the detection sensitivity (d') (Green & Swets, 1966) and compared d' among three conditions. In the first condition, the color of the probed bar was associated with a high reward during the visual search training; in the second, it was associated with low reward; and in the third, the probed bar was a nontarget (control) color. A repeated measures analysis of variance (ANOVA) was performed on the raw d', in both pretest and posttest sessions, respectively (Figure 2B). No significant difference was found in d' in the pretest session ($F(2, 26) = 1.56$, $p = .23$, $\eta_p^2 = 0.11$). Bonferroni post hoc tests confirmed that there were no significant differences between the high and low reward-associated colors (mean difference $= -0.074$, $SE = 0.09$, $p = 1.0$), the high reward-associated and control colors (mean difference $= -0.152$, $SE = 0.07$, $p = .15$), or the low reward-associated and control colors (mean difference $= -0.078$, $SE = 0.096$, $p = 1.0$). In contrast, there was significant difference in d' among the three conditions ($F(2, 26) = 5.28$, $p < .05$, $\eta_p^2 = 0.29$) in the posttest session. Bonferroni post hoc tests showed significant differences between the high and low reward-associated colors (mean difference $= 0.329$, $SE = 0.085$, $p < .01$), but no significant differences were found between the high reward-associated and control colors (mean difference $= 0.210$, $SE = 0.122$, $p = .33$), and the low reward-associated and control colors (mean difference $= -0.119$, $SE = 0.099$, $p = .75$). Furthermore, to directly evaluate the effect of learned reward association on the improvement of VWM performance between the three conditions, we calculated their performance change ($\Delta d'$) before and after the training session. A repeated measures analysis of variance (ANOVA) revealed a significant difference in $\Delta d'$ among the three conditions ($F(2, 26) = 7.39$, $p < .01$, $\eta_p^2 = 0.36$). Bonferroni post hoc tests showed that when the color of the probed bar was associated with a high reward, $\Delta d'$ was significantly higher than when the color was associated with a low reward (mean difference $= 0.404$, $SE = 0.119$, $p < .05$) or was a control color (mean difference $= 0.362$, $SE = 0.116$, $p < .05$). There was no significant difference in $\Delta d'$ between the condition in which the bar in the low reward-associated color was probed and that in which the bar in a control color was probed (mean difference $= -0.041$, $SE = 0.110$, $p = 1.00$). We also calculated the decision criterion for each of the three conditions, and further revealed that the improvement in d' that occurred after the training session was not accompanied by a shift in the decision criterion ($F(2, 26) = 0.26$, $p = .77$, $\eta_p^2 = 0.02$). Bonferroni post hoc tests showed no significant differences among the three conditions with regard to Δc ($p = 1.00$ for all comparisons). These results suggest that the learned reward association plays an important role in transforming transient perceptual representations into durable VWM, making the high reward-associated items easier to detect in a dynamically changing environment.

Moreover, we also examined the differences in raw d' and $\Delta d'$ among three color conditions (red, green, and control colors) to rule out the possibility that our observed reward effect can be accounted by observers' color bias. Repeated measures ANOVAs revealed no significant differences among the three color conditions in either the pretest ($F(2, 26) = 1.41$, $p = .26$, $\eta_p^2 = 0.01$) or posttest ($F(2, 26) = 0.09$, $p = .91$, $\eta_p^2 = 0.01$) sessions. Bonferroni post hoc tests confirmed that there were no significant differences among all paired conditions (pretest: $p > .3$ for all comparisons; posttest: $p = 1.0$ for all comparisons). We also calculated the changes before and after the training session among the three conditions and revealed no significant effect on color as well ($F(2, 26) = 0.97$, $p = .39$, $\eta_p^2 = 0.07$). Bonferroni post hoc tests revealed no significant differences among all paired conditions ($p > .5$ for all comparisons). These results suggest that the observed reward effect could not be explained in terms of the possible brightness variations among the equiluminant colors.

Given the nature of task irrelevance of the reward-associated feature (i.e., color), it is unlikely that the observed reward effect was a result of goal-driven selective attention toward the high reward-associated color. However, an alternative interpretation of the observed reward effect concerns the involvement of reward-

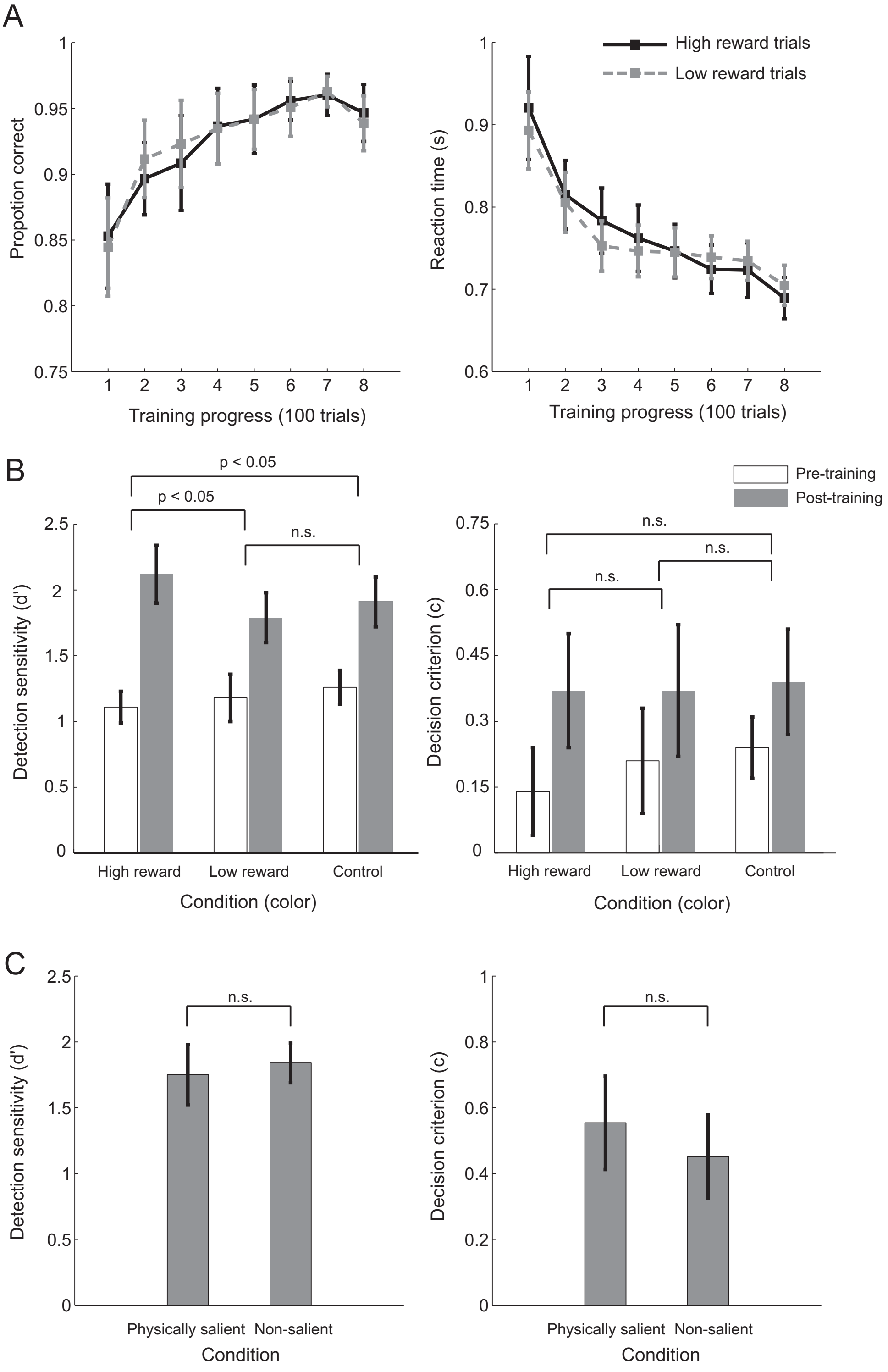
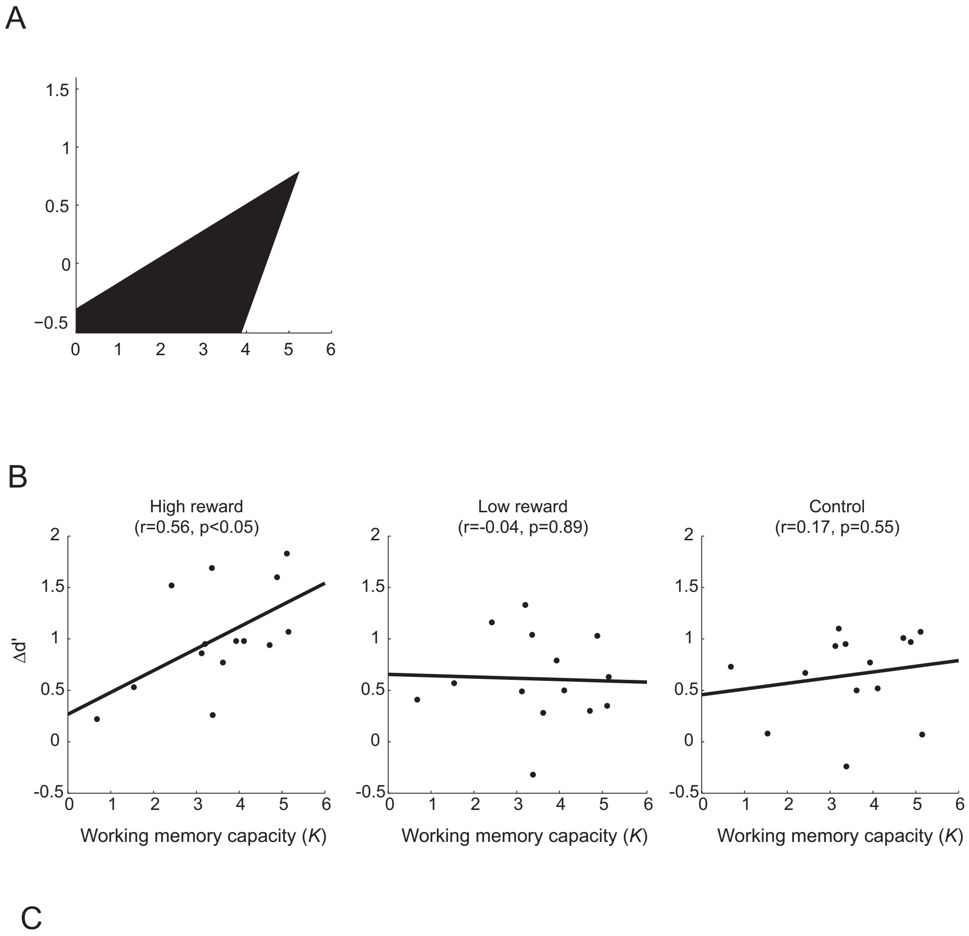


Figure 2. Behavioral results for Experiment 1. (A) Observers improved their performance on the visual search task with respect to both accuracy and RT during the course of the training session. Observers' performance is grouped for every 100 trials during the training session. (B) Effect of reward association on the change detection task. The detection sensitivity (d') and decision criterion (c) for both the pretest and posttest sessions are shown for three conditions. (C) Effect of physical salience on the change detection task. The detection sensitivity (d') and decision criterion (c) are shown for the physically salient target condition and the nonsalient target condition. Error bars represent standard errors of the means.

driven attentional capture toward the color that was associated with a high reward (Anderson et al., 2011; Della Libera & Chelazzi, 2009). To test this possibility, we performed additional analysis on trials in which the control colors were the targets, and compared the situation that the high reward-associated color served as the distractor with that the low reward-associated color served as the distractor. If attention was consistently captured by the high reward-associated color, we would expect to observe detection deficiency for the probed control color target when the high reward-associated color served as distractor. However, our data revealed no such interference effect. A paired *t* test revealed no significant difference in either $\Delta d'$, $t(13) = 0.72$, $p = .49$ or Δc, $t(13) = 1.16$, $p = .27$ between the two conditions. This suggests that the observed benefit in VWM toward the high reward-associated item does not depend on the impairment of other items in the nonrewarded colors. We also analyzed the behavioral data from the physical salience run in the posttest session (Figure 2C). The results showed no significant differences in d', $t(13) = 0.63$, $p = .54$ and c, $t(13) = 1.46$, $p = .17$ between trials with physically salient targets and those with nonsalient targets. This suggests that the advantage of physical salience cannot lead to superiority in VWM performance under the current task context in which both reward-associated and physically salient features are task-irrelevant. Taken together, the findings suggest that the advantage of reward association in VWM performance may not be sufficiently accounted by the reward-induced attentional capture.

Relationship between WM capacity and reward effect. We estimated the WM capacity of each observer by applying Cowan's K formula to the data from the pretest session (Cowan, 2001). We found that the difference in $\Delta d'$ between the colors associated with the high reward and low reward was correlated significantly with the WM capacity of the observer ($r = .67$, $p < .01$). The correlation also approached significance ($r = .47$, $p = .088$) if we compared the difference in $\Delta d'$ between the high reward-associated color and the control colors with respect to the observers' WM capacity (Figure 3A). Furthermore, we calculated the correlation between $\Delta d'$ and WM capacity separately for the three conditions described above (Figure 3B). The results showed that $\Delta d'$ was correlated with the WM capacity of the observer for the condition in which the high reward-associated color was probed ($r = .56$, $p < .05$), but not for those in which the low reward-associated color ($\mathrm{r} = -0.04$, $p = .89$) or control colors ($r = .17$, $p =$



Furthermore, we conducted a paired *t* test on search performance in Experiment 1, which demonstrated similar results for differences in RT, $t(13) = 4.98$, $p < .05$ and accuracy, $t(13) = 0.93$, $p = .37$ between the red and green colors.

Change detection task. In relation to the change detection task, a repeated measures ANOVA was performed among the conditions in which the probed target was in red, green, or a control color (Figure 4B). The ANOVA revealed no significant differences in d' among the three conditions both in the pretest ($F(2, 26) = 0.18$, $p = .84$, $\eta_p^2 = 0.01$) and posttest ($F(2, 26) = 0.07$, $p = .93$, $\eta_p^2 = 0.01$) sessions. Bonferroni post hoc tests confirmed that there were no significant differences among all paired conditions ($p = 1.0$ for all comparisons both in the pretest and posttest sessions). We also calculated $\Delta d'$ ($F(2, 26) = 0.09$, $p = .92$, $\eta_p^2 = 0.01$) and Δc ($F(2, 26) = 0.08$, $p = .92$, $\eta_p^2 = 0.01$) among the three conditions. Bonferroni post hoc tests showed that the use of neither red (mean difference $= -0.062$, $SE =$

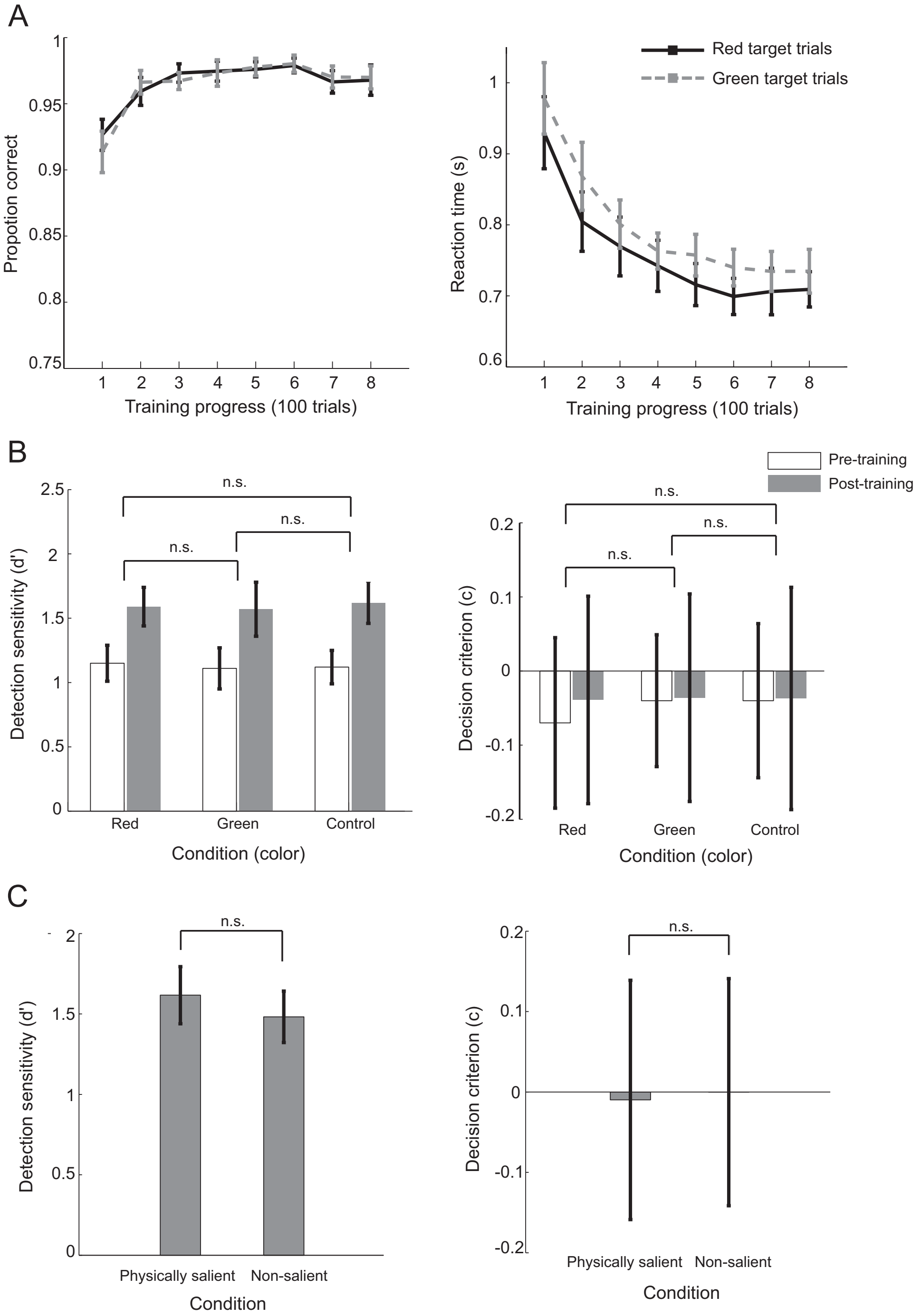


Figure 4. Behavioral results for Experiment 2. (A) Accuracy and RT of the observers during the course of the training session. Observers' performance is grouped for every 100 trials during the training session. (B) Effect of selection history on the change detection task. The detection sensitivity (d') and decision criterion (c) for both the pretest and posttest sessions are shown for three conditions. (C) Effect of physical salience on the change detection task. Error bars represent standard errors of the means.

0.110, $p = 1.00$) nor green (mean difference = -0.043, $SE = 0.168$, $p = 1.00$) for the target yielded a significantly greater improvement in d' than use of the control colors. There were also no significant differences among the three conditions with regard to Δc ($p = 1.00$ for all comparisons).

Physical salience test. We analyzed the behavioral data from the physical salience run in the posttest session. The results showed no significant differences in d', $t(13) = 1.46$, $p = .17$ or c, $t(7) = 0.122$, $p = .90$ between trials with physically salient targets and those with nonsalient targets (Figure 4C). These results suggest that the reward effect that was observed in Experiment 1 cannot be explained in terms of either a deliberate search for red or green bars as the influence of selection history inherited from the training session.

The lack of saliency effect for the thicker bar in the physical salience test in Experiments 1 and 2 has two alternative explanations. One possibility is that the thicker bar was not salient enough to elicit an observable capture effect, and the other is that the prolonged presentation of the sample display and the extended stimulus onset asynchrony (SOA) between the sample and test displays in the change detection task prevented a significant physical salience effect. To clarify these issues, we conducted two control experiments (see Appendices A and B for details of methods and results) to provide the possible explanations for the lack of saliency effect for the thicker bar in the physical salience test of Experiment 1. The results of these two control experiments validated the assumption that the thicker bar was more salient. Specifically, in a visual search task, response times were faster when the thicker bar was the target than when the target bar was of normal thickness (Appendix A). Furthermore, when used in a change detection task, detection sensitivity was greater for the thicker target than for targets of normal thickness, but only if the interval between the sample and test displays was short (500 ms), not if it was long (1,500 ms) as in Experiments 1 and 2 (Appendix B). These results suggest that our manipulation of physical salience was indeed successful in capturing attention with a brief display of multiple items, but this advantage was short-lived. While the reward-induced VWM improvement in Experiment 1 remained robust under the same length of the sample display presentation and the SOA between the sample and test displays, it is currently unclear, however, whether the same timing parameters between the physically salient and reward-associated stimuli were exactly equivalent to each other. Further investigations will be required to clarify this issue.

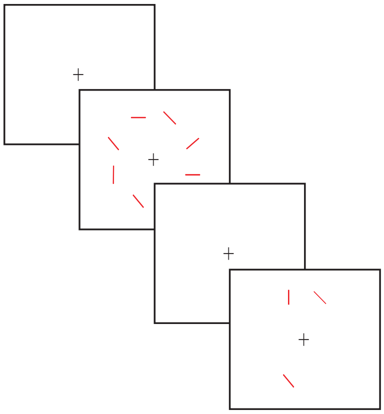
Moreover, to further minimize the reward-driven attentional capture, we conducted Experiment 3, in which the bars in both the sample and test displays had the same color (high reward-associated, low reward-associated, or nonrewarded color). This manipulation ensured that, for any display in the change detection task, attentional capture induced by a single item in the high reward-associated color was not possible. In this situation, any observed reward effect on VWM performance could not be accounted by attentional capture.

Experiment 3

Method

Participants. Twenty-two observers (9 male; mean age 20.9 years) participated in the experiment. All participants were students from Peking University, had normal or corrected-to-normal vision, and gave written informed consent. The experiment was approved by the local ethics committee. The observers were paid ¥20 for their participation in pre- and posttest sessions. The payment to observers in the training session were based on their performance (mean: ¥19.6 ± 0.96).

Stimuli and procedure. The stimuli and procedure were similar to Experiment 1 with few exceptions (Figure 5A). The experiment comprised three sessions on two successive days: (1) a pretest session that involved the change detection task on the first day, (2) a training session on the visual search task after the pretest on the same day, and (3) a posttest session that involved the change detection task on the second day. The change detection task in the pre- and posttest sessions comprised three blocks with different number of items in the display (four, six, and eight items, respectively). Each block consisted of 120 trials. The bars in sample and test displays within a trial were in the same color (red, green, or gray) with equal luminance (15 cd/m^2). The number of displays in each color was balanced across the blocks. The order of the blocks was randomized. The procedure of the training session was identical to Experiment 1 with one exception that the number of trials was reduced to 600.



To test whether the color-reward association established during the training session was learned explicitly by the observers, an awareness test was conducted after the posttest session (Dienes & Perner, 1999) (Figure 5B). Two colored circles (red and green) appeared on the left and right sides of the screen. The observer was informed that different reward magnitudes (high or low) were associated with different colors (red or green) in the training session. They were instructed to press one of the two keys (the left and right arrow keys on the keyboard) to choose the color that was more likely being associated with high or low reward. Observers were then asked to rate their confidence level between scales ranging from 0.5 (*unconfident*) to 1 (*very confident*).

Results and Discussion

Visual search training. The results during training session replicated the findings in Experiment 1. Neither the accuracy, $t(21) = 0.83$, $p = .42$ nor the RT, $t(21) = -0.65$, $p = .52$ differed significantly between high reward- and low reward-associated colors (Figure 6A).

Change detection task. For the change detection task, memory performance (d') was decreased along with the increase of set size from four to eight items, demonstrating a significant set size effect both before and after the training session (pretest session: $F(2, 42) = 23.55$, $p < .01$, $\eta_p^2 = 0.53$; posttest session: $F(2, 42) = 60.43$, $p < .01$, $\eta_p^2 = 0.74$) (Figure 6B). The behavioral performance was indexed by d' separately for both the pretest and posttest sessions (Figure 6C). Trials were divided into three conditions: the stimulus displays consisted of the bars in (1) the high reward-associated color, (2) the low reward-associated color, or (3) the control color. A repeated measures ANOVA revealed no significant differences in d' among the three conditions before the training session ($F(2, 42) = 0.85$, $p = .44$, $\eta_p^2 = 0.04$). Bonferroni post hoc tests revealed no significant differences between all paired conditions ($p > .4$ for all comparisons). In contrast, there was a significant difference in d' among the three conditions after the training session ($F(2, 42) = 7.94$, $p < .01$, $\eta_p^2 = 0.27$). Bonferroni post hoc tests showed significant differences between the high and low reward-associated color (mean difference $= 0.232$, $SE = 0.065$, $p < .01$), while no significant differences were found between high reward-associated and control colors (mean difference $= 0.056$, $SE = 0.066$, $p = 1.0$). WM performance for the control color was significantly higher than that of the low reward-associated color (mean difference $= -0.176$, $SE = 0.050$,

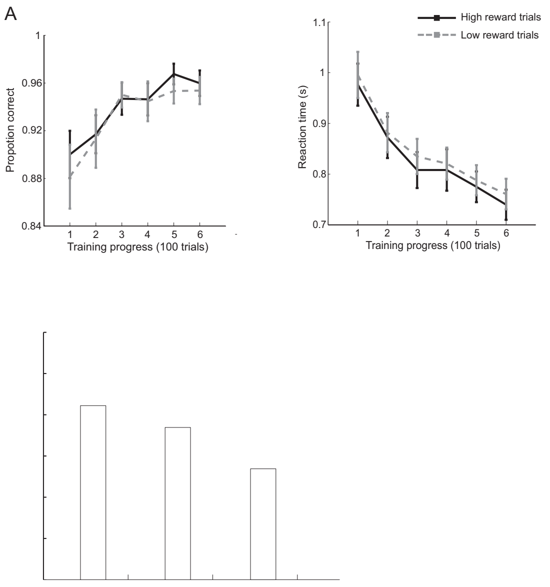


Figure 6. Behavioral results for Experiment 3. (A) Accuracy and RT of the observers during the course of the training session. Observers' performance is grouped for every 100 trials during the training session. (B) Effect of set size on observers' detection sensitivity for pre- and posttraining sessions. (C) Effect of reward association on the change detection task. The detection sensitivity (d') and decision criterion (c) for both the pretest and posttest sessions are shown for three conditions. (D) Effect of reward association on the WM capacity. The capacity (K) for both the pre- and posttraining sessions are shown for three conditions. (E) Behavioral results of the awareness test are shown for the proportion of correct choices based on response types (i.e., choose the high- or low-reward associated color) (left) and the confidence level following the correct and incorrect choices (right). Error bars represent standard errors of the means.

$p < .01$). Furthermore, we calculated the improvement in behavioral performance ($\Delta d'$). A repeated measures ANOVA revealed a significant difference in $\Delta d'$ ($F(2, 42) = 8.39$, $p < .01$, $\eta_p^2 = 0.28$) among the three conditions. Bonferroni post hoc tests showed that $\Delta d'$ was significantly higher for the stimulus displays that consisted of the bars in the high reward-associated color, than those consisted of the bars in the low reward-associated (mean difference = 0.312, $SE = 0.086$, $p < .05$) or control colors (mean difference = 0.146, $SE = 0.055$, $p < .05$). There was no significant difference in $\Delta d'$ between bars in the low reward-associated and control color condition (mean difference = −0.166, $SE = 0.084$, $p = .19$). In contrast, no significant changes in decision criterion (Δc) was observed ($F(2, 42) = 1.44$, $p = .25$, $\eta_p^2 = 0.06$), as revealed by a repeated measures ANOVA. Bonferroni post hoc tests confirmed no significant differences among the three conditions with regard to Δc ($p > .4$ for all comparisons). Furthermore, we calculated the improvement in WM capacity (Δk) between the pre- and posttest sessions for the three stimulus conditions (high reward-associated, low reward-associated, and nonrewarded color). A repeated measures ANOVA revealed a significant difference in Δk ($F(2, 42) = 5.21$, $p < .01$, $\eta_p^2 = 0.20$) among the three conditions (Figure 6D). Bonferroni post hoc tests showed that Δk was significantly higher for the stimulus displays that consisted of the bars in the high reward-associated color, than those consisted of the bars in the low reward-associated (mean difference = 0.410, $SE = 0.148$, $p < .05$) or the control (mean difference = 0.293, $SE = 0.09$, $p < .05$) colors. There was no significant difference in Δk between the conditions of the low reward-associated color and the control color (mean difference = −0.117, $SE = 0.146$, $p = 1.00$). These results confirm that the learned reward association improves the WM capacity and further demonstrate the occurrence of the improvement in VWM in the absence of attentional capture.

Awareness test. The analysis of the awareness test revealed no higher than chance level accuracy when observers paired the colors with their reward levels (binomial test, $z = 0.43$, $p = .34$). There was also no significant difference in accuracy between response types (i.e., whether the observer was instructed to choose the high reward- or low reward-associated color; binomial test, $z = 0.86$, $p = .19$). However, we found that the correct choices were paired with significantly higher confidence rating compared with the incorrect choices, $t(20) = 2.78$, $p < .05$. These seemingly contradictory results can be explained by observers' oral reports. Among the observers who chose the color–reward association correctly, seven out of 12 reported being aware of the association during the training session and thus gave higher scores (≥ 0.8) for the confidence rating (Figure 6E). In order to demonstrate whether the implicit or explicit knowledge of reward association played a significant role in the observed reward effect, we separated the seven correct and high confidence scored observers (explicit group) from the others (implicit group), and analyzed the differences between the two groups of observers in their reward effects. A repeated measures ANOVA on $\Delta d'$ showed no significant differences between the explicit and implicit groups ($F(1, 20) =$

& O'Brien, 2009), and between attention and working memory systems (Awh et al., 2006; Gazzaley & Nobre, 2012; Zanto et al., 2011). Particularly, recent studies with brain imaging techniques have suggested that the reward signal interacts with the fronto-parietal attentional network through the midbrain dopaminergic system and immediately impacts on human's behavior (Engelmann, Damaraju, Padmala, & Pessoa, 2009; Hickey et al., 2010; Mohanty, Gitelman, Small, & Mesulam, 2008; Small et al., 2005). In our experiments, the learned reward association can be viewed as information stored in memory-related areas. The reciprocal connections between the midbrain dopaminergic system (such as ventral tegmental area) and hippocampus have been proposed to bridge dopamine neurons and memory plasticity, ensuring that such associative memory is accessible for future adaptive behavior (Shohamy & Adcock, 2010). In a situation that the sensory input matches the stored reward-associated representation, such as in our study, the reward-associated input could trigger the dopaminergic system and influence the attentional network.

There are two possible but not mutually exclusive influence modes that the dopaminergic system can exert on the attentional system: spatially biasing the attentional selection with bottom-up capture and modulating the representation of the attended items based on their features. While the reward-driven attentional capture effect has been shown by a number of studies (Anderson et al., 2011; Della Libera & Chelazzi, 2006; Hickey et al., 2010), our results suggest that learned reward association could improve VWM through enhanced attentional modulation on the reward-associated features. It was shown that feature-based attentional modulation enhanced the representation of items that shared a specific feature throughout the visual field (Liu, Larsson, & Carrasco, 2007; O'Craven, Rosen, Kwong, Treisman, & Savoy, 1997; Treue & Martinez Trujillo, 1999). Furthermore, when the representation of the images were required to be held in WM for the completion of the task, feature-based attentional modulation was shown to enhance the representation during the VWM maintenance period (Lepsien & Nobre, 2007). Recent studies extended this proposal by showing that such modulation effect could emerge as early as 100 ms after the stimulus onset during the encoding stage (Rutman, Clapp, Chadick, & Gazzaley, 2009; Zanto & Gazzaley, 2009). Together with these findings, our results suggest that learned reward association could influence the encoding and/or maintenance stages of VWM through feature-based attentional modulation. Under this mechanism, the items with the high reward-associated feature could be better represented in the VWM and have the advantage of being accessed by the task at hand. This modulation-based effect is complementary to the reward-induced attentional capture effect, demonstrating the importance of reward association in cognitive control and other adaptive behaviors.

Concerning the particular stages (encoding and/or maintenance) that the reward induced attentional modulation acted upon, the design of the present study does not allow us to identify it precisely. Previous studies have shown that the effect of reward association was present at the early stage of sensory processing (Hickey et al., 2010; O'Brien & Raymond, 2012), and influenced the representation of sensory stimuli in primary visual cortex (Serences, 2008; Weil et al., 2010). On the other hand, the interaction between WM-related theta band and reward-related beta band activities at frontal regions was shown to facilitate the maintenance efficiency of rewarded items (Kawasaki & Yamaguchi, 2013). However, further investigations with neurophysiological approaches are required to clarify this issue.

Finally, the results from the correlation analyses were consistent with the reward effect in VWM performance, and demonstrated a direct relationship between the reward effect and the WM capacity of a given individual. The analyses revealed that observers with higher WM capacity showed a stronger effect of reward on VWM. Individual differences in WM capacity have been suggested to indicate the ability to control attention (Fukuda & Vogel, 2009; Kane, Bleckley, Conway, & Engle, 2001), visual search efficiency (Sobel, Gerrie, Poole, & Kane, 2007), and other higher cognitive function (Barrett, Tugade, & Engle, 2004). Our results provide new evidence that WM capacity can also serve as a reliable predictor of an individual's susceptibility to the influence of a cued reward. Physiological studies that investigated the causal connection between dopamine receptor and WM capacity have provided supporting evidence for the impact of reward on WM capacity (Curtis & Lee, 2010; Klingberg, 2010). Our results are consistent with this proposal and suggest a shared attentional mechanism between the WM capacity and the reward association.

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Appendix A

Estimate the Physical Salience with Visual Search Task

Methods

Participants. Fourteen observers (7 males; mean age 24.1 years) participated in the experiment. All participants were students from Peking University, had normal or corrected to normal vision, and gave written informed consent. The experiments were approved by the local ethics committee. The observers were not paid for their participation.

Stimuli and Procedure. We adopted a visual search task to estimate the physical salience of the stimuli (i.e. the four-times thicker bar) used in the post-test session of Experiment 1 (Figure A1A). The stimuli were identical to the displays used to assess the physical salience effect during the post-test of Experiment 1. Each trial started with a period of fixation for a random duration of 400–600 ms and this was followed by presentation of a search display. The observers were instructed to find the bar with horizontal or vertical orientation and press a button to indicate the orientation of the target (i.e. left button for horizontal and right button for vertical). An incorrect response was followed by auditory feedback. The session was composed of 384 trials. The observers were informed that the probability of the thicker bar being probed was the same as that for the other seven bars (12.5%).

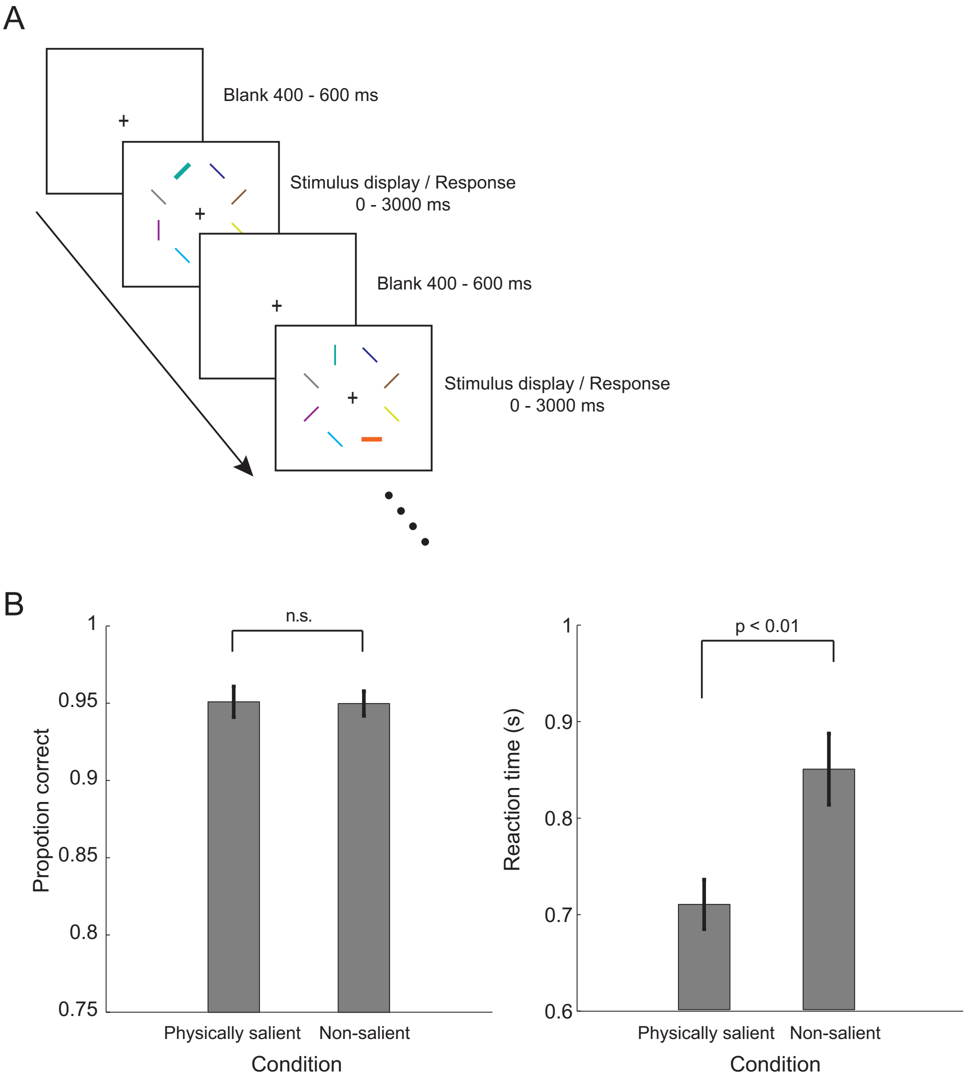

Figure A1. Procedure and results. (A) Schematic illustration of the experimental procedure for the visual search. (B) Behavioral results are shown for accuracy and reaction time for physically salient targets and non-salient targets. Error bars represent standard errors of the means.

(*Appendices continue*)

Results

Paired t-tests showed no significant difference in the accuracy of detection between the salient and non-salient targets ($t(13) = 0.14$, $p = 0.89$). However, the observers responded significantly faster when the target was a four-times thicker bar than when the target was of normal width ($t(13) = 7.29$, $p < 0.01$) (Figure A1B). These results further verify the physical salience of the thicker bars used in Experiment 1. However, although the reaction time is widely used to assess the physical salience effect, it may be less powerful in explaining the null effect of physical salience in Experiment 1. Previous studies have suggested that the physical salience-driven attentional capture could occur within 100 ms from the stimulus onset, and diminish with increasing delay or goal-driven attention (Connor, Egeth, & Yantis, 2004; Kim & Cave, 1999; Lamy, Tsal, & Egeth, 2003). We therefore conducted another control experiment to reveal the temporal dynamics of the physical salience effect for the thicker bar used in Experiment 1.

Appendix B

The Effect of SOA on Physical Salience

Methods

Participants. Fourteen observers (5 male; mean age: 21 years) participated in the experiment. All participants were students from Peking University, had normal or corrected to normal vision, and gave written informed consent. The experiment was approved by the local ethics committee. All observers were paid ¥20 for their participation in this experiment.

Stimuli and Procedure. A change detection task was used in the experiment (Figure B1A). The stimuli and procedure were similar to those used in the physical salience run in Experiment 1 with two exceptions. First, the bars presented in the sample and test displays were in the same color (gray; 15 cd/m^2). Second, the experiment comprised two runs: the presentation time of the sample display was reduced to 100 ms in both runs, and the blank interval between the sample and test displays was fixed to 500 ms for short SOA condition and 1500 ms for long SOA condition. We reduced the sample display time and introduced the short SOA condition to ensure the dominance of bottom-up physical salience effect during the encoding and maintenance periods. Each run consisted of 320 trials. The order of the two runs was randomized across observers.

Results

Paired t-tests showed significant difference in the detection sensitivity (d') between the salient and non-salient targets under

(*Appendices continue*)

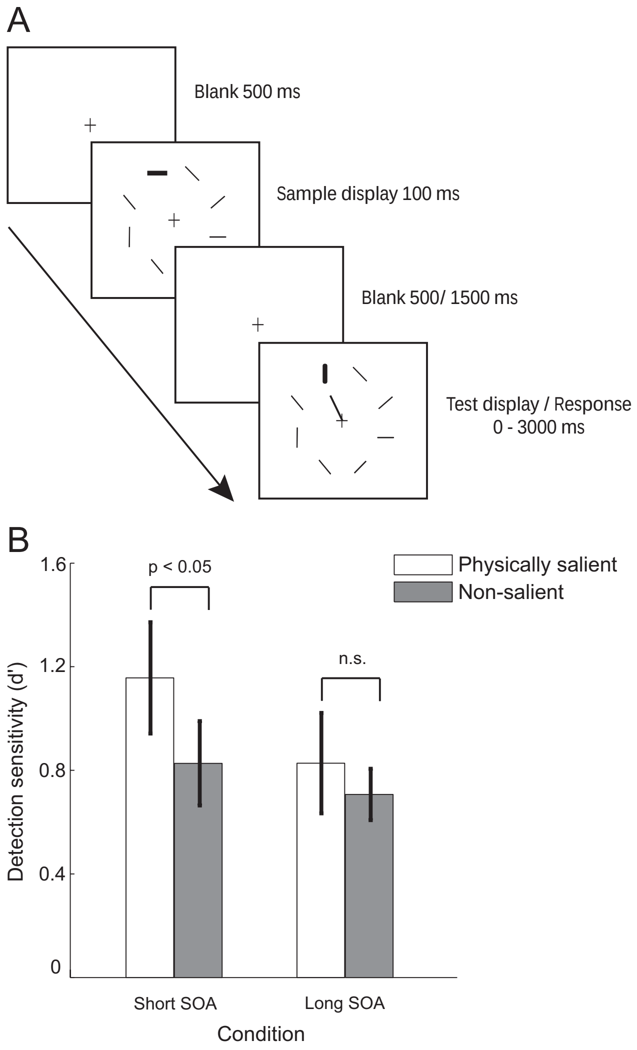

Figure B1. Procedure and results. (A) Change detection task: physical salience run in the post-test session. The probed bar could be of normal width or four-times thicker (physically salient). (B) Behavioral results are shown

the short SOA condition (t(13) = 2.59, $p < 0.05$). This result is consistent with previous studies reporting the superiority of physically salient item in VWM task (Belopolsky, Kramer, & Godijn, 2008; Schmidt, Vogel, Woodman, & Luck, 2002). In contrast, the physical salience effect was eliminated when the blank interval between the sample and test display was increased to 1500 ms (t(13) = 0.84, p = 0.42), a temporal interval that approximated to the mean SOA in Experiment 1 (Figure B1B).

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