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Visual working memory enhances target discrimination accuracy with single-item displays

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Abstract

The maintenance of information in visual working memory has been shown to bias the concurrent processing in favor of matching visual input. The present study aimed to examine whether this bias can act at an early stage of processing to enhance target feature perception in single-item displays. Participants were sequentially presented with two distinct colored stimuli as memory samples and a retro-cue indicating which of the two samples should be maintained for subsequent memory test. During the retention interval, they had to discriminate the gap orientation of a Landolt target presented through a single visual stimulus that could match one or neither of the two samples. Across two experiments, we consistently found that discrimination performance was more accurate when the Landolt target was situated within a stimulus that matched the sample being retained in visual working memory, as compared with when the target was not. This effect cannot be attributed to the mechanism of passive priming, because we failed to observe priming effects when the stimulus containing the target matched the sample that was retro-cued to be irrelevant to the working memory task, as compared to when the stimulus matched neither sample. Given the fact that target stimuli were presented in single-item displays wherein external noise was precluded, the present findings demonstrate that the working memory bias of visual attention operating in the absence of stimulus competition facilitates early perceptual processing at the attended location via signal enhancement.

Keywords Visual working memory · Visual perception · Target signal · Priming

Introduction

There is considerable evidence that working memory biases visual attention in favor of stimuli that match the memorized information during the retention interval (see Kiyonaga & Egner, 2013; Soto, Hodsoll, Rotshtein, & Humphreys, 2008, for reviews). Moreover, it has been suggested by previously reported data of manual or oculomotor response time that this working memory bias can operate at a relatively early stage of visual processing (e.g., Hollingworth, Matsukura, & Luck, 2013; Schneegans, Spencer, Schöner, Hwang, & Hollingworth, 2014; Soto, Heinke, Humphreys, & Blanco, 2005; Soto, Humphreys, & Heinke, 2006). For instance, as measured by saccade latencies, an effect of visual working memory on rapid eye movements to abrupt-onset targets has been found to occur in less than 150 ms after target onset (Hollingworth et al., 2013). Furthermore, this line of evidence demonstrates that the content of visual working memory can also bias attentional orienting towards matching visual stimuli presented alone in the visual field (i.e., in the absence of stimulus competition). In the experiments reported here, we aimed to provide a further demonstration for the working memory bias of early visual processes by examining whether the content of visual working memory can enhance the sensory quality of the target representation at the location of matching visual stimuli presented in isolation (i.e., in single-item displays). Given that response latencies may reflect post-perceptual rather than perceptual processes (Prinzmetal, McCool, & Park, 2005), the present study is concerned primarily with the effects of the working memory bias on perceptual accuracy. If the working memory bias of attention can enhance target perception at the early perceptual stage of visual processing, then one might expect this to be most clearly manifested in measurements of discrimination accuracy with brief target displays. Thus, the present study sought to demonstrate the working memory-driven attentional effects with single-item displays in a target discrimination task with accuracy as the main dependent variable.

Of particular relevance to the present purpose are behavioral studies revealing that discrimination accuracy for a target

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feature is improved when the target item matches the current content of working memory (Cosman & Vecera, 2011; Han, 2015; Pan, Cheng, & Luo, 2012; Soto, Wriglesworth, Bahrami-Balani, & Humphreys, 2010). It is noteworthy, however, that these studies have observed preferential target processing at the memory-matching location only when the target item is presented along with distracting stimuli and followed by post-masks. Because distractors and masks are considered to introduce visual noise that can interfere with target processing (Eckstein, 1998), the content of working memory may enhance target feature discrimination at the location of matching visual stimuli through reducing the interference of the external noise introduced by distractors and/or masks. This performance enhancement could be generated even without any changes in the visual signal of the target feature. From this perspective, it is possible that the previously reported effects of the working memory bias on target discrimination accuracy might be due not to signal enhancement but to noise reduction.

Thus, in order to determine whether the working memory bias can enhance target signal at the location of visual stimuli matching the memorized information, it is critical to preclude added external noise by presenting the target stimulus in isolation without distractors or post-masks. In an effort to achieve this goal, Pan, Luo, and Cheng (2016) recently asked participants to discriminate a single Landolt target during the retention interval of a working memory task. Two irrelevant prime stimuli were simultaneously presented before the target presentation. One of the prime stimuli matched the information being held in working memory and the other did not. The target appeared at the location of either the memory-matching stimulus or the memory-mismatching stimulus. The results show that target discrimination accuracy was improved when the target appeared at the location previously occupied by the memory-matching item. This suggests that attention is biased by working memory content towards the matching item and thereby enhances the quality of the target representation at the location of the attended item. However, because the match between the target stimulus itself and the content of working memory was not manipulated by Pan et al. (2016), their results cannot provide evidence suggesting that the working memory bias of attention can enhance target signal at the location of attended stimuli presented alone in the visual field.

To examine whether the working memory bias of visual attention can enhance visual perception of matching target stimuli presented in isolation without stimulus competition, two studies on neuropsychological patients with vision deficits have directly manipulated the congruency between working memory content and a single target stimulus presented in the absence of distractors and masks (Smith & Lane, 2017; Soto & Humphreys, 2006). However, the findings from these two studies are mixed and subject to alternative interpretations. Soto and Humphreys (2006) asked patients with visual extinction to report object features during working memory maintenance. They found that the patients showed enhanced awareness of the contralesional stimulus that matched rather than mismatched the current content of working memory when the contralesional stimulus was presented simultaneously with a stimulus in the ipsilesional visual field. However, there was no significant effect of working memory on awareness of a single target stimulus presented either in the contralesional or in the ipsilesional visual field. On the other hand, Smith and Lane (2017) recently reported improved performance in the perception of a single target item. In their experiment, a patient with right-sided hemianopia was shown a single visual target presented briefly in the blind hemifield during the retention interval of working memory. The target could be presented either before or after the presentation of two tones. The patient had to discriminate whether the target had been presented before or after the tones. The results show that performance was more accurate when the target exactly matched the content of working memory than when the target did not. On the basis of this finding, Smith and Lane (2017) concluded that the content of working memory can enhance the signal of a matching visual target stimulus presented in isolation. However, this finding might reflect the working memory effect on temporal rather than nontemporal processing of the visual target, considering that the experimental task was actually to discriminate the temporal order of the target presentation relative to the presentation of the tones during working memory maintenance. As such, it is possible that the performance improvement in temporal discrimination observed when the target exactly matched working memory content was produced without enhancement of target signal. To be able to conclude that the working memory bias of attention enhances target signal at the location of the attended stimuli presented in isolation, one needs to demonstrate the presence of working memory effects when perceptual processing of a nontemporal feature (e.g., color, shape, or orientation) of a single target item is directly assessed.

Perhaps the strongest evidence for the working memory bias of visual signal with single-item displays, then, comes from a functional magnetic resonance imaging study by Gayet et al. (2017), who examined whether the neural response to a single visual probe could vary according to whether it matched the visual information being maintained in working memory. They found that visual working memory enhanced the neural response to a matching visual probe in terms of both signal strength and information content. Note that here visual probes were task-irrelevant and participants were not asked to detect or discriminate them. Thus, although it is implicit in the neuroimaging evidence reported by Gayet et al. (2017), we do not know whether the enhanced neural response to a memory-matching visual stimulus has significant consequences for perceptual processing at the location of that stimulus presented alone in the visual field.

In the present study, we sought to provide further evidence for the hypothesis that the content of visual working memory facilitates early perceptual processing at the location of matching visual stimuli presented in isolation. To directly test this hypothesis, we assessed whether visual working memory modulates target discrimination accuracy in single-item displays. This was accomplished by using the task shown in Fig. 1. In the memory sample period, two randomly chosen circles filled with distinct colors were sequentially presented at the center of the screen. After a delay, a number cue ("1" or "2") was displayed to instruct observers whether the color of the first or the second sample needed to be maintained in working memory. During the retention interval, observers were asked to discriminate a Landolt target embedded in a stimulus that could match one or neither of the two samples. Critically, the target was presented alone without distractors or post-masks, thereby excluding any external noise added. We examined whether the match between the memory samples and the stimulus containing a target would influence target discrimination accuracy with single-item displays. A key characteristic of the present experimental design is that it allows us to distinguish between passive priming effects and working memory effects in a single task paradigm, while controlling for depth of stimulus encoding and cognitive control load across different conditions (cf. Pan, Han, & Zuo, 2019; Pan, Zhang, & Zuo, 2019). If priming a stimulus representation facilitates subsequent target discrimination, then we should expect that target discrimination would benefit when the stimulus containing a Landolt target matched the uncued sample compared to when it matched neither sample. If active maintenance of information in visual working memory biases attention towards a matching stimulus presented alone in the visual field and enhances target feature perception at the memory-matching location, then discrimination accuracy would be improved when the stimulus containing a target matched the cued sample compared to when it matched the uncued sample.

Experiment 1

Method

Participants

A group of 30 naïve volunteers participated in this experiment for monetary compensation. All of them reported having normal or corrected-to-normal vision. Informed consent was obtained from each participant prior to the experiment that was conducted in accordance with the tenets of the Declaration of Helsinki and local ethics regulations.

Apparatus and stimuli

The experiment was controlled by E-Prime software. Responses were made on a standard keyboard. The stimuli were presented on a 17-in. CRT monitor with a resolution of 1,024 × 768 pixels and a 100-Hz refresh rate. The memory samples were two distinct colored circles (2° × 2°) presented at the center of the screen. The colors of the two sample circles on each trial were selected at random from a pool of four equiluminant (~36 cd/m^2) colors (in RGB space: red: [255, 128, 128], green: [0, 185, 0], blue: [98, 98, 255], and yellow: [255, 255, 68]). The target display consisted of a single black

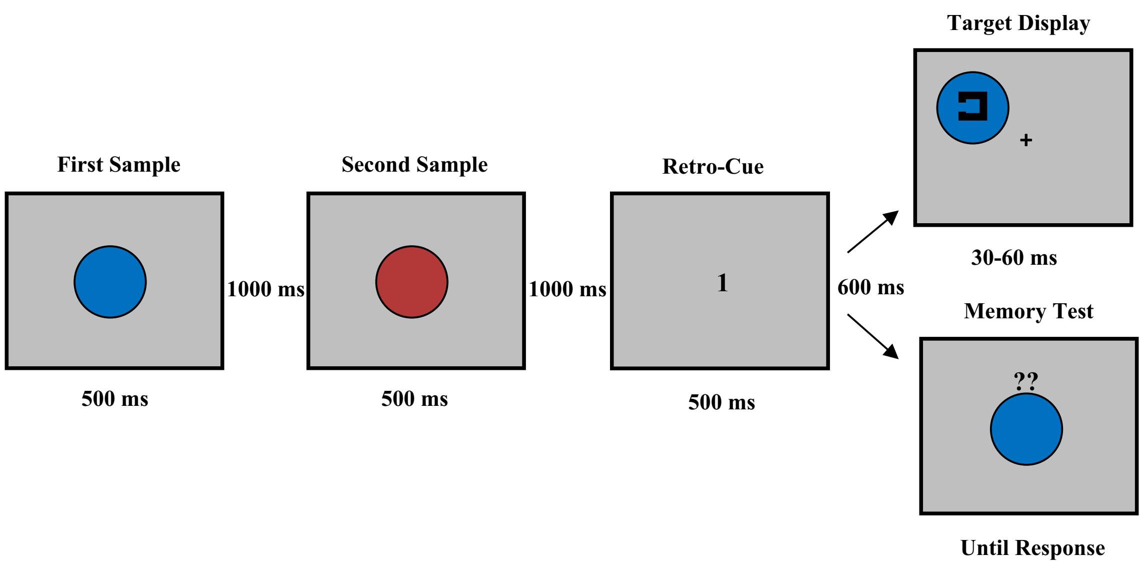

Fig. 1 Schematic illustration of the trial sequence and example stimuli in Experiment 1

Landolt-square (1° × 1°) embedded in a colored circle. The Landolt-square had a spatial gap (0.1°) on either the left or the right side. All stimuli were presented on a gray background at a viewing distance of 57 cm.

Procedure and design

A trial began with the display of a black central fixation cross (0.2° × 0.2°) for 1,000 ms. Then, four digits were randomly selected without replacement from the integers 1–9 and were presented for 1,000 ms at the center of the screen. Participants were asked to overtly rehearse the four digits throughout the trial, at a rate of about three to four items per second. This articulatory suppression procedure served to minimize verbal recoding of the visual stimuli (Besner, Davies, & Daniels, 1981), ensuring that visual working memory would be used. After a delay of 1,000 ms following the offset of the digits, two different colored circles were shown to participants as the memory samples. The two sample circles were sequentially presented for 500 ms each at the center of the screen, with a blank interval of 1,000 ms between them. After a delay of 1,000 ms following the offset of the second sample, a number cue (“1” or “2”) was centrally presented for 500 ms to instruct participants on whether the first or the second sample color had to be retained in mind throughout the trial. The first sample was cued on half of the trials, while the second sample was cued on the other half. The presentation order of the cued sample was randomized across trials. The number cue was followed by a 600-ms period during which only a central fixation cross was presented. Then, the target item was presented at one of the four corners of an imaginary square centered on fixation, with an eccentricity of 6° of visual angle. The target item appeared equally often at four possible locations. In this target display, a Landolt-square with a gap on its left or right side was presented through a colored circle. Participants were asked to discriminate the orientation of the Landolt-square gap by pressing one of two keys. They were required to respond as accurately as possible within an unlimited time window, without emphasis on response speed. Although observers were not pressed to respond quickly, response times were also recorded to evaluate the possibility of a speed-accuracy trade-off. Crucially, the colored circle containing a Landolt-square in the target display could match the cued sample (cued-matching condition), the uncued sample (uncued-matching condition), or neither sample (mismatching condition). These three congruency conditions occurred equally often and varied randomly within the critical trials.

In the experimental session, on 30% of all trials, instead of the target display, a memory test was presented to ensure that the cued sample was actively maintained in working memory. Because memory would not be probed after the target display, there should be no explicit incentive for participants to orient towards a memory-matching stimulus in the target display in order to refresh memory representations to help complete the memory test. On these memory catch trials, a colored circle was presented at the center of the screen, and participants were asked to indicate with a keypress whether it was the same as the cued sample. The memory-test item and the cued memory sample shared the same color on half of the catch trials, and they differed in color on the other half. The memory-test item remained visible on the screen until response (see Fig. 1).

Using a training procedure similar to that of Soto et al. (2010), an exposure duration yielding about 75% correct discrimination of Landolt targets was determined per observer. Specifically, after being familiarized with the target discrimination task, the observer carried out training trials with different presentation times of the target item. The target duration was set to 500 ms during the first training block and was reduced progressively in subsequent blocks of training trials (i.e., 300 ms, 200 ms, 100 ms) and then further decreased in steps that were multiples of 10 ms. This continued until the observer achieved a level of about 75% correct discriminations during the initial ten trials of a given training block. This exposure duration was then used in the subsequent experimental session, such that ceiling and floor effects would be avoided for the experimental trials. Consequently, the target display was presented for 30 ms to 60 ms, depending on the observer. There were a total of 300 experimental trials.

Results and discussion

Accuracy for memory catch trials was high (94% correct on average), suggesting that participants were indeed maintaining the cued sample in visual working memory as instructed. Mean accuracy results in the target discrimination task are presented in Fig. 2. Analysis of the accuracy data showed that there was a significant main effect of congruency, $F(2, 58)$ =

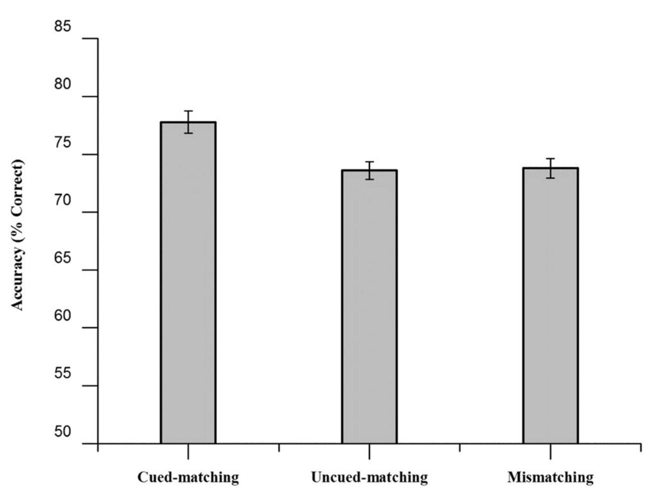

Fig. 2 Target discrimination accuracies for different experimental conditions in Experiment 1. Error bars represent within-subjects 95% confidence intervals (Loftus & Masson, 1994)

20.676, p < .001, η_p^2 = .416. Bonferroni-corrected planned comparisons revealed that target discrimination performance was significantly more accurate in the cued-matching condition than in both the uncued-matching (p < .001) and the mismatching conditions (p < .001), which did not differ from each other (p > .9). The main effect of congruency on mean correct response times (RTs) was not significant, F < 1, indicating that there was no sign of speed-accuracy trade-off. Table 1 shows the mean RTs and accuracies for all conditions. The results show that actively retaining a sample color in visual working memory biased attention towards a single matching stimulus and improved discrimination accuracy for a target at the memory-matching location, whereas there was no effect when the sample was initially encoded into memory but did not need to be actively maintained in mind by the time the target display appeared. This finding suggests that the improvement in target discrimination accuracy with single-item displays was due not to passive priming but to active working memory maintenance. Before delving into further discussion, we wished to replicate this finding by using more controlled experimental settings. Experiment 2 was devised with this in mind.

Experiment 2

Method

This was similar to that used in Experiment 1 with the following exceptions. The color categories of the two sample circles on each trial were selected randomly without replacement from a set of three (red, green, and blue) rather than four. Within a selected color category, the specific color value was chosen randomly from a set of four similar colors, each of which was produced by RGB permutations. The four reds were [255, 128, 128], [179, 56, 56], [192, 107, 126], and [170, 68, 79]; The four greens were [0, 185, 0], [0, 176, 80], [89, 255, 89], and [128, 255, 128]; The four blues were [98, 98, 255], [0, 112, 192], [0, 176, 240], and [153, 160, 255]). Given that the three congruency conditions occurred with the same probability, the stimulus containing a Landolt target would be equally likely to be in any of the three color categories. As such, neither of the two samples presented at the start of the trial predicted the color category of the subsequent stimulus in which the Landolt target would be presented. There was no articulatory suppression task in this experiment. To prevent participants from adopting a verbal, rather than visual, encoding strategy for the working memory task, the memory-test display contained two circles: one in the cued color (correct alternative) and the other in a color selected randomly from the remaining three colors in the same category (false alternative). The two colored circles were presented 3° to the left and right of the central fixation cross, with the positions of the two alternatives determined randomly (see Fig. 3). A new group of 30 volunteers participated, each of whom performed a total of 300 experimental trials.

Results and discussion

Overall, mean accuracy on the memory test was 76.8% correct, which was markedly lower than the memory accuracy in Experiment 1, suggesting that the within-category discrimination task used here was more difficult. Mean accuracy results in the target discrimination task are presented in Fig. 4. Analysis of the accuracy data showed that there was a significant main effect of congruency, $F(2, 58) = 16.756$, p < .001, η_p^2 = .366. Bonferroni-corrected planned comparisons revealed that target discrimination performance was significantly more accurate in the cued-matching condition than in both the uncued-matching (p < .001) and the mismatching conditions (p < .001), which did not differ from each other (p > .9). The main effect of congruency on RTs was not significant, F < 1, suggesting that there was no sign of speed-accuracy trade-off. Table 1 shows the mean RTs and accuracies for all conditions. This pattern of results replicates the finding of Experiment 1 in a more controlled setting. The results confirm that active maintenance of a sample color in visual working memory biased attention towards a single matching visual stimulus and enhanced discrimination accuracy for a Landolt target presented at the memory-matching location, whereas there was no priming effect when the sample was retro-cued to be irrelevant to the current working memory task.

Table 1 Mean response times (RTs) and percentages of correct responses in the target discrimination task for Experiments 1 and 2. Standard deviations are included in parentheses

	Experiment 1		Experiment 2	
Congruency conditions	RTs (ms)	Accuracy (%)	RTs (ms)	Accuracy (%)
Cued-matching	719 (174)	77.8 (3.6)	743 (203)	79.8 (5.0)
Uncued-matching	731 (178)	73.6 (2.5)	754 (205)	74.3 (5.7)
Mismatching	727 (186)	73.8 (2.9)	729 (165)	73.7 (6.5)

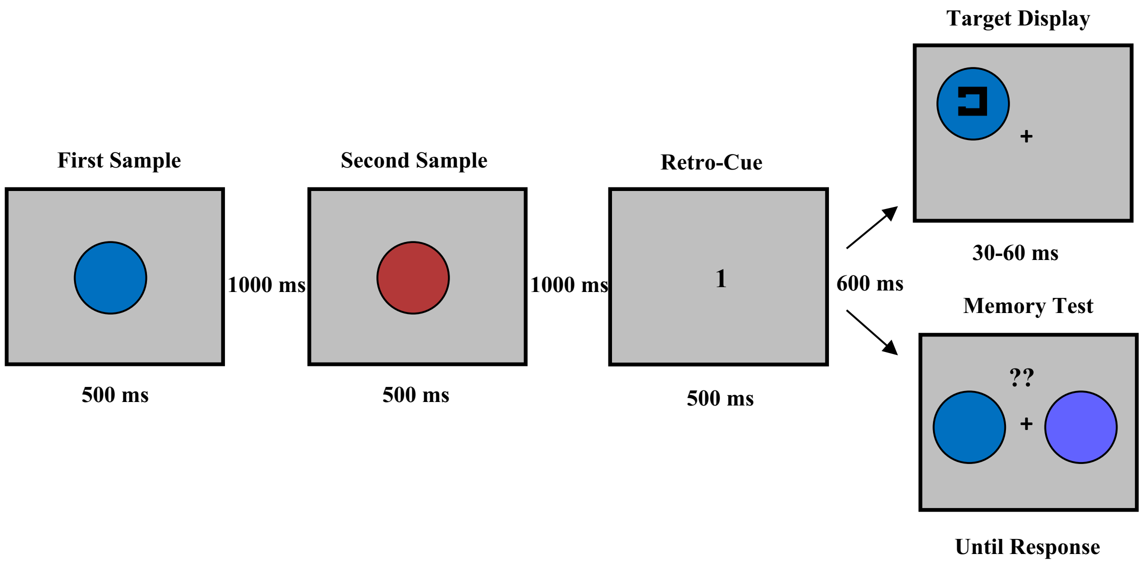

Fig. 3 Schematic illustration of the trial sequence and example stimuli in Experiment 2

General discussion

Previous studies have shown that working memory content can improve target discrimination performance at the location of a matching visual stimulus that was presented in a multi-item display (e.g., Han, 2015; Pan, Cheng, & Luo, 2012; Soto et al., 2006, 2010). Because the reported performance benefit in these studies occurred only when the target appeared with distracting stimuli and was followed by masks, it might be due to noise reduction at the post-perceptual decision stage rather than target signal enhancement at the early perceptual stage of visual processing (e.g., Cosman & Vecera, 2011; Dosher & Lu, 2000; Shiu & Pashler, 1994). The present findings extend previous work by showing that the content of visual working memory can also enhance target discrimination accuracy at memory-matching locations with single-item displays. This performance enhancement effect cannot be attributed to the mechanism of passive priming from the presentation of the memory sample, because we failed to observe priming effects when the sample was retro-cued to be irrelevant to the current working memory task. The results provide further evidence that the content of visual working memory can act to bias attention towards matching visual stimuli presented in isolation without stimulus competition (Hollingworth et al., 2013; Schneegans et al., 2014). Furthermore, given that here the target item was presented alone against a blank visual field without any external noise added (i.e., no distractors or post-masks), the present findings extend the earlier evidence by demonstrating that the working memory bias of attention operating in the absence of stimulus competition can facilitate target discrimination at the attended location through direct enhancement of target signal.

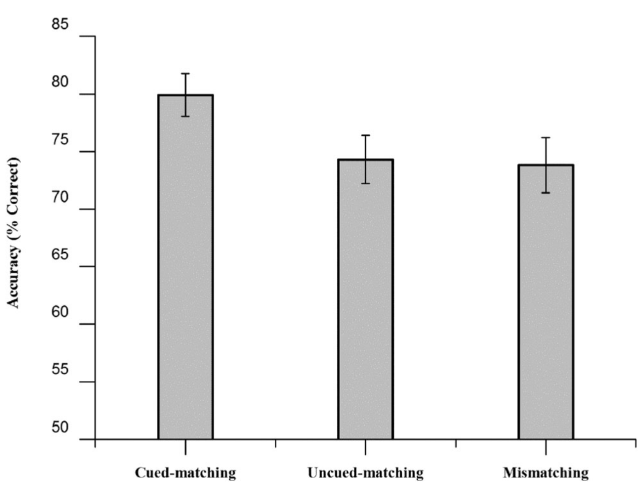

Fig. 4 Target discrimination accuracies for different experimental conditions in Experiment 2. Error bars represent within-subjects 95% confidence intervals (Loftus & Masson, 1994)

How does the working memory bias of attention enhance target feature perception in single-item displays? At least two possibilities are suggested in the literature. One is that attention is oriented towards the isolated stimulus containing a Landolt target more rapidly when the stimulus matches the color representation being retained in visual working memory (Hollingworth et al., 2013; Schneegans et al., 2014). Because the target display is quite brief (30–60 ms), it is possible that this leaves more time for the observers to process a target feature at the memory-matching location and hence enhances its perceptibility. Another possibility is that the working memory bias of attention boosts early perceptual processing by improving spatial resolution at the attended location (Carrasco, Williams, & Yeshurun, 2002; Pan, Luo, & Cheng, 2016), as a result of which discrimination of a Landolt target benefits from appearing at the memory-matching location. Thus, under these accounts, working memory-driven attention operating in the absence of stimulus competition enhances visual perception by more efficient processing at the memory-matching location, by a higher spatial resolution at the attended location, or by both.

With single-item visual displays, beneficial effects of working memory content on target discrimination accuracy have previously not been observed by Cosman and Vecera (2011) and Soto and Humphreys (2006). One reason for failure to find such an effect may be a lack of sensitivity and power of their experiments. Specifically, the duration of single targets was fixed at 70 ms for each subject and target discrimination accuracy was relatively high in Cosman and Vecera's (2011) study; it could be that the improvement in target discrimination accuracy with single-item displays emerges only under more data-limited conditions, in which target discrimination is more difficult. Indeed, when the level of performance was reduced by presenting targets more briefly, Soto and Humphreys (2006) observed a marginally significant beneficial effect of working memory on target discrimination accuracy. Given that there were only five subjects in Soto and Humphreys' (2006) study, it is very likely that their failure to find a significant effect of working memory on perception of single targets may be due to a lack of a larger sample of participants. In the experiments reported here, however, we used a bigger sample size ($N = 30$) for each experiment, and an exposure duration resulting in approximately 75% correct discrimination of single targets was determined for each subject. This exposure time was used in the subsequent experimental sessions. Moreover, given the evidence that the effects of the working memory bias on visual processing are more pronounced under the condition of processing Landolt-C stimuli (Jung, Han, & Min, 2020), we used Landolt targets in single-item displays. With these adaptations in experimental conditions, here we found a small but significant improvement in target discrimination accuracy when the single target appeared at the location of stimuli that matched the content of visual working memory. Thus, visual working memory does enhance target discrimination accuracy with single-item displays, but this effect can only be shown if optimal experimental conditions are used.

The present findings support the view that the content of visual working memory biases visual processing at an early perceptual stage (e.g., Han, 2015; Hollingworth et al., 2013; Pan et al., 2016; Schneegans et al., 2014; Soto et al., 2010). However, this does not necessarily exclude the possibility that the working memory bias may also operate at relatively late, post-perceptual stages of visual processing (Cosman & Vecera, 2011). Our results are also in agreement with the neuroimaging evidence showing that visual working memory enhances the neural representation of concurrent visual input that matches the to-be-remembered information (Gayet et al., 2017; Soto, Humphreys, & Rotshtein, 2007). The enhanced neural responses to memory-matching stimuli may reflect sensory recruitment in visual working memory maintenance (e.g., Harrison & Tong, 2009; Gayet et al., 2016, 2018; Serences, Ester, Vogel, & Awh, 2009; Silvanto & Cattaneo, 2010), which renders both the working memory bias of attention and the perceptual enhancement at the attended location plausible.

It should be noted that the present results do not necessarily suggest a general perceptual enhancement for any visual stimuli appearing at memory-matching locations. While our current data provide evidence suggesting that the content of visual working memory can enhance perceptual processing at the location of matching visual stimuli that are task relevant (i.e., containing targets), they do not directly speak to the fact that perceptual processing at the location of task-irrelevant stimuli (i.e., containing distractors) can also be enhanced by visual working memory. To examine whether the working memory bias of attention enhances perceptual processing at memory-matching locations that are task irrelevant, recent research by Dowd, Nag, and Golomb (2019) assessed how a memory-matching distractor would interfere with perception of a target feature. It was assumed that if the content of working memory automatically biases attention towards the matching distractor and enhances perception of its features, then there should be interference of the perceptual processing of the target feature. However, this assumption was not confirmed. Dowd et al. (2019) found no evidence for specific perceptual interference of target processing from a memory-matching distractor, as measured by a continuous feature report task interposed during the retention interval of working memory. The finding indicates that distractor perception seems not to be affected by the working memory bias of attention in the same way as target perception.

In conclusion, the current results show a small but significant improvement in target discrimination accuracy with single-item displays when the target appeared at the working memory-matching location. The effect is more likely to be attributed to enhancement of target signal than to reduction of external noise, since the target item was presented alone without any distractors or masks that may introduce noise to interfere with target processing. The present findings therefore demonstrate that the sensory quality of the perceptual representation of a target feature can be enhanced by the working memory bias of visual attention operating in the absence of stimulus competition.

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