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BRIEF REPORT

Working memory can enhance unconscious visual perception

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Abstract We demonstrate that unconscious processing of a stimulus property can be enhanced when there is a match between the contents of working memory and the stimulus presented in the visual field. Participants first held a cue (a colored circle) in working memory and then searched for a brief masked target shape presented simultaneously with a distractor shape. When participants reported having no awareness of the target shape at all, search performance was more accurate in the valid condition, where the target matched the cue in color, than in the neutral condition, where the target mismatched the cue. This effect cannot be attributed to bottom-up perceptual priming from the presentation of a memory cue, because unconscious perception was not enhanced when the cue was merely perceptually identified but not actively held in working memory. These findings suggest that reentrant feedback from the contents of working memory modulates unconscious visual perception.

Keywords Working memory · Unconscious perception · Awareness · Attention

Because the visual system is limited in processing capacity, only a minority of stimuli in the visual field can be fully processed at any given moment. According to the biased competition model of attentional selection (Desimone & Duncan, 1995), different objects in the visual field must compete for processing capacity, and the competition is biased in favor of some objects, depending on the influences of many factors. One of those factors is the contents of working memory (WM). At the neural level, content representations actively held in WM provide feedback signals from higher cortical areas (e.g., the prefrontal cortex) to the visual cortex, biasing neurons to respond preferentially to stimuli matching WM representations so that there is a competitive advantage for those memory-matching stimuli in accessing higher-level cognitive processes. The model has been proved to be correct by many studies, which provided converging evidence suggesting that the contents of WM can guide attention in visual search, even when they are irrelevant to the search task (for a recent review, see Soto, Hodsoll, Rotshtein, & Humphreys, 2008).

There is also evidence that perceptual sensitivity to visual stimuli can be strengthened by matches between WM representations and sensory stimuli (Soto, Wriglesworth, Balani, & Humphreys, 2010). Nevertheless, it should be noted that because the durations of search array used by Soto et al. (2010) were long enough (e.g., 94–164 ms) for participants to be conscious of targets (evidenced by the significant above-chance search performance), their findings may just suggest that reentrant feedback from the preactivation of items in WM can enhance conscious awareness. However, it remains unknown whether WM modulates unconscious perception. In the present study, we examined whether WM contents can enhance unconscious processing of matching stimuli in the visual field.

A recent study by Soto and Humphreys (2006) showed that visual extinction patients showed reduced extinction when there was a match between WM contents and the stimuli presented in the visual field. The authors interpreted this finding as evidence that WM can enhance awareness. However, because patients' subjective experiences in this study were not directly assessed, the effects of WM on objective performance and on subjective experience were not distinguished. Note that the patients' task in Soto and Humphreys' study was to report object features from a fixed set of selection (three colors and four shapes). Although the patients' responses were not force-

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choiced, they might in fact just guess from the fixed set of selection when they were not aware of the object features. Moreover, given that patients with visual extinction often unconsciously process contralesional stimuli when there is also a simultaneous ipsilesional stimulation (e.g., Farah, Monheit, & Wallace, 1991; Rees et al., 2000), we conjectured that the phenomenon of reduced extinction observed by Soto and Humphreys might reflect the enhancement of unconscious perception rather than of conscious awareness through reentrant feedback from WM. However, the idea that WM may affect unconscious processing was not mentioned by Soto and Humphreys.

The aim of the present study was to directly test the hypothesis that WM contents can enhance unconscious perception of matching stimuli in the visual field with normal humans as participants. Observers were asked to hold a color cue in WM, followed by a brief masked search array where there were a target and a distractor differing from each other in color. The search target could match the color of the memory cue. Search performance was compared between conditions in which the search target matched the memory cue and those in which it did not in order to assess WM effects on perceptual processing. Here, an important methodological point to address is the question of how unconscious perception and conscious awareness of the target should be measured. Traditional psychophysical measures, such as sensitivity or accuracy of identification of a target in the two-alternate forced choice task, might inform us only as to whether observers have access to information about stimuli and how much information they have access to, but not whether those stimuli reach awareness (Kentridge, Nijboer, & Heywood, 2008). Thus, a direct subjective measure is needed. Here, we asked observers to report their subjective experiences of targets. Then, we examined whether search performance on trials where observers reported being unconscious of search targets varied significantly according to whether or not the targets matched the memory cue. We reasoned that if WM could enhance unconscious perception, search performance would be more accurate for memory-matching targets than for mismatching targets when observers reported having no awareness of targets.

Experiment 1

Method

Participants

Thirteen naive students at the Hangzhou Normal University participated for partial course credit. All of them reported having normal or corrected-to-normal vision.

Stimuli

The memory cue was a colored circle (3° × 3°). The search target was a colored pentagon (2.7° × 2.7°) or a colored hexagon (3° × 2.5°), and the distractor was a colored diamond (3° × 3°). The color of each shape was chosen randomly from a set of five colors (red, green, blue, yellow, and cyan). Each mask was composed of four colored squares that were abutted to form a 2 × 2 checkerboard pattern (3.5° × 3.5° total size). The colors of the squares in each mask were selected with replacement from the above set of five colors. All stimuli were presented on a gray background at a viewing distance of 57 cm.

Procedure and design

Participants initiated each trial by pressing the space bar. Each trial began with the display of a white central fixation cross (0.2° × 0.2°) for 1,000 ms. A colored circle followed for 600 ms. Here, participants were required to memorize the color of the circle and to keep it in mind throughout the entire trial. After a delay of 500 ms, the search array consisting of two different colored objects was presented for 36 ms. The two search items were centered 3° to the left and right of fixation, one the target and the other the distractor. The two masks centered at the locations of each of the search items followed immediately after the offset of the search array. Here, participants were instructed to make an unspeeded discrimination to the target shape. The masks remained visible until response. Immediately after a response had been made, participants were asked to provide a confidence rating for their response to the target shape. Confidence ratings were made on a scale of 1–3, with 1 representing *I have no confidence at all in my response. I could not see the target shape and just randomly chose a response*; 2 representing *I had a little feeling of the target shape, but I'm not very confident in my response since I could not see the target shape clearly*; and 3 representing *I'm very confident in my response since I could see the target shape clearly.* A memory test followed 500 ms after a confidence rating had been made. Here, a circle appeared at the center of the screen, and participants were asked to indicate by buttonpress whether or not it had the same color as the memory cue (see Fig. 1).

In the search array, the target and the distractor always had different colors on each trial. The target matched the color of the memory cue on half of the trials (valid condition), and neither the target nor the distractor matched the color of the memory cue on the other half (neutral condition). Also, it was equally likely for the two target shapes to match the color of the memory cue. The memory test item and the memory cue shared the same color on half of the trials, and they had different colors on the other half. Trial order was randomized across these factors. The target shapes (pentagon vs. hexagon) and the locations of the targets (left vs. right) were counterbalanced

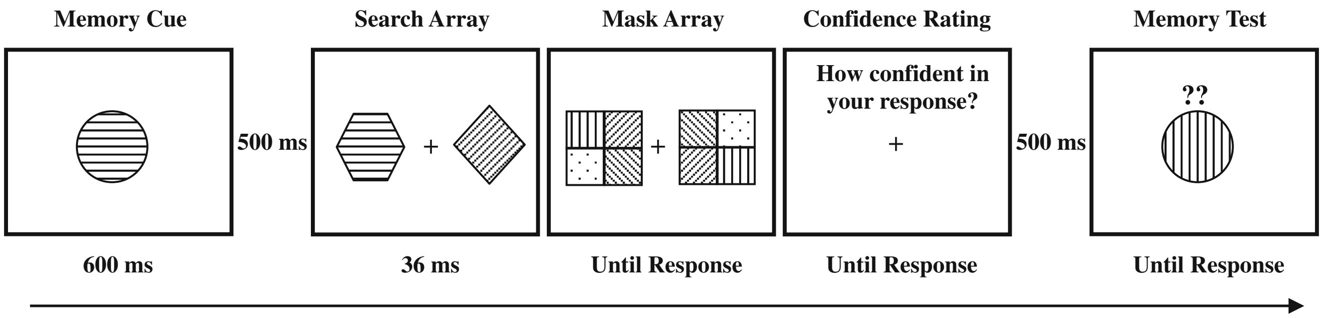

Fig. 1 Schematic illustration of the trial sequence and example stimuli in Experiment 1. The different patterns represent different colors

across trials. Sixteen practice trials were followed by 160 experimental trials. In all of the experiments reported here, before the practice trials, participants were first familiarized with the task where the search array was presented with a longer duration (e.g., 1,000 ms).

Results and discussion

There were, on average, 37%, 40%, and 23% of trials for the confidence ratings of 1–3, respectively. On average, memory accuracy was 91.4% correct, and it did not vary across confidence ratings ($F < 1$). Search accuracy rates varied significantly across confidence ratings, $F(2, 20) = 27.393$, $p < .0001$, partial $\eta^2 = .733$, with the greatest accuracy rate on 3-rating trials ($M = 83\%$, $SE = 4.5\%$), smaller accuracy rate on 2-rating trials ($M = 63.4\%$, $SE = 3.7\%$), and the smallest accuracy rate on 1-rating trials ($M = 47\%$, $SE = 4\%$; data from 2 participants were excluded from analyses because they had no 3-rating trials). Search performance was significantly above chance level on 2- and 3-rating trials (ps < .005), but it did not differ from chance level on 1-rating trials ($p = .473$). This suggests that different confidence ratings indeed reflected different levels of perceptual processing, with a rating of 1 indicating unconscious perception and ratings of 2 and 3 indicating conscious awareness.

In all of the experiments reported here, we focused our interest exclusively on trials where observers were unconscious of the targets. Responses in the search task were unspeeded, and as a result, search RTs did not significantly vary as a function of the cue validity in every experiment reported here. This indicates no sign of a speed–accuracy trade-off in the present study. Search accuracy rates between valid and neutral conditions were compared to determine whether WM affected unconscious perception. Search performance was more accurate in the valid condition ($M = 56.5\%$, $SE = 3\%$) than in the neutral condition ($M = 49.6\%$, $SE = 4\%$), $F(1, 8) = 12.12$, $p < .01$, partial $\eta^2 = .602$ (data from 4 participants were excluded from this analysis because their percentages of 1-rating trials were less than 15% and, thus, were not reasonably sufficient for comparison). This suggests that the contents of WM enhanced unconscious processing of matching stimuli in the visual field.

Experiment 2

The aim of this experiment was to examine whether the enhanced unconscious perception of stimuli that matched the color cue in Experiment 1 was indeed due to the active maintenance of the cue in WM. Would mere exposure to the color cue without WM processing be sufficient to enhance unconscious perception of the matching stimuli?

Method

The method was similar to that used in Experiment 1, with the following exceptions. A new group of 16 volunteers from the same pool participated. Observers were asked to attend to the cue, but they did not need to memorize it, and there was no memory test at the end of the trial. A go/no-go procedure was used to make the cue be processed without being held in WM. Observers had to discriminate the search target and to rate the confidence in their discrimination when the cue was a colored circle on 80% of the trials, while not discriminating the target when the cue was a black circle on the remaining 20% of the trials (here, observers were asked to end the trial by pressing the space bar). Twenty practice trials were followed by 200 experimental trials.

Results and discussion

Observers performed appropriately as requested on catch trials where the cue was a black circle. There were, on average, 34.1%, 30.1%, and 35.8% of trials for the confidence ratings of 1–3, respectively. As in Experiment 1, search accuracy rates varied significantly across confidence ratings, $F(2, 26) = 18.075$, $p < .0001$, partial $\eta^2 = .582$, with the greatest accuracy rate on 3-rating trials ($M = 77.1\%$, $SE = 4.3\%$), smaller accuracy rate on 2-rating trials ($M = 60.6\%$, $SE = 3.1\%$), and the smallest accuracy rate on 1-rating trials ($M = 45.7\%$, $SE = 4.1\%$; data from 2 participants were excluded from this analysis because one had no 1-rating trials and the other had no 3-rating trials). Search performance was significantly above chance level on trials with ratings of 2 and 3 ($ps < .004$), but it did not differ from chance level on 1-rating trials ($p = .275$).

Search accuracy rates between valid and neutral conditions on 1-rating trials were compared to determine whether priming affected unconscious perception. Search accuracy rates in the valid condition ($M = 47.9\%$, $SE = 2.9\%$) and in the neutral condition ($M = 51.3\%$, $SE = 2.7\%$) did not significantly differ from each other ($F < 1$; data from 7 participants were excluded from this analysis because their percentages of 1-rating trials were less than 15%). This suggests that priming an object's representation without WM requirements did not facilitate unconscious processing of matching stimuli, although the prime was perceptually identified for observers to decide whether to carry out the search task. Thus, the enhanced unconscious perception effect observed in Experiment 1 was not due just to the mechanism of perceptual priming. This was further confirmed by a comparison of search accuracy on 1-rating trials across Experiments 1 and 2, showing a significant interaction between experiment and cue validity (valid vs. neutral), $F(1, 16) = 4.784$, $p < .05$, partial $\eta^2 = .23$. The main effect of experiment was not significant ($F < 1$), showing that the overall task difficulty was similar across experiments. We suggest that object representations need to be actively maintained in WM to enhance unconscious processing of matching stimuli in the visual field.

Experiment 3

In this experiment, we sought to replicate the effect of WM on unconscious perception, using a much shorter duration of the search array. Here, the duration of the target display was reduced to only 10 ms, enabling observers always to be unconscious of the masked targets.

Method

The method was identical to that used in Experiment 1, with the following exceptions. A new group of 14 volunteers from the same pool participated. The search array was presented for 10 ms. Thirty-two practice trials were followed by 128 experimental trials. Because the search duration before masking was sufficiently short that all observers reported being absolutely unconscious of targets on every practice trial, they were not asked to rate target visibility in a trial-by-trial manner in the experimental session. Here, observers just had to report their overall subjective experiences of targets after the experiment. As in the practice session, all observers reported having no awareness of targets on the experimental trials.

Results and discussion

On average, memory accuracy was 93.5% correct, and it did not differ significantly between the valid and neutral conditions ($F < 1$). Analyses of search accuracy included only trials where participants responded correctly to the memory test. Search performance was more accurate in the valid condition ($M = 55.7\%$, $SE = 1.8\%$) than in the neutral condition ($M = 50.6\%$, $SE = 2\%$), $F(1, 13) = 7.896$, $p < .02$, partial $\eta^2 = .378$. Because the duration of masked targets was only 10 ms and participants reported being completely unconscious of targets, this result suggests that the contents of WM intensified unconscious perception of matching stimuli in the visual field.

General discussion

The competition for processing capacity among different stimuli in the visual field is biased in favor of those matching the current contents in WM (Desimone & Duncan, 1995). What is the impact of such biased competition via top-down modulation from WM on unconscious perception? Our results demonstrate the hypothesis that reentrant feedback from WM contents can enhance unconscious processing of matching stimuli in the visual field. Perceptual discrimination was more accurate for memory-matching targets than for memory-mismatching targets when observers reported being unconscious of targets. This effect was established even though the duration of masked targets was sufficiently short (i.e., 10 ms) that observers were always completely unconscious of targets. The effect of WM on unconscious processing cannot be attributed to a bottom-up perceptual priming mechanism, because we failed to observe priming effects when cues were only perceptually identified but not actively held in WM. The present work goes beyond previous studies, which focused on the effects of WM on attentional selection (e.g., Chen & Tsou, 2011; Huang & Pashler, 2007; Olivers, Meijer, & Theeuwes, 2006; Pan, Xu, & Soto, 2009; Soto, Heinke, Humphreys, & Blanco, 2005; Woodman & Luck, 2007) or on conscious awareness (Soto & Humphreys, 2006; Soto et al., 2010). Here, we demonstrate that when a brief masked stimulus among multiple stimuli in the visual field matches the contents of WM, perceptual processing of its unconscious features can be facilitated by WM.

Our results are consistent with global workspace theory, which proposes that conscious contents are widely distributed to many unconscious specialized networks in the brain, recruiting neuronal resources for unconscious processing of the related information (Baars, 1988). We suggest that the conscious contents actively held in WM can boost unconscious processing of the matching sensory input via this process. Also, the present results provide converging evidence for the dissociation between visual attention and awareness

(Lamme, 2003). The data showing that search accuracy was more correct in the valid condition than in the neutral condition indicate that the contents of WM biased spatial allocation of attention to the matching stimulus. However, such WM-driven attention shifts did not render the shape of the memory-matching stimulus in such a way as to reach awareness, since observers reported having no awareness of its shape at all. Therefore, the results corroborate the view that visual attention cannot be a sufficient precondition for awareness (Kentridge et al., 2008; Woodman & Luck, 2003).

Cosman and Vecera (2011) have recently proposed an “uncertainty reduction” account for the effects of WM on search performance. According to this account, the contents of WM do not enhance perception but, rather, operate post-perceptually to reduce uncertainty of the target’s location by prioritizing the memory-matching stimulus in visual search. In other words, attention would be automatically directed to the memory-matching item whenever there is uncertainty regarding the target’s location, reducing the deleterious effect of masking and, thus, facilitating search performance when the target is actually at the location of the memory-matching item (Soto et al., 2010). The uncertainty reduction account predicts that such an attentional prioritization effect via WM would be eliminated when the target’s location is known with certainty. This prediction seems to be supported by the findings of Cosman and Vecera showing that there were no WM effects on search performance when the search array consisted of only one item. However, the null results do not necessarily mean that the contents of WM cannot actually affect perception. We suggest that the reason why Cosman and Vecera did not observe WM effects on perceptual sensitivity of the masked target presented in isolation might be the influence of transient attention elicited by a peripheral abrupt onset. When only one object is flashed peripherally, covert attention is involuntarily directed to that object, rendering the signal enhancement of its representation (Carrasco, Ling, & Read, 2004). Such an effect of transient attention may be sufficiently strong that it can completely obscure any WM effects on perception. By contrast, as in the present study, when more than one object is presented simultaneously, no such transient attention is elicited, and therefore, there is a favorable opportunity for the perceptual enhancement effect of WM to be detected. That is, WM effects on perception can be detected with a stronger statistical power in the condition where memory-matching and mismatching stimuli in the visual field compete for a limited attentional capacity to access perceptual processing. Because observers were unconscious of the target in the present study, it is quite plausible that they were always uncertain of the target’s location even when attention was automatically guided to the target by WM. Thus, although there was uncertainty regarding the target’s location in the present study, it is reasonable to believe such uncertainty cannot be reduced by WM-driven attention and, therefore, the results cannot be accounted for by the uncertainty reduction account. As such, the present study combining WM and unconscious perception provides evidence favoring the idea that the contents of WM can enhance perceptual sensitivity to visual matching stimuli.

It is noteworthy, however, that by having observers in the present experiments merely report whether they saw the target shapes, our study may have included trials where there was no awareness of the shape of the stimulus but a little awareness of its color. If so, it may indicate that the conscious system has some limited access to unconscious processing. Although we believe that this does not invalidate our argument that WM can enhance unconscious perception, prudence is necessary in drawing the conclusion from our data that WM influences the processing of unseen stimuli. Considering the potential limitations of the present approach, future research using a more elegant paradigm may be needed to further explore WM effects on unseen stimuli.

In conclusion, the present results provide the first direct evidence demonstrating that WM contents can enhance unconscious processing of matching stimuli in the visual field. We suggest the underlying neural mechanism of such WM effects on unconscious visual perception may be that the quality of a stimulus representation in the visual cortex is improved by reentrant feedback from higher cortical areas (e.g., the prefrontal cortex) involved in WM (Desimone, 1996).

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