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The priority state of items in visual working memory determines their influence on early visual processing

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ABSTRACT

Items held in visual working memory (VWM) influence early visual processing by enhancing memory-matching visual input. Depending on current task demands, memory items can have different priority states. Here, we investigated how the priority state of items in VWM affects two key aspects of early visual processing: access to visual awareness and attention allocation. We used three perceptual tasks: the breaking continuous flash suppression task (Experiment 1), the attentional capture task (Experiment 2), and a visual search task (Experiment 3). We found that stimuli matching prioritized VWM items yielded a large perceptual advantage over stimuli matching non-prioritized VWM items (despite minimal memory loss). Additionally, stimuli matching non-prioritized memory items exhibited a (small but consistent) perceptual advantage over VWM-unrelated stimuli. Taken together, observers can flexibly de-prioritize and re-prioritize VWM contents based on current task demands, allowing observers to exert control over the extent to which VWM contents influence concurrent visual processing.

1. Introduction

In daily life, we use visual working memory (VWM) to maintain visual information available for subsequent goal-directed behavior (for a review, see Baddeley, 2003; D'Esposito & Postle, 2015; Duncan & Humphreys, 1989; Wolfe, 2021). Information maintained in VWM is known to influence concurrent perception at early processing stages. Specifically, visual input that matches the contents of VWM attracts attention (Olivers et al., 2006; for a review, see Soto et al., 2008; Wang et al., 2023), gains preferential access to visual awareness (Ding et al., 2021; Gayet et al., 2013; Pan et al., 2012), and evokes an enhanced neural response (Bahmani et al., 2018; Gayet et al., 2017; Merrikhi et al., 2017), compared to visual input that mismatches the content of VWM. By doing so, the contents of VWM help prioritizing behaviorally relevant information from the vast amount of visual input that we gather from our complex and dynamic visual environment. For example, when we go to the supermarket to buy coffee, we can activate a visual representation of our favorite coffee brand (e.g., a dark red rectangular packaging) to help us detect it among all other brands in the aisle.

A growing body of evidence has revealed that when we store multiple items in visual memory, their representational state can differ depending on the task requirements (i.e., for what purpose or output behavior the memory content is memorized). An important distinction can be made between items that are currently relevant (for an imminent task), typically referred to as prioritized memory items, and items that are also maintained in memory but are only prospectively relevant (for a subsequent task), typically referred to as non-prioritized memory items (LaRocque et al., 2014, 2017). For instance, we might need to buy both bananas (yellow) and coffee

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(dark-red) at the supermarket, but since we are approaching the coffee aisle, we prioritize the dark-red memory item first while retaining the yellow memory item to prioritize later.

A single (i.e., currently relevant) memory item has been shown to bias the processing of visual input in a stimulus-specific manner (Gayet, et al, 2017), arguably because it is stored in the same neural populations that also process the visual input (e.g., Chota et al., 2023; Harrison, & Tong, 2009; Rademaker et al, 2019). It has indeed been argued that the role of early visual cortex in VWM maintenance might be to interact with visual input (e.g., Christophel et al., 2017; Chota & Van der Stigchel, 2021; Gayet et al., 2017, 2018; Iamshchinina et al., 2021). However, it remains unclear whether and how non-prioritized memory items influence concurrent perception. This question persists partly because there is no consensus in the literature on how these non-prioritized memory items are stored in the brain. Some evidence suggests that non-prioritized memory items are either stored outside the early visual cortex (Christophel et al., 2018), maintained through synaptic mechanisms (Rose et al., 2016; Wolff et al., 2017), or exhibit different neural activity patterns compared to prioritized memory items (van Loon et al., 2018; Yu et al, 2020). These findings may suggest there are no interactions between non-prioritized memory items and concurrent visual input. On the other hand, other research indicates that both prioritized and non-prioritized memory items are stored in early visual processing regions using shared, sensory-like neural codes (Iamshchinina et al., 2021), suggesting possible interactions between non-prioritized memory items and concurrent visual input.

Whether and how non-prioritized memory items influence early visual processing might also depend on the task that is used to measure the influence of VWM on concurrent visual input. Previous studies have used various perceptual tasks to measure the impact of memory items on current visual input, but the results have been inconsistent. First, in tasks measuring access to awareness, previous studies have found that visual information gains preferential access to awareness when it matches the content of VWM. This effect has been observed under various circumstances; when initially memorizing a single item (Gayet et al., 2013; Pan et al., 2012), when initially memorizing multiple items while utilizing a *retro*-cue to retain one item and discard the other (Gayet et al., 2013, 2017), and when simultaneously maintaining multiple memory items in the same state (van Moorselaar et al., 2018). However, there are no specific studies that investigate whether non-prioritized memory items facilitate access to awareness for VWM-matching stimuli. Second, in tasks measuring attention allocation, previous studies have found that stimuli matching the content of VWM attract attention, even when this was disruptive to the behavioral goals of the participant (Olivers et al., 2006; Soto et al., 2008). This attention-grabbing effect occurs both when a single stimulus was initially memorized (Soto et al., 2005, 2007), and when two stimuli were memorized but only one was retained while the other was discarded (Mallett & Lewis-Peacock, 2018; Olivers et al., 2006; Peters et al., 2009; van Moorselaar et al., 2015a; Wang et al., 2023). However, there is controversy regarding whether non-prioritized memorized items can allocate attention to VWM-matching stimuli (Bahle et al., 2018; Chen & Du, 2017; Hollingworth & Beck, 2016; Zhu et al., 2024), or not (Downing & Dodds, 2004; Park & Zhang, 2024; van Moorselaar, Theeuwes, & Olivers, 2014; Zhang & Yamada, 2023). In the current study, we therefore focus on perceptual tasks that capture two distinct hallmarks of early visual processing: access to visual awareness and allocation of spatial attention. It remains unclear whether non-prioritized memory items influence conscious access and attention allocation of visual input simultaneously, and there might be a difference between these two aspects of early visual processing.

In the present study, we asked whether the impact of VWM content on early visual processing depends on the priority state of the memory items. That is, we investigated how memory items in different states affect behavioral responses to concurrent visual input (i.e., detection and search performance). To increase the generalizability of our findings, we sought converging evidence from multiple established experimental paradigms that measure distinct aspects of early visual processing. To manipulate the priority state of VWM content, we used a double serial *retro*-cuing paradigm in three different experiments (Christophel et al., 2018; LaRocque et al., 2017; Rose et al., 2016). In this paradigm, participants need to remember two items and are then instructed (with a cue: 1 or 2) which item they will be asked to reproduce after the first retention period (out of two consecutive retention periods). After reproducing the first memory item, a second cue indicates which item participants need to reproduce after the second retention period; this could either be the same item as before or the other item. During the first retention period, by virtue of this paradigm, one memory item is prioritized, and the other item is non-prioritized. Critically, the non-prioritized memory item is not discarded, but must be maintained in memory, in a non-prioritized state, in case it is cued for the second reproduction task.

To quantify how memory items in different priority states influence early visual processing, we utilized two types of perceptual tasks, each corresponding to different aspects of early visual processing. The first task that we employed, in Experiment 1, measures differences in access to awareness. We used the established breaking continuous flash suppression (b-CFS) paradigm, which offers a straightforward and cost-effective means to rapidly evaluate differences in access to visual awareness between stimulus conditions (Gayet et al., 2013, 2014, 2016; Jiang et al, 2007; Stein et al, 2011) In this paradigm, target stimuli presented to one eye are temporarily rendered invisible by presenting a dynamic mask to the other eye. The moment in time at which an initially suppressed target is detected by the participant (i.e., overcoming interocular suppression) serves as a proxy for access to awareness. The second type of task that we used (in Experiments 2 and 3) measures the interaction between VWM content and visual attention. We employed the attentional capture paradigm (Experiment 2; Theeuwes, 1992) and a variant of it (Experiment 3) which more closely matches the setup of Experiment 1. The attentional capture paradigm provides a direct way to investigate the automatic attention allocation by VWM content (Olivers et al., 2006; Soto et al., 2008). In this paradigm, participants engaged in search for a diamond-shaped target surrounded by several disk-shaped distractors, while one of the distractors bore a unique color (the singleton distractor). If the singleton distractor attracts more attention (for instance because it matches rather than mismatches the color in VWM) this causes participants to respond more slowly to the target stimulus (Olivers et al., 2011; Soto et al., 2007). We used both types of tasks (measuring conscious access in Experiment 1, and attention allocation in Experiments 2 and 3), to investigate how VWM items in different priority states influence early visual processing.

2. Experiment 1

In Experiment 1, we combined the double serial *retro*-cuing task with the b-CFS task to investigate the impact of VWM contents in different priority states on access to visual awareness. If memory content influences access to visual awareness of concurrent visual input, we expect that the VWM-matching targets will be perceived before the simultaneously presented memory-unrelated targets in the b-CFS task. Crucially, we test how this depends on the priority state of the VWM content (prioritized versus non-prioritized).

2.1. Methods

2.1.1. Participants

To determine the appropriate sample size for Experiment 1, we conducted a power analysis using G*Power 3.1 (Faul et al., 2007). A repeated measures ANOVA (2 × 2, as described in the experimental design section) was planned to investigate the impact of different states of memory items on visual awareness, with an alpha level of 0.05, and a medium effect size of 0.25 (as suggested by Cohen, 1988), and the desired power (1-β) of 0.8. Based on these parameters, the power analysis indicated that a total sample size of twenty-four participants would be required to achieve the desired power. Therefore, we recruited twenty-four participants for Experiment 1 (*Mean* = 23.5, *SD* = 2.1; 5 males), one participant was replaced due to consistently reported perceiving a target when no targets were presented in b-CFS tasks (in catch trials, see below). All participants signed informed consent before participation and received compensation in the form of money or course credits. All participants had normal or corrected-to-normal vision and no history of epilepsy. The study was approved by the Ethical Committee of the Utrecht University.

2.1.2. Apparatus

The stimuli were shown to the participants in a dark room using a desktop computer and a linearized 27-inch LCD monitor (2560 × 1440 pixels, 120 Hz refresh rate). All stimuli were created and presented with MATLAB 2021 (The Math Works, Inc) and its PsychToolbox extension software. The viewing distance was maintained at 60 cm with a chin and forehead rest. A stereoscope with four mirrors (two per eye) was fixed on the chin rest to allow for separately stimulating the two eyes of the participant.

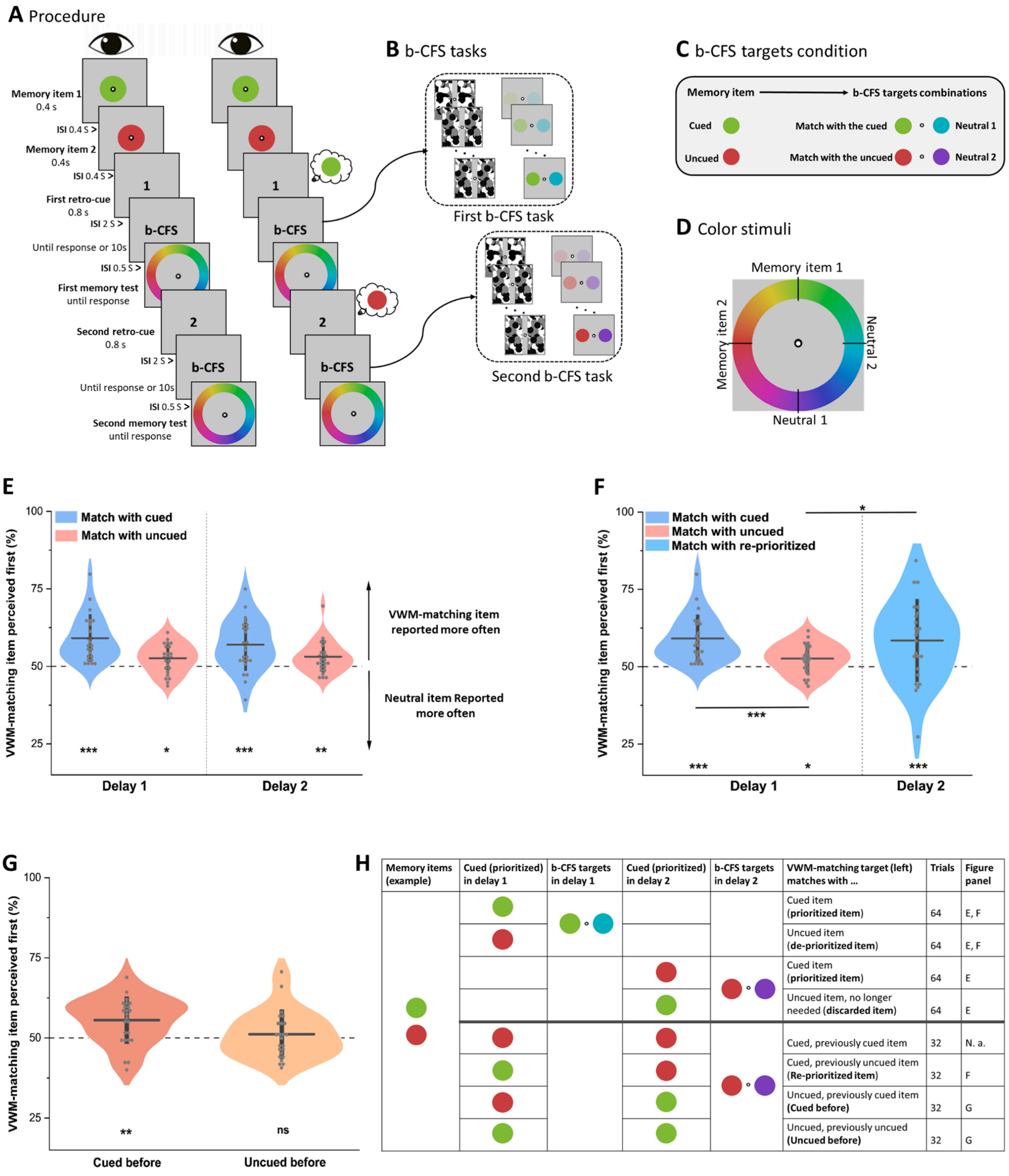
2.1.3. Experimental procedure

In the main experiment (depicted in Fig. 1A), participants started each trial in a self-initiated manner (pressing the up arrow). After which a fixation bullseye appeared for 500 ms, participants needed to memory two items sequentially, the first colored memory item (400 ms), a blank (400 ms), the second colored memory item (400 ms), a blank (400 ms). Then the number "1″ or "2" appeared (0.28 dva *0.56 dva, 800 ms), which instructed participants that either the first or second memory item would need to be reported first. During the delay (after a 2000 ms blank), the first b-CFS task was initiated. In this task, two targets were presented to the left and right of fixation of the recessive eye, while dynamic masks (refreshing every 100 ms) were presented to the corresponding locations of the dominant eye. The opacity of the b-CFS target increased linearly from zero to full opacity within 1500 ms and remained at full opacity until the end of the first b-CFS task. Simultaneously, the mask began at full opacity for the initial 1500 ms, followed by a linear decrease in opacity between 1500 ms and 9000 ms, maintaining zero opacity until the end of the b-CFS task. Participants were instructed to report on which side of fixation (left or right) they saw a target appear first, as soon as they perceived it, by pressing the left or right arrow keys of the keyboard, respectively. Additionally, participants were asked to press the down arrow in case no target was presented on that trial (in so-called catch-trials). The b-CFS task continued until the participant responded or until 10 s had elapsed without a response (Fig. 1B). At the end of the b-CFS tasks, three frames of masks (same as those used in the b-CFS task) were presented to both eyes at a refresh rate of 10 Hz to reduce visual afterimages. Following a 500 ms blank interval, the first memory recognition task initiated. Participants moved the mouse to select the color that precisely matched the cued memory item. After confirming the selected color with a mouse click, participants received feedback, with a white line on the color wheel indicating the reported color and a black line indicating the color of the memory item (500 ms). Then, the second *retro*-cue was presented, which could either be the same cue as the first (i.e., referring to retrieve the same memory item) or the other cue (referring to retrieve the other memory item), with equal probability. After a blank of 2000 ms, the second b-CFS task was initiated, followed by the second memory recognition task. The procedures were identical to the first b-CFS task and memory task.

Before the experiment was initiated, participants performed a b-CFS task (with two targets at the left and right side of the fixation) to determine sensory eye-dominance. Throughout the main experiment, the target was presented to the participants' recessive eye while the masks were presented to the participants' dominant eye, to minimize trial-by-trial within subject variability in suppression durations. Next, participants took part in two consecutive practice sessions, to get acquainted with the different parts of the experimental (dual) task progressively. In the first part, participants completed 8 trials of the VWM task only. In the second part, they completed 8 trials combining the b-CFS task with the VWM task, which was identical to the task performed in the main experiment. The main experiment comprised 136 trials divided into 8 blocks, including 8 catch trials (one trial per block). These trials were included to verify that participants only reported perceiving targets when targets were presented (rather than pressing keys randomly). The entire experiment lasted approximately 1 h.

2.1.4. Experimental design

In the memory task, participants were instructed to remember two items sequentially and use the *retro*-cue to regulate their priority state (i.e., cued and uncued). In the b-CFS task, there were only two distinct combinations of b-CFS targets that could occur: one of the two b-CFS targets was identical to one of the memory items (either identical to the cued memory item, or to the uncued memory item),



Memory items (example)	Cued (prioritized) in delay 1	b-CFS targets in delay 1	Cued (prioritized) in delay 2	b-CFS targets in delay 2	VWM-matching target (left) matches with ...	Trials	Figure panel
🟢 🔴	🟢	🟢 ∘ 🔵			Cued item **(prioritized item)**	64	E, F
	🔴				Uncued item **(de-prioritized item)**	64	E, F
			🔴	🔴 ∘ 🟣	Cued item **(prioritized item)**	64	E
			🟢		Uncued item, no longer needed **(discarded item)**	64	E
	🔴		🔴	🔴 ∘ 🟣	Cued, previously cued item	32	N. a.
	🟢		🔴		Cued, previously uncued item **(Re-prioritized item)**	32	F
	🔴		🟢		Uncued, previously cued item **(Cued before)**	32	G
	🟢		🟢		Uncued, previously uncued **(Uncued before)**	32	G

(caption on next page)

Fig. 1. Methods and results of Experiment 1. **(A)** Schematic depiction of a trial in Experiment 1. Participants were instructed to memorize two sequentially presented colors. A *retro*-cue indicated whether the first or second memory item would be tested next ("1″ or "2"). During the retention interval, participants performed a b-CFS task (see Panel B), in which they reported on which side of fixation (left or right) they first perceived a target to appear. In the subsequent memory test, participants selected the color of the cued memory item on the color wheel. Following this, a second *retro*-cue instructed whether the first or second memory item would be tested next (this could be the same item as in the first delay, or the other item). Subsequently, participants completed the second b-CFS task, and the second memory test (both identical to the first). In this example, memory item 1 (green) is cued for the first memory test and is also used as a VWM-matching target in the first b-CFS task; then memory item 2 (red) is cued for the second memory test and is also used as a VWM-matching target in the second b-CFS task. **(B)** Schematic depiction of the b-CFS tasks: The dominant eye was presented with a mask, while the non-dominant eye was presented with two targets that gradually ramped up from zero to full intensity. Participants were required to report on which side of fixation (left or right) they first saw a target appear. **(C)** Visualization of the different b-CFS target conditions. One of the two b-CFS targets was always one of the two memory items (i.e., it either matched the cued memory item or the uncued memory item), whereas the other target was always unrelated to the memory task (or: neutral). **(D)** Selection of stimulus colors. On each trial, four equally (i.e., 90 degrees) spaced colors were chosen from the color wheel. Two of those were randomly selected as memory items (here: green and red), while the other two served as neutral items for the two separate b-CFS tasks (here blue in the first b-CFS task, and purple in second b-CFS task). **(E)** The main result of Experiment 1, separated by Delay (delay 1, delay 2) and Target-Memory Match (match with cued, match with uncued) on the X-axis. The Y-axis depicts the percentage of trials in which the VWM-matching b-CFS target was perceived before the accompanying neutral b-CFS target. Values above 50 % (horizontal dashed line) reflect that the VWM-matching b-CFS target was reported more often than the neutral b-CFS target. Each dot represents one participant's mean response preference. Error bars in each plot illustrate the standard deviation across participants (grey vertical lines). The horizontal gray lines in each plot represent the mean value of the whole participants. Asterisks reflect that VWM-matching items were reported to appear first more often than neutral items. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$. **(F)** Visualization of de-prioritization and re-prioritization. Specifically, the two left-most violin plots are identical to those of Panel E, but the right plot selectively depicts trials in which the currently cued item (in the second delay) was not cued in the first delay. Differences between conditions show to what extent de-prioritization and re-prioritization of memory items influence conscious access of matching b-CFS targets. **(G)** This panel displays the right-most data from Panel E (trials in the second delay, where the VWM-matching b-CFS target was the of the uncued color), but now separated by whether this uncued item was cued or uncued in the first delay. **(H)** Overview of experimental conditions in Experiment 1. Each row represents a specific condition, starting with the initial memory items on the left (here as an example, the items are red and green), their prioritization states during Delay 1 and Delay 2, and possible target stimuli in the perceptual (b-CFS) task presented during each delay. The table also describes the condition labels (depending on the relation between a b-CFS target, a memory item, and the state of the memory item), and the corresponding theoretical interpretation. The second-to-last column represents the number of trials for each condition. The final column indicates the corresponding figure panels for each condition. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

while the other target always consisted of a neutral item that was unrelated to the memory task (see Fig. 1C, and 1D). The experimental design for the b-CFS task comprised two within-subject factors of interest: 2 Target-Memory Match conditions (match with cued, match with uncued) × 2 Delay conditions (delay1, delay2), resulting in a total of 64 trials in each of these four main conditions. For a subset of analyses, these conditions were subdivided into the "match with re-prioritized" condition (32 trials), and the "cued before" and "uncued before" conditions (both 32 trials; see Fig. 1H). Within-subject factors of non-interest included the first memory cue ("1" or "2"), the second memory cue ("1" or "2"), the location of the VWM-matching b-CFS target in the first delay (left or right of fixation), and the location of the VWM-matching b-CFS target in the second delay (left or right of fixation). All conditions described above were fully counterbalanced within participants and presented in randomized order.

2.1.5. Stimuli

To enhance binocular fusion of the complementary images, identical Brownian noise frames were simultaneously presented to both eyes, delineating the gray presentation area where all stimuli were displayed, with a diameter of 11.4 degrees of visual angle (dva). Throughout the experiment, a black fixation bullseye (0.28 dva) and a white fixation bullseye (0.17 dva) were consistently displayed at the center of the presentation areas.

The colored stimuli (b-CFS targets and memory items) were derived from a circular isoluminant HSV color space. The hue values spanned from 1° to 360° within this HSV space, with a fixed brightness of 0.8 and a fixed saturation value of 0.7. On each trial, a set of four colors were chosen randomly, each spaced by 90 degrees on the color wheel (see Fig. 1D). Two of those four colors were randomly assigned as colors for the memory task, whereas the remaining two colors were used as neutral (i.e., memory-unrelated) colors for the two consecutive b-CFS tasks within a trial (Fig. 1D). The colored circles (used in the memory task and in the b-CFS task) had a diameter of 2 dva. The memory items were presented at fixation. In the b-CFS task, the memory circles (i.e., target stimuli) were presented at a fixed eccentricity of 3.34 dva to the left and right of fixation. The color wheel used for the memory reproduction task (and the end of each retention interval) had an outer circle diameter of 11.4 dva and an inner circle diameter of 8.58 dva and was randomly oriented on each memory test.

150 masks were generated for use in the b-CFS task, each consisting of black and white circles. The size of the circles in the masks matched those of the colored b-CFS target items, thus increasing suppression depth. In each trial, separate masks (4.9 dva * 11.4 dva) were simultaneously displayed at the left and right sides of fixation, with a refresh rate of 10 Hz.

2.1.6. Data analyses

We excluded b-CFS task data based on the following criteria: (1) trials in which no target was presented (i.e., catch trials, participants reported no targets in 96.1 %, $SD = 6.6$ %); (2) trials in which targets were presented but participants reported no targets (2.9 %, $SD = 4.45$ %); (3) trials in which no response was provided in b-CFS task; (4) trials with memory recall errors beyond 45 degrees on the color wheel (indicating a category recall error) in the first (7.66 %, *SD* = 5.51 %) or second memory recall tasks (10.46 %, *SD* = 7.35 %).

We computed the percentage of trials in which the VWM-matching item was reported to appear before the neutral item, separately for each b-CFS trial type (match with cued memory item, match with uncued memory item). These percentages reflect the influence of VWM content on conscious access; for VWM items in a prioritized state (cued memory items) as well as in a non-prioritized state (uncued memory items in delay 1). A Greenhouse-Geisser correction was applied in case of sphericity violations and Bonferroni correction was used to adjust the P-values in ANOVA. In all post-hoc tests, we primarily use parametric tests. However, if the normality assumptions are violated, we opt for non-parametric alternatives (i.e., Wilcoxon signed-rank test).

The current experimental paradigm was optimized for analyzing response choice data. We did not report response time (RT) as a dependent variable because, firstly, the number of trials differ between VWM-matching and neutral conditions due to participants' response choices. This imbalance could introduce additional variance and complicate the interpretation of RT results. Secondly, using two targets, the breakthrough of one target inherently accelerates detection of the other target (which is presented to the same eye), thereby attenuating RT differences between memory-match conditions. Accordingly, RTs did not differ significantly between 'match with cued' and 'match with uncued' conditions, when using two targets per eye in our earlier work (Gayet et al., 2016). In contrast, these conditions did differ substantially using the response choice metric, which we also employ in the current study.

We utilized circular standard deviation (Mardia & Jupp, 2009) to quantify participants' memory performance. To compute the circular standard deviation, we initially adjusted memory errors (the difference between the angle of the presented memory item and the angle of participants' response) to 0 to 360. These errors were treated as points on a unit circle, and we computed the mean resultant length R of the unit vectors corresponding to all errors. The circular standard deviation is subsequently obtained through $\sqrt{-2^{*}\log R}$. The higher the value of circular standard deviation, the poorer the memory performance.

A permutation test was conducted to determine whether participants' memory performance exceeded chance levels. For each participant, we randomly shuffled the associations between the reported angle (response degree) and the true target angle (present degree) within each condition, and the circular standard deviation was calculated for each permutation. These values were then averaged across participants, and the process was repeated 10,000 times to generate a distribution of circular standard deviations for each condition. We reported the mean and standard deviation of the permutation-derived distribution for each condition, and the actual circular standard deviation for each condition was compared to the permuted distribution by converting it into a Z-score. Z-scores exceeding 1.96 indicates that participants successfully maintained the item in memory, as it reflects a deviation from the permuted (null) distribution with a probability (i.e., p-value) below the standard alpha threshold of 0.05.

2.2. Results

2.2.1. Memory performance

To evaluate participants' memory performance in Experiment 1, we assessed their circular standard deviation during the first memory test, and during the second memory test. For the second memory test, we separately analyzed memory recall performance for items that were also cued for the first memory test (repeat cue) and items that were not cued for the first memory test (switch cue). The permutation results showed that participants successfully maintained both the prioritized items (delay 1: *Mean* = 0.48, *SD* = 0.11; z = 50.68; repeat cue delay 2: *Mean* = 0.45, *SD* = 0.15, z = 36.42) and the non-prioritized items (switch cue delay 2: *Mean* = 0.57, *SD* = 0.14, z = 31.32) in memory. Moreover, the circular standard deviation was lower after a repeat cue compared to a switch cue ($t(23) = 3.69$, $p = 0.001$), indicating that storing items in (or retrieving items from) a less prioritized state causes a loss in memory precision (Fig. 4A).

2.2.2. Effects of cued and uncued memory items on visual awareness

The overall mean RTs in the b-CFS task was 1552 ms (*SD* = 329 ms). For delay 1, in the match with cued condition, the mean RTs to select stimuli matching the cued items saw first was 1518 ms (*SD* = 341 ms), while for memory-unrelated items it was 1502 ms (*SD* = 342 ms). In the match with uncued condition, the mean RTs to select stimuli matching the uncued items saw first was 1524 ms (*SD* = 313 ms), while for memory-unrelated items it was 1495 ms (*SD* = 317 ms). For delay 2, in the match with cued condition, the mean RTs to select stimuli matching the cued items saw first was 1597 ms (*SD* = 368 ms), while for memory-unrelated items it was 1538 ms (*SD* = 342 ms). In the match with uncued condition, the mean RTs to select stimuli matching the uncued items saw first was 1600 ms (*SD* = 394 ms), while for memory-unrelated items it was 1561 ms (*SD* = 400 ms).

We set out to investigate whether there was a difference between cued and uncued memory items in facilitating conscious access of matching visual input. The percentage of VWM-matching (relative to VWM-unrelated) items perceived first was entered in a repeated-measures ANOVA with the within-subjects factors Delay (delay 1, delay 2) and Target-Memory Match (match with cued, match with uncued). There was a main effect of Target-Memory Match ($F(1, 23) = 10.39$, $p = 0.004$, $\eta_p^2 = 0.31$). Neither the main effect of Delay ($F(1, 23) = 0.63$, $p = 0.434$, $\eta_p^2 = 0.03$) nor the interaction between Delay and Target-Memory Match ($F(1, 23) = 1.66$, $p = 0.211$, $\eta_p^2 = 0.07$) was significant (Fig. 1E). The results show that cued memory items have a greater effect in facilitating visual awareness of matching input, compared to uncued memory items, and that this is independent of delays (i.e., first or second).

Next, we conducted a one-sample test to determine whether memory items in different priority states influence conscious access of matching visual input (Fig. 1E). In the first delay, the VWM-matching item was reported to be perceived before the neutral item; this was the case for b-CFS targets matching the cued item ($W = 0$, $p < 0.001$) as well as the uncued item ($t(23) = 2.68$, $p = 0.013$, *Cohen's d* = 1.12). This was also the case in the second delay, for b-CFS targets matching the cued item ($t(23) = 4.12$, $p < 0.001$, *Cohen's d* = 1.72) and surprisingly also for b-CFS targets matching the uncued item ($W = 42.5$, $p = 0.005$). The results show that both cued and uncued memory items can facilitate conscious access of VWM-matching visual input, and this was the case in both delays.

2.2.3. *The influence of de-prioritizing and re-prioritizing memory items on visual awareness*

During the first delay, the cued memory item was regarded as the prioritized memory item, as compared to the uncued item which was referred to as the non-prioritized memory item, because it was not relevant for the upcoming memory task but needed to be kept in memory for the potential second memory test. A paired *t*-test was conducted to test whether prioritized memory items and non-prioritized memory items had a differential influence on conscious access (Fig. 1F). The result showed that the VWM-matching item was reported to be perceived before neutral items more often when it matched the cued (prioritized) items compared to the uncued (non-prioritized) memory items ($t(23) = 3.67$, $p = 0.001$, *Cohen's* $d = 1.53$). This indicates that the non-prioritized memory item had less influence on conscious access than the prioritized memory item, further suggesting that participants successfully de-prioritized the uncued item following the first cue.

Next, we asked whether re-prioritizing memory items that were previously not prioritized would, correspondingly, increase the influence of VWM on conscious access. To this end, we tested to what extent items that were not cued in delay 1 but were cued in delay 2 would influence responses in the b-CFS task (Fig. 1F). The result showed that b-CFS targets matching these re-prioritized items were perceived first more often than neutral items ($t(23) = 3.12$, $p = 0.005$, *Cohen's* $d = 1.3$), and more often than b-CFS targets matching this same memory item when it was uncued in delay 1 ($t(23) = 2.18$, $p = 0.04$, *Cohen's* $d = 0.91$). Together, these results show that participants can flexibly switch the priority state of memory items, which in turn determines the influence of the memory item on conscious access of concurrent visual input.

2.2.4. *Persistent influence of uncued items on visual awareness in delay 2*

Surprisingly, we observed that uncued items in delay 2 still exerted an influence on conscious access, even though these items were no longer task-relevant (i.e., they would never be asked about in a memory recall test). This result stands in stark contrast with that of similar tasks using a single delay, in which the uncued (i.e., discarded) item does not influence responses in the b-CFS task (Gayet et al., 2013; 2017). To further scrutinize this surprising observation, we separately analyzed these trials (in which the target matches the uncued memory item in delay 2) into two conditions (Fig. 1H): one in which the uncued memory item was also uncued in delay 1 (hence this memory item had never been in a prioritized state before) and one in which the uncued memory item was cued in delay 1 (and, hence, had been de-prioritized in delay 2). This analysis was motivated by the idea that once an item has been in a prioritized memory state before (i.e., in delay 1), it may become resistant to decay or might be effortful to discard (van Moorselaar et al., 2015b; Rerko & Oberauer, 2013), thus continuously influencing early visual processing. In line with this possibility, we found that b-CFS targets matching the uncued item in the second delay, were perceived first more often than chance when it was also cued during the first delay ($t(23) = 3.73$, $p = 0.001$, *Cohen's* $d = 1.55$), but not if it was uncued during the first delay ($t(23) = 0.77$, $p = 0.452$, *Cohen's* $d = 0.32$). There was no significant difference between these two conditions ($t(23) = 2.05$, $p = 0.052$, Cohen's $d = 0.86$). These exploratory results (Fig. 1G) show that even memory items that are no longer relevant may influence visual awareness, but only when they were previously prioritized (i.e., cued).

2.2.5. *Correlating working memory recall errors and b-CFS targets perception*

We replicated earlier work in showing that VWM-matching b-CFS targets were prioritized for conscious access. This led us to ask whether stronger VWM representations would also induce a stronger perceptual bias in the b-CFS task. To this end, we conducted a correlation between recall errors on the memory test (i.e., cued items) and the likelihood that the VWM-matching b-CFS target was perceived first (Fig. 4B). We computed within-participant correlations across trials and observed a negative correlation between recall errors and perceptual reports in the b-CFS task (mean r across participants = -0.043, $t(23) = 2.4$, $p = 0.026$, *Cohen's* $d = 1$). This shows that the lower the recall error of a memory report, the more likely participants were to perceive the VWM-matching b-CFS target first.

2.3. *Discussion*

The results of Experiment 1 showed that participants were more likely to perceive a VWM-matching target before perceiving a target unrelated to the memory task. This effect dropped nearly to baseline when memory items were deprioritized, and nearly returned to initial levels when memory items were then reprioritized again. These results indicate that participants can flexibly de-prioritize and re-prioritize items in visual working memory. This perceptual bias toward VWM-matching items was more pronounced for b-CFS targets matching prioritized memory items compared to those matching non-prioritized memory items. Moreover, b-CFS targets matching the non-prioritized (i.e., uncued) memory items were also perceived before the VWM-unrelated items. These results suggest that both prioritized memory items and non-prioritized memory items can impact early visual processing, as measured through reports of conscious access, with prioritized memory items influencing early visual processing more strongly than non-prioritized memory items. In Experiment 2, our aim is to investigate whether this pattern of findings generalizes to another aspect of early visual processing: the allocation of spatial attention.

3. Experiment 2

In Experiment 2, we combined an attentional capture task with a double serial *retro*-cuing task to investigate whether memory items in different states (differentially) influence the capture of attention toward VWM-matching stimuli. In the attentional capture task participants search for a target, while a colored distractor item is presented. The distractor either matches one of the memory items (cued or uncued) or has a color that is unrelated to the memory task. If memory items (in different states) indeed guide attention toward VWM-matching distractor stimuli, this should impair target-search performance. Consequently, we anticipate that RTs in response to a target will be prolonged when the distractor matches items in memory, compared to when the distractor is unrelated to memory items. Crucially, we again test how this depends on the state of the memory content (prioritized versus non-prioritized).

3.1. Method

3.1.1. Participants

Experiment 2 comprised an identical number of participants (twenty-four participants; *Mean* = 23.7, *SD* = 4.39; 7 males) as Experiment 1 to maintain the same statistical power.

3.1.2. Apparatus and stimuli

The setup was identical to Experiment 1 except the stereoscope was removed and all stimuli was presented in the center area of the screen with a gray background. All color stimuli were selected from the same color wheel as in Experiment 1.

3.1.3. Procedure

The procedure was similar to that of Experiment 1, except that the b-CFS task performed during the memory delays was replaced by an attentional capture task. The attentional capture task (Fig. 2A) consisted of one white diamond-shaped target (2.9 dva*2.9 dva), one singleton (colored) disk-shaped distractor, and six white disk-shaped nontargets (radius 1.4 dva), each containing a horizontal or

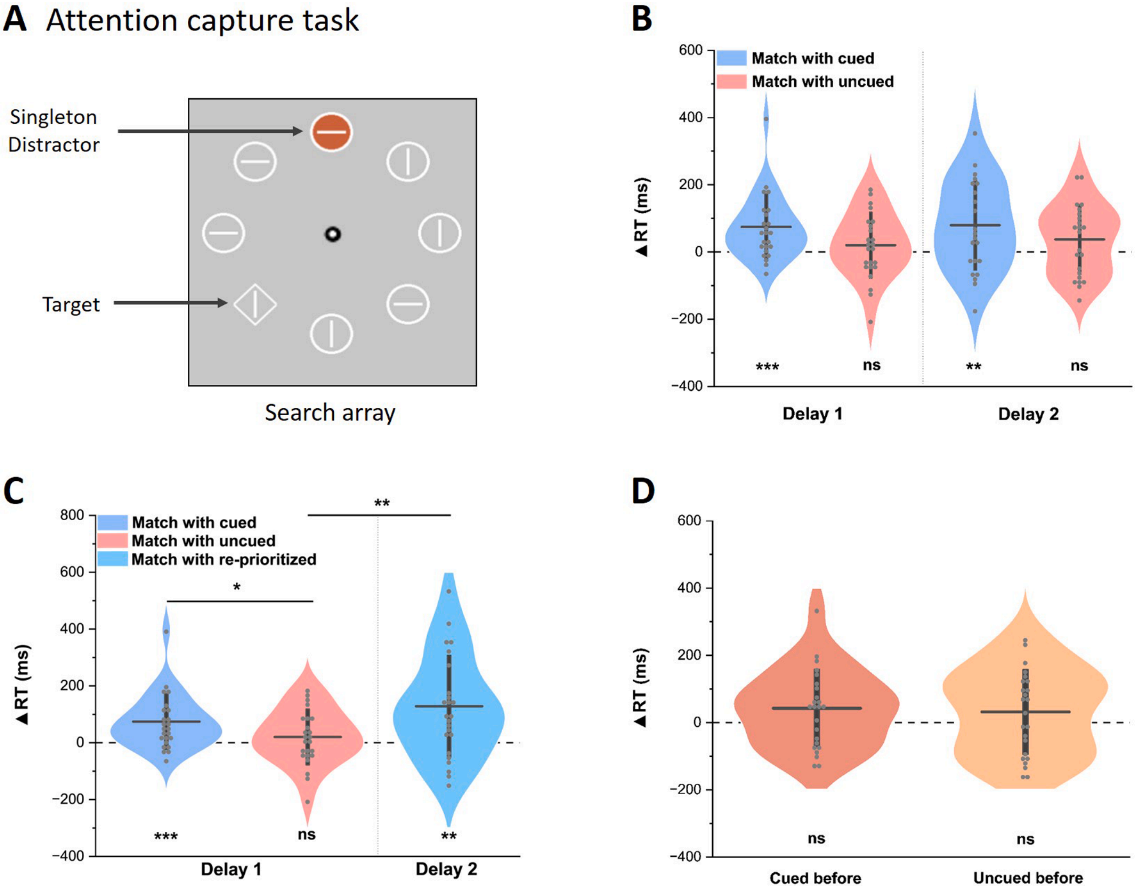


Fig. 2. Methods and Results of Experiment 2. **(A)** Schematic depiction of the attentional capture task: the search target (a vertical or horizontal bar) lies within the diamond. The color-singleton distractors either match with one of the memory items (the cued or uncued memory item) or are of a color that is unrelated (neutral) to the memory task. **(B)** The main result of Experiment 2. A positive value indicates that the RTs for searching a target were longer when the distractor matched the memory item compared to when the distractor was a neutral item. **(C)** Visualization of de-prioritization and re-prioritization. **(D)** Akin to Fig. 1G, above, this panel displays the right-most data from Panel B (trials in the second delay, where the singleton distractor matched with uncued memory stimuli), but now separated by whether this currently match with uncued stimuli in the search display was cued in the first delay or not. *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

vertical white line segment at their center (0.96 dva in length). All stimuli were equally interspaced on an imaginary circle (radius 3.8 dva) around the central fixation dot. The locations of the target and singleton distractor were randomly selected from the 8 locations, with the restriction that the singleton distractor was never presented adjacent to the target. Participants were instructed to indicate whether the line segment in the target was vertical (by pressing the right arrow) or horizontal (by pressing the left arrow) as quickly and accurately as possible.

In Experiment 2, participants took part in three consecutive practice sessions (first practicing the attentional capture task only, then practicing the memory task only, and finally practicing the combined attentional capture and memory dual task) to get acquainted with the different parts of the experimental procedures progressively. The main experiment comprised 144 trials, divided into 8 blocks.

3.1.4. Experimental design

In the attentional capture task, there were three types of singleton distractor conditions: the distractor either matched the cued memory item, the uncued memory item, or was of a color that was unrelated to the memory task (neutral items). The dependent variable was the difference response times (▲RTs) to the target between the VWM-matching distractor condition and the corresponding memory-unrelated distractor condition. Positive difference scores would demonstrate that attention was drawn toward memory matching stimuli. The experimental design for the attentional capture task comprised two within-subject factors of interest: 2 Distractor-Memory Match conditions (match with cued, match with uncued) × 2 Delay conditions (delay 1, delay 2), resulting in a total of 48 trials in each of these four main conditions. For a subset of analyses, these conditions were subdivided into the “match with re-prioritized” condition (24 trials), and the “cued before” and “uncued before” conditions (both 24 trials). All other conditions as described in Experiment 1 were fully counterbalanced within participants and presented in randomized order.

3.1.5. Data analysis

We excluded attentional capture task data based on the following four criteria: (1) incorrect target discrimination trials (delay 1: 2.78 %, $SD = 2.58$ %; delay 2: 2.95 %, $SD = 2.62$ %); (2) trials with RTs shorter than 200 ms and longer than 5,000 ms; (3) trials with RTs larger than 2.5 *SD* from the mean per participant; (4) trials with memory recall errors beyond 45 degrees on the color wheel in the first (9.06 %, $SD = 7.74$ %) or second (11.11 %, $SD = 8.65$ %) memory recall tasks.

3.2. Results

3.2.1. Memory performance

To evaluate participants’ memory performance in Experiment 2, a permutation test was performed on the circular standard deviation for the first memory test, and separately for repeat cued and switch cued memory items from the second memory test. The permutation results showed that participants successfully maintained both the prioritized item (delay 1: $Mean = 0.51$, $SD = 0.12$, $z = 51.41$; repeat cue delay 2: $Mean = 0.45$, $SD = 0.15$, $z = 38.19$) and the non-prioritized item (switch cue delay 2: $Mean = 0.56$, $SD = 0.15$, $z = 33.82$) in memory. Moreover, the circular standard deviation was lower after a repeat cue compared to a switch cue ($t(23) = 3.09$, $p = 0.006$), indicating that storing items in (or retrieving items from) a less prioritized state causes a loss in memory precision (Fig. 4A).

3.2.2. Effects of cued and uncued memory items on attention allocation

We asked whether there was a difference between cued and uncued memory items in attention allocation toward VWM-matching stimuli (Fig. 2 B). Participants’ mean ▲RTs were entered in a repeated-measures ANOVA with the within-subjects factors Distractor-Memory Match conditions (match with cued, match with uncued) and Delay conditions (delay1, delay2). There was a main effect of Distractor-Memory Match ($F(1, 23) = 8.73$, $p = 0.007$, $\eta_p^2 = 0.28$). Neither the main effect of Delay ($F(1, 23) = 0.42$, $p = 0.525$, $\eta_p^2 = 0.018$) nor the interaction between Delay and Distractor-Memory Match ($F(1, 23) = 0.244$, $p = 0.626$, $\eta_p^2 = 0.01$) was significant. These results indicated that cued memory items had a greater impact on attention allocation than uncued memory items, and this was independent of delays.

Next, we conducted a one-sample test against chance to determine whether memory items in different priority states could allocate attention to VWM-matching stimuli (Fig. 2 B). The results revealed that mean ▲RTs were higher than chance level in the match with cued condition, for the first delay ($W = 31$, $p < 0.001$) and the second delay ($t(23) = 2.91$, $p = 0.008$, *Cohen’s* $d = 1.22$). However, this was not the case for the match with uncued condition, in neither the first delay ($t(23) = 1.01$, $p = 0.322$, *Cohen’s* $d = 0.42$) nor the second delay ($t(23) = 1.76$, $p = 0.091$, *Cohen’s* $d = 0.74$). These results show that only cued memory items can effectively affect attention allocation, and this was the case in both delays.

3.2.3. The influence of de-prioritizing and re-prioritizing memory items on attention allocation

A paired *t*-test was conducted within the first delay to test whether prioritized memory items and non-prioritized memory items had a differential influence on attention allocation (Fig. 2C). We found that the mean ▲RTs were significantly higher in the match with cued (prioritized) condition compared to the uncued (non-prioritized) condition ($t(23) = 2.6$, $p = 0.016$, *Cohen’s* $d = 1.09$). This indicates that the non-prioritized memory item had less influence on attention allocation than the prioritized memory item, further suggesting that participants successfully deprioritized the uncued item following the first cue.

Next, we asked whether re-prioritizing memory items that were previously not prioritized would, correspondingly, increase the influence of VWM on attention allocation. To this end, we tested to what extent items that were not cued in delay 1 but were cued in delay 2 would influence RTs in the attentional capture task again (Fig. 2C). The results showed that the mean ▲RTs were higher than chance level in the match with re-prioritized condition ($t(23) = 3.5$, $p = 0.002$, *Cohen's d* = 1.46) and higher than match with uncued condition in delay 1 ($t(23) = 2.91$, $p = 0.008$, *Cohen's d* = 1.21).Taken together, these results suggest that participants can flexibly switch the priority state of memory items, and that the priority state of the memory item determines its influence on attention allocation.

3.2.4. No influence of uncued items on attention allocation in delay 2

We did not observe that uncued items in delay 2 exerted an influence on allocating attention to VWM-matching stimuli, which contrasted with Experiment 1, where we did find an effect of uncued memory items in delay 2 on conscious access of VWM-matching stimuli. For consistency with Experiment 1, we tested this separately for uncued items (in delay 2) that were cued in delay 1 versus those that were not cued in delay 1 (Fig. 2D).We found that the mean ▲RTs for matched the uncued items was not higher than chance level, regardless of whether they were cued in delay 1 ($t(23) = 1.79$, $p = 0.087$, *Cohen's d* = 0.75) or not ($t(23) = 1.23$, $p = 0.232$, *Cohen's d* = 0.51). There was no significant difference between these two conditions ($t(23) = 0.42$, $p = 0.677$, *Cohen's d* = 0.18). Again, these results provide no evidence that uncued memory items influence attention allocation.

3.2.5. Correlating working memory recall errors and attention allocation effect

We conducted a within-participant correlation analysis between the recall errors on the memory test (i.e., cued items) and the mean RTs when singleton distractors matched with cued memory items (Fig. 4B). These two variables were not correlated (mean r across participants = -0.0003, $t(23) = -0.01$, $p = 0.992$, *Cohen's d* = 0.004), indicating that memory performance does not predict attention allocation to VWM-matching stimuli.

3.3. Discussion

Akin to the findings of Experiment 1, Experiment 2 showed that the influence of memory content on attentional capture dropped nearly to baseline when memory items were deprioritized, when memory items were then re-prioritized again in delay 2, their influence on attentional capture was almost fully reinstated (i.e., similar to that of prioritized items in delay 1). This shows that altering the priority state of VWM contents also alters the influence they exert on the allocation of attention toward concurrent visual input. Moreover, we found that stimuli matching prioritized memory items captured attention more strongly than stimuli matching non-prioritized memory items. In contrast to Experiment 1, however, we found that only memory items in a prioritized state influenced early visual processing, as measured through the allocation of spatial attention. There was no difference in attentional capture between stimuli matching non-prioritized memory items and stimuli that were unrelated to the memory task.

Considering that there are several differences between the perceptual tasks used in Experiments 1 and 2, it is unclear whether the discrepant findings (whether non-prioritized memory items exert an influence on early visual processing or not) can be explained by the different processes that they intend to measure (i.e., conscious access and attention allocation, respectively), or by task differences that are not related to these processes per se. One such possible task difference is that, in Experiment 1, the b-CFS task comprises only two items in the search array (one that matches a memory item and one that does not), while the attentional capture task in Experiment 2 includes eight items (with the VWM-matching and memory-unrelated singleton distractors appearing on different trials). Possibly, the difference in perceptual load between tasks might also affect the allocation of attentional resources leading to a reduction in the processing of distractors in Experiment 2 (for a review, see Lavie, 2005). Another possible factor is that, in the attentional capture paradigm, the memory items matched with the distractors (stimuli that should be avoided by the participant), whereas in the b-CFS task the memory items matched with the targets (stimuli that the participants should interact with). Previous studies found that salient distractors in the search display can be (at least partly) suppressed through top-down mechanisms (Gasper & McDonald, 2014; Jannati et al., 2013). Consequently, the (relatively weaker) influence of non-prioritized memory items on early visual processing might be dampened through such a top-down distractor suppression mechanism.

Both of these factors could explain why we did not find an effect of non-prioritized-memory items on attention allocation toward VWM-matching stimuli in Experiment 2. In Experiment 3, we introduced a new visual search task that closely resembles the b-CFS task in terms of the two factors described above, while measuring the allocation of attention (Soto et al., 2008). In this task, the search target is either located within a VWM-matching item or within a juxtaposed memory-unrelated item. Here, we ask whether targets are reported faster when presented within a VWM-matching stimulus compared to a memory mismatching stimulus. Critically, we again tested whether the influence of VWM content on early visual processing depends on the priority state of the memory item.

4. Experiment 3

We employed a visual search task to examine whether different priority states of memory items could influence the allocation of spatial attention, by allocating attention toward VWM-matching stimuli. If VWM content drives the allocation of attention toward VWM-matching stimuli, RTs should be shorter when targets are presented within VWM-matching stimuli compared to memory-unrelated items. This was then separately tested for prioritized and non-prioritized items in delays 1 and 2.

4.1. Method

4.1.1. Participants

In Experiment 3, we recruited twenty-four participants to match the statistical power of the two previous experiments (*Mean* =

23.4, *SD* = 3.04; 7 males). Three of these participants also participated in Experiment 1, and one in Experiment 2. One participant was replaced because their target discrimination accuracy in the visual search task did not surpass chance level (48.6 %).

4.1.2. *Procedure and design*

The procedure of Experiment 3 closely mirrored that of Experiment 2, except that the attentional capture task was replaced with a visual search task. In this visual search task (Fig. 3A), two colored circles (radius 1.4 dva) were presented at a fixed eccentricity of 3.8 dva to the left and right of fixation. Both colored circles featured a white line at its center (0.96 dva in length), one of which was tilted (25° clockwise or counterclockwise from the vertical), while the other was vertical. The search target was the tilted line, which was randomly presented in the left or right circle, and participants were instructed to indicate as quickly and accurately as possible whether the line was tilted counterclockwise (by pressing the left arrow key) or clockwise (by pressing the right arrow key). Participants also performed three separate practice sessions to get acquainted with the experimental (dual) task progressively, akin to the approach of Experiments 1 and 2. The main experiment comprised 144 trials, divided into 8 blocks.

In the visual search task, the circle surrounding the search target could be of three different color conditions: the color either matched the cued memory item or the uncued memory item, or it was of a color that was unrelated to the memory task (i.e., neutral). The non-target item in the search task (a vertical line) was always surrounded by a neutral color, but was never the same color as the one surrounding the search target. We used the difference in response time (▲RTs) between the VWM-matching condition and the corresponding neutral condition as the dependent variable, allowing for a direct comparison with the outcome metrics of Experiments 1 and 2. Positive values indicate that attention is allocated toward VWM-matching stimuli. The experimental design for the visual search task comprised two within-subject factors of interest: 2 Target-Memory Match conditions (match with cued, match with uncued) × 2 Delay conditions (delay 1, delay 2), resulting in a total of 48 trials in each of these four main conditions. For a subset of analyses, these conditions were subdivided into the "match with re-prioritized" condition (24 trials), and the "cued before" and

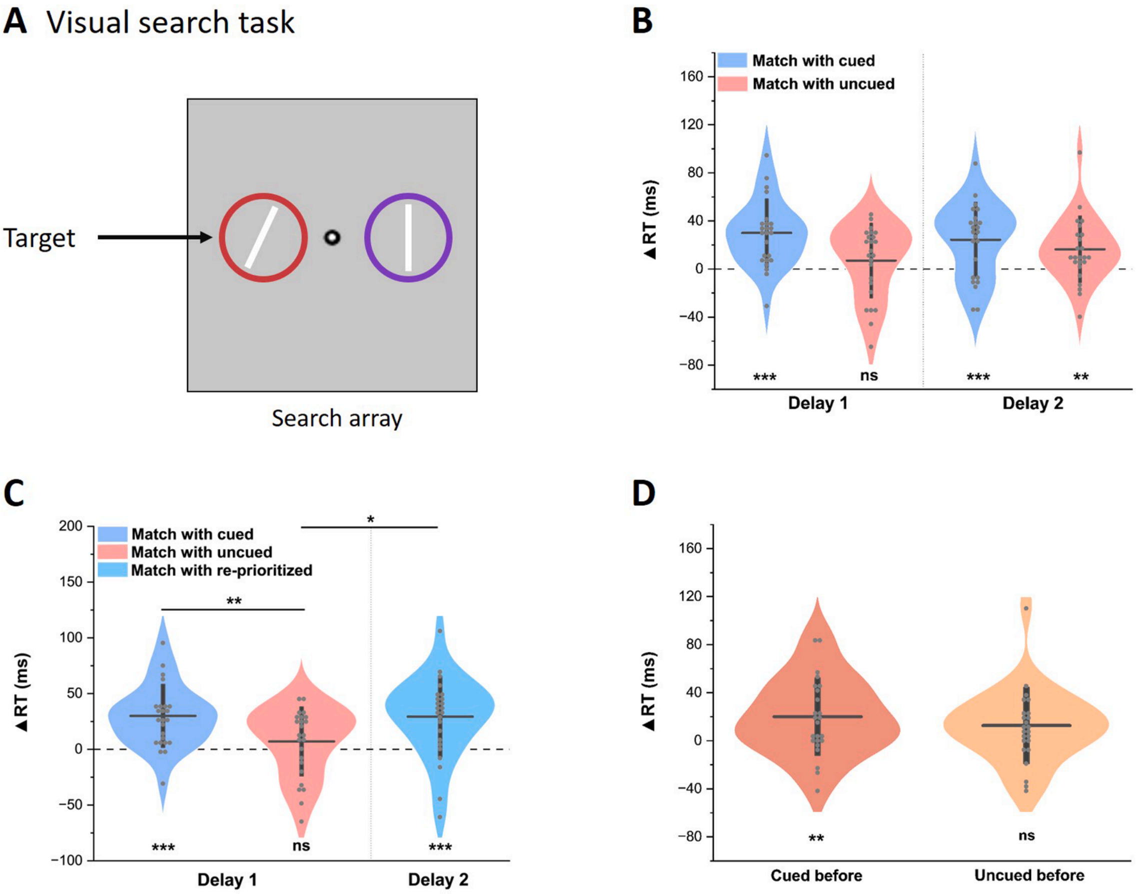


Fig. 3. Methods and Results of Experiment 3. **(A)** Schematic depiction of the visual search task: the search target is the tilted line, and participants were tasked to report whether it was tilted clockwise or counterclockwise from the vertical midline. **(B)** The main results of Experiment 3. A positive value indicates that the RTs to targets were faster when presented within a VWM-matching color than when presented within a circle of neutral color. **(C)** Visualization of de-prioritization and re-prioritization. **(D)** Akin to Fig. 1G, above, this panel displays the right-most data from Panel B, but now separated by whether this currently match with uncued stimuli in the search display was cued in the first delay or not. $^{*}p \leq 0.05$, $^{**}p \leq 0.01$, $^{***}p \leq 0.001$.

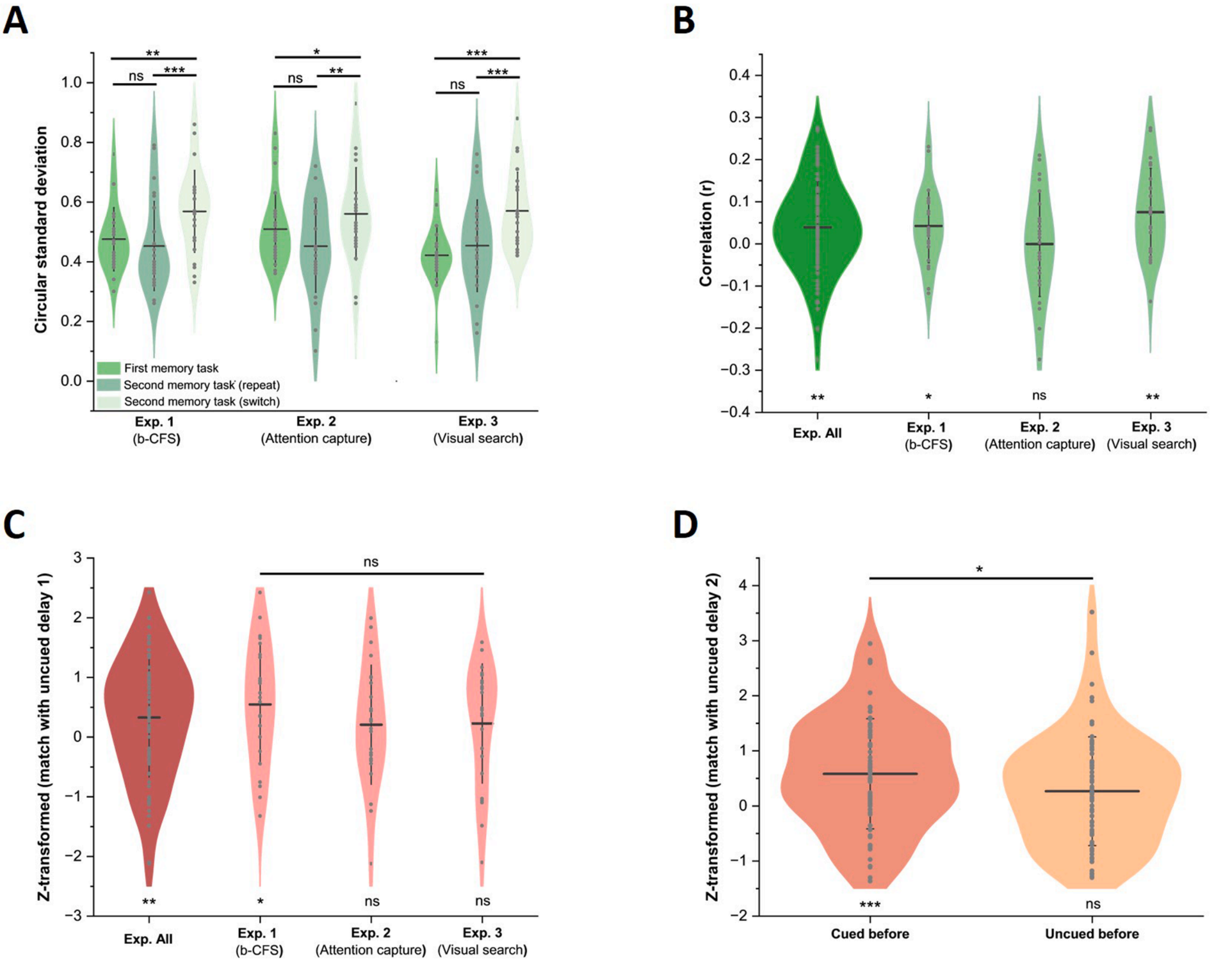


Fig. 4. (A) Memory recall error (circular standard deviation) in all experiments across three conditions. Horizontal lines represent the mean of observed mean circular standard deviation for each condition. A higher value of the circular standard deviation indicates lower memory performance. (B) Correlation between recall errors and perceptual bias, pooled across experiments (left) and separately for all three experiments. **(C)** Testing for an effect of non-prioritized memory items (in delay 1) on early visual processing, across (left) and between experiments, based on standardized (z-transformed) data. **(D)** Testing for an effect of irrelevant memory items (i.e., non-prioritized memory items in delay 2) on early visual processing across experiments, separately for items that were prioritized in delay 1, and items that were non-prioritized in delay 1. $^{*}p \le 0.05$, $^{**}p \le 0.01$, $^{***}p \le 0.001$.

"uncued before" conditions (both 24 trials). All other conditions as described in Experiment 1 were fully counterbalanced within participants and presented in randomized order.

4.1.3. *Data analysis*

We excluded visual search task data based on the following criteria: (1) incorrect target discrimination trials (delay 1: 1.62 %, *SD* = 1.47 %; delay 2: 1.68 %, *SD* = 1.68 %); (2) trials with RTs shorter than 200 ms and longer than 5,000 ms; (3) trials with RTs larger than 2.5 *SD* from the mean per participant; (4) trials with memory recall errors beyond 45 degrees on the color wheel in the first (7.29 %, *SD* = 5.15 %) or second (10.08 %, *SD* = 6.4 %) memory recall tasks.

4.2. *Results*

4.2.1. *Memory performance*

To evaluate participants' memory performance in Experiment 3, a permutation test was performed on the circular standard deviation for the first memory test, and separately for repeat cued and switch cued memory items from the second memory test. The results showed that participants successfully maintained both the prioritized item (delay 1: *Mean* = 0.42, *SD* = 0.10, $z = 53.8$; repeat cue delay 2: *Mean* = 0.45, *SD* = 0.15, $z = 36.38$) and the non-prioritized item (switch cue delay 2: *Mean* = 0.57, *SD* = 0.13, $z = 31.28$) in memory. Moreover, the circular standard deviation was lower after a repeat cue compared to a switch cue ($t(23) = 4.31$, $p < 0.001$), indicating that storing items in a less prioritized state causes a loss in memory precision (Fig. 4A).

4.2.2. *Effects of cued and uncued memory items on attention allocation*

We asked whether there was a difference between cued and uncued memory items in allocating attention toward VWM-matching stimuli (Fig. 3B). Participants' mean ▲RTs were entered in a repeated-measures ANOVA with the within-subjects factors Target-Memory Match conditions (match with cued, match with uncued) and Delay conditions (delay 1, delay 2). There was a main effect of Target-Memory Match ($F(1, 23) = 7.05$, $p = 0.014$, $\eta_p^2 = 0.24$). Neither the main effect of Delay ($F(1, 23) = 0.07$, $p = 0.791$, $\eta_p^2 = 0.003$) nor the interaction between Delay and Target-Memory Match ($F(1, 23) = 2.26$, $p = 0.146$, $\eta_p^2 = 0.089$) was significant. These results demonstrate that cued memory items had a greater impact on attention allocation than uncued memory items, irrespective of delay.

Next, we conducted a one-sample test against chance to determine whether memory items in different priority states could influence attention allocation to VWM-matching stimuli. The results revealed that mean ▲RTs were higher than chance level in the match with cued condition, for the first delay ($t(23) = 5.2$, $p < 0.001$, *Cohen's* $d = 2.17$) and the second delay ($t(23) = 3.83$, $p = 0.001$, *Cohen's* $d = 1.6$). Akin to Experiment 2, however, this was not the case for non-prioritized memory items (i.e., match with uncued condition) in the first delay ($t(23) = 1.12$, $p = 0.275$, *Cohen's* $d = 0.47$), while the effect was significant in the second delay ($t(23) = 2.93$, $p = 0.008$, *Cohen's* $d = 1.22$). These results showed that cued memory items and uncued memory items (but only in delay 2) can effectively influence attention allocation to VWM-matching stimuli.

4.2.3. *The influence of de-prioritizing and re-prioritizing memory items on attention allocation*

A paired *t*-test was conducted to test whether prioritized memory items and non-prioritized memory items had a differential influence on attention allocation in delay 1(Fig. 3C). We found that the mean ▲RTs were significantly higher when matched with the cued (prioritized) condition compared to the uncued (non-prioritized) condition. ($t(23) = 3.25$, $p = 0.003$, *Cohen's* $d = 1.36$). This indicates that the non-prioritized memory item had less influence on attention allocation than the prioritized memory item, further suggesting that participants successfully deprioritized the uncued item following the first cue.

Next, we asked whether re-prioritizing memory items could also influence VWM on attention allocation. To this end, we tested to what extent items that were not cued in delay 1 but were cued in delay 2 would influence searching RTs in visual search task (Fig. 3C). The results showed that the mean ▲RTs was higher than chance level in the match with re-prioritized condition ($t(23) = 3.96$, $p = 0.001$, *Cohen's* $d = 1.65$), and higher than match with the uncued condition in delay 1 ($t(23) = 2.21$, $p = 0.038$, *Cohen's* $d = 0.92$). Together, these results indicate that participants can flexibly switch the priority state of memory items, and that the priority state of the memory item determines its influence on attention allocation.

4.2.4. *Persistent influence of uncued items on attention allocation in delay 2*

Surprisingly, we observed that uncued items in delay 2 exerted an influence on attention allocation, thereby replicating the findings of Experiment 1. Following the same approach as before, we separated the data depending on whether the uncued item in delay 2 was cued during delay 1 or was also uncued during delay 1 (Fig. 3D). We found that the mean ▲RTs (in the match with uncued condition of delay 2) were higher than chance level when they were cued during delay 1 ($t\,(23) = 3.06$, $p = 0.006$, *Cohen's* $d = 1.27$), but not when they were uncued during delay 1 ($t(23) = 1.96$, $p = 0.062$, *Cohen's* $d = 0.82$). There was no significant difference between these two conditions ($t(23) = 1.14$, $p = 0.267$, Cohen's $d = 0.48$). The result showed that even items that are no longer relevant may influence attention allocation, but only when they were previously activated (i.e., cued).

4.2.5. *Correlating working memory recall errors and attention allocation effect*

We conducted a within-participant correlation analysis between the recall errors on the memory test (i.e., cued items) and the mean RTs when targets matched with cued memory items (Fig. 4B). These two variables were negative correlated (mean r across participants = -0.075, $t(23) = 3.53$, $p = 0.002$, Cohen's $d = 1.47$). This shows that the lower the recall error of a memory report, the more likely participants' attention was allocated to memory-match stimuli.

4.3. *Discussion*

The results of Experiment 3 confirmed and extended the findings of Experiments 1 and 2, namely that prioritized memory items influence attention allocation. This effect dropped nearly to baseline levels when memory items were deprioritized and nearly returned to initial levels when the memory items were subsequently reprioritized (similar to those associated with prioritized memory items). These findings further demonstrate that participants could flexibly deprioritize and reprioritize items in visual working memory. Furthermore, it was observed that prioritized memory items influenced early visual processing in terms of the allocation of spatial attention. Specifically, in a visual search task, RTs to a search target were faster when the targets were surrounded by a color that matched the prioritized memory item, compared to a color that was unrelated to the memory task. This was not the case, however, for non-prioritized memory items. Thus, mirroring the findings of Experiment 2, we again find no evidence that non-prioritized memory items can impact the attention allocation.

5. Comparison between experiments

In our study, we aimed to investigate how the priority state of items in VWM influences early visual processing. To this end, we used three widely employed perceptual tasks measure early visual processing. However, experiments 1, 2, and 3 yielded partially divergent results. In particular, non-prioritized memory items influenced conscious access (in a b-CFS task, Experiment 1), but we found no evidence that non-prioritized memory-items influenced the allocation of spatial attention (Experiments 2 and 3). This raises the question whether non-prioritized memory items differentially affect conscious access and the allocation of spatial attention, two different hallmarks of early visual processing. To test this, we next standardized (i.e., z-transformed) the data of each experiment to allow for direct comparisons between experiments. By doing so, we could test whether non-prioritized memory items differentially influence concurrent visual processing in the three experiments. In case the influence of non-prioritized memory items does not differ between experiments, combining the data allows us to establish whether a consistent influence of non-prioritized memory items is observed across all experiments (i.e., testing for a main effect of non-prioritized memory items on concurrent early visual processing).

5.1. *VWM performance*

Before addressing the main question, we first aimed to verify whether working memory performance was comparable across the three experiments. We assessed the circular standard deviation during the first memory test (WM1), and for repeat-cued and switch-cued memory items during the second (Fig. 4A). The circular standard deviation was analyzed using a repeated-measures ANOVA with the within-subjects factor Memory Task (first memory task, second memory task: repeat cue, second memory task 2: switch cue), and the between-subjects factor Experiment (Experiment 1, Experiment 2, Experiment 3). There was a main effect of Memory Task ($F(2, 46) = 27.86, p < 0.001, \eta_p^2 = 0.55$). To further investigate the differences in Memory task, a post-hoc test was conducted. The results showed that the circular standard deviation was lower in the first memory task compared to the second memory task: switch cue ($p < 0.001$). Additionally, the circular standard deviation was lower in the second memory task: repeat cue, compared to the second memory task: switch cue ($p < 0.001$). The difference between first memory task and second memory task 2: repeat cue was not significant ($p = 0.762$). Neither the main effect of Experiment ($F(2, 46) = 0.33, p = 0.724, \eta_p^2 = 0.01$) nor the interaction between Memory Task and Experiment ($F(4, 92) = 1.76, p = 0.169, \eta_p^2 = 0.07$) was significant. These results confirm that working memory performance (and therefore the manipulation of priority state) was comparable across the three experiments. This provides a foundation for comparing how the priority state of items in VWM influences early visual processing across the different perceptual tasks. These results also demonstrate that storing items in (or retrieving items from) a less prioritized state led to a small but consistent loss in memory precision.

Another finding that was inconsistent was the relationship between memory performance and the strength of the perceptual bias toward stimuli that matched the prioritized memory items. We found a positive correlation between recall errors on the memory test (i.e., cued items) and choice bias towards stimuli that matched the prioritized memory items in Experiment 1. Similarly, we found faster RTs to stimuli located in prioritized memory items in Experiment 3. However, we found no such relationship in Experiment 2. Thus, we next tested whether this correlation was reliable when combining all three experiments (Fig. 4B). The analysis showed that the combined correlation was higher than chance ($t(71) = 3.03, p = 0.003$), indicating that smaller recall errors in memory reports were associated with overall stronger perceptual biases towards stimuli that matched the prioritized memory items.

Finally, we note that the present dataset also allows for investigating the influence of stimuli presented during the perceptual task on subsequent VWM performance (e.g., as a function of trial duration, or VWM-match). Although we do not report the results of these analyses here, as they do not directly relate to our research question, we do encourage others to retrieve the publicly accessible data from our three experiments for this purpose.

5.2. *The influence of non-prioritized memory items on early visual processing*

In Experiment 1, we found that non-prioritized memory items enhanced access to visual awareness of VWM-matching visual input. In Experiments 2 and 3, however, we found no evidence that non-prioritized memory items influence the allocation of attention toward VWM-matching visual input. Here we ask (1) whether non-prioritized memory items indeed affect conscious access and attention allocation, by directly comparing between experiments. This would indicate that non-prioritized memory items differentially influence different aspects of early visual processing. If we find no such difference, we next ask (2) whether a reliable influence of non-prioritized memory items exist, across all experiments. This would indicate that, overall, non-prioritized memory items also influence early visual processing.

To address these questions, we standardized the data of all three experiments through z-transformations. More specifically, we computed individual participant mean difference scores between the non-prioritized and unrelated conditions, and divided these participant means by the population standard deviation of the difference scores. Firstly, a one-way ANOVA with the factor Experiment (Experiment 1, Experiment 2, Experiment 3) revealed that the influence of non-prioritized (i.e., uncued) memory items on early visual processing did not differ between the three experiments ($F(2, 69) = 0.88, p = 0.423$). To further test whether there was a systematic difference in the influence of non-prioritized memory items on access to visual awareness (Experiment 1) and attention allocation (Experiments 2 and 3), we combined the standardized data from Experiments 2 and 3 and conducted an independent samples *t*-test, directly contrasting Experiment 1 with the combined data of Experiment 2 and 3 (Fig. 4C). Again, we found no evidence for a difference between the two types of task ($t(70) = 1.33, p = 0.188$). Thus, we found no evidence that the influence of non-prioritized memory items on early visual processing differs between the three experimental paradigms that we employed.

This latter result raises the question whether a reliable influence of non-prioritized memory items on early visual processing exists, when pooling across all three experiments. To ensure the validity of our approach, we had established that (1) the memory manipulation was comparable across experiments and (2) the influence of memory content on the perceptual tasks did not differ significantly between experiments. This allowed us to combine the data from all experiments, in order to address several research questions using the full dataset (e.g., examining the effect of the uncued item on the perceptual task). This approach aligns with standard practices in traditional within-experiment analyses, where main effects are interpreted in the absence of significant interaction effects, or where data from conditions yielding comparable results are aggregated for further analysis.

Building on these foundations, we next conducted a one-sample *t*-test combining the z-transformed scores from all three experiments, to test whether the influence of non-prioritized memory items was larger than zero (Fig. 4C). We found that the influence of non-prioritized memory items on early visual processing was higher than chance level when pooling across all three experiments ($t(71) = 2.78$, $p = 0.007$).

Together, these results demonstrate that non-prioritized memory items influence early visual processing. Tasks measuring access to visual awareness might be more sensitive to test these effects than tasks measuring the attention allocation, but there is no evidence that non-prioritized memory items differentially impact these two hallmarks of early visual processing.

5.3. The unexpected influence of uncued items in delay 2 on early visual processing

An unexpected finding in the current series of experiments, was that uncued items in delay 2 (that were no longer needed for the memory task, and thus could be discarded), nonetheless still influenced early visual processing in Experiments 1 and 3. One explanation for this, is that memory items (in delay 2) that were previously prioritized (in delay 1) take longer to decay or are more difficult to discard, thus still influencing early visual processing when they were no longer relevant in delay 2. Indeed, in all three experiments, we found numerical evidence that the uncued item in delay 2 predominantly influenced early visual processing when it had been a prioritized item in delay 1, but this finding was not supported by robust statistical evidence in all individual experiments. To address this issue, we standardized the results of the “cued before” and “uncued before” conditions from each experiment (akin to the standardization procedure described in the previous paragraph), and pooled the data across experiments (Fig. 4D). A one-sample *t*-test conducted in the “cued before” condition confirmed that uncued items in delay 2 influenced early visual processing when they were cued in delay 1 ($t(72) = 4.95, p < 0.001$). In contrast, this was not the case when the uncued item in delay 2 was also uncued in delay 1 ($W = 653, p = 0.056$). A paired-samples *t*-test between these two conditions confirmed that the influence of uncued items in delay 2 on early visual processing was indeed larger when the item was cued in delay 1 then when it was not ($t(71) = 2.32$, $p = 0.024$). These results demonstrate that irrelevant memory items influence early visual processing only when they were previously maintained in a prioritized state.

6. General discussion

Recent studies have demonstrated that visual working memory (VWM) can regulate early visual processing by prioritizing stimuli that match the contents of VWM over stimuli that are unrelated to VWM. Such VWM-based prioritization of visual input may underly basic cognitive functions such as visual search (Gayet et al., 2013; Soto et al., 2007; van Moorselaar et al., 2014). When multiple items are held in visual memory, their representational priority can vary depending on the task requirements, for example which object is currently being searched for (LaRocque et al., 2014, 2017). This raises the question whether the impact of VWM content on early visual processing depends on the priority state of the memory items. In the present study, we combined a double serial *retro*-cuing task with various perceptual tasks (measuring access of awareness and allocation of attention) to investigate this question. Across all experiments, we found that: (1) participants could flexibly de-prioritize and re-prioritize items in VWM, and items that had been deprioritized were subsequently reported with slightly but consistently lower precision; (2) memory items in a prioritized state influenced early visual processing by facilitating conscious access of VWM-matching stimuli and by allocating attention to VWM-matching stimuli; (3) and this influence of VWM content on early visual processing was severely reduced when items were de-prioritized, and re-emerged when items were re-prioritized; (4) We found that even items in a non-prioritized memory state could facilitate conscious access of VWM-matching stimuli (Experiment 1), but we found no evidence that stimuli matching non-prioritized memory items attracted spatial attention (Experiments 2 and 3); (5) Finally, the influence of non-prioritized memory items on early visual processing did not reliably differ between experiments, but non-prioritized memory items reliably influenced early visual processing when collapsing across all three experiments. This demonstrates that, overall non-prioritized memory items influence early visual processing, but more evidence is needed to establish whether this differentially applies to different aspects of early visual processing (e.g., conscious access versus attention allocation).

We used a double serial *retro*-cuing task to control the priority state based on task relevance (Christophel et al., 2018; LaRocque et al., 2017). Previous studies have shown that prioritized memory items are associated with better memory precision (Zhang et al., 2018; Zhang et al., 2022) and evoke stronger neural activity (Christophel et al., 2018; Rose et al., 2016) compared to non-prioritized items. This leads to the question whether information about a memory item is lost when it is brought into a non-prioritized state. Here, we found that recall precision was reliably but minimally reduced when a memory item was previously brought into a non-prioritized state (and then later reprioritized) compared to a memory item that was never de-prioritized. These findings show that participants indeed de-prioritized memory items when instructed to do so by a cue. Consistent with this loss in recall precision, but more compellingly, the influence of memory content on early visual processing dropped nearly to baseline when memory items were deprioritized, and nearly increased back to initial levels when memory items were then reprioritized again. These findings suggest that participants can flexibly de-prioritize and re-prioritize items in VWM, at a minimal loss of precision, thereby exerting a strong influence on the extent to which early visual processing is affected by VWM content.

Our findings are in line with previous findings that items in a prioritized state could influence early visual processing, facilitate VWM-matching items access to visual awareness (Gayet et al., 2013) and allocate more attention to VWM-matching stimuli (Bahle et al., 2018; Chen & Du, 2017; Wang et al., 2023; Zhang et al., 2018). For example, Gayet and colleagues (Experiment 4, 2013) required participants to remember two items and then instructed them to actively retain either the first or the second color stimulus for later recall via a *retro*-cue before a b-CFS task (the cued items were in the prioritized state). In the b-CFS task, participants needed less time to perceive the targets when the targets matched the cued items compared to memory-unrelated items. Chen and Du (2017) found that participants needed more time to find a target in a search array containing a distractor that matched the prioritized memory item compared to a memory-unrelated item. Taken together, these findings confirm a wide array of earlier work that prioritized VWM contents modulate early visual processing. Importantly, the current work extends these findings by showing that participants can flexibly alter the extent to which VWM content influences concurrent early visual processing, by changing the priority state of individual items in VWM.

To test whether non-prioritized memory items influence early visual processing, we collapsed our data across all three experiments. Although we did not find evidence for such an influence of non-prioritized memory items on early visual processing in all individual experiments, we did find a perceptual advantage for stimuli that matched non-prioritized memory items compared to those that were memory-unrelated when combining the data from all experiments. It has been suggested before that prioritized memory items may be stored in a sensory-like state in the early visual cortex, to allow for interactions with visual input (Chota & Van der Stigchel, 2021; Christophel et al., 2017; Gayet et al., 2017, 2018; Iamshchinina et al., 2021). Such interactions would allow for the type of memory-based biases observed here, which underlie goal-directed visual search (Desimone & Duncan, 1995). Non-prioritized memory items may then be stored in different cortical regions (Christophel et al., 2018), different representational formats (van Loon et al., 2018; Yu et al., 2020), or in an activity silent manner (Rose et al., 2016; Wolff et al., 2017). This may, in turn, ensure that memory items that are not imminently relevant also do not interact with visual input (i.e., guide search). However, our behavioral findings may suggest that non-prioritized memory items are in fact stored in early visual cortex in a sensory-like format, where they can interact with visual input, albeit to a lesser extent than prioritized memory items. Storing non-prioritized memory items (partly) in visual cortex may ensure that a high-resolution representation is maintained to minimize memory loss or may allow for faster reinstatement of the memory item into a prioritized state once they need arises.

When analyzing the perceptual task separately, we observed that non-prioritized memory items only facilitated the conscious access of memory-matching items in Experiment 1, while having a negligible influence on the allocation of attention in Experiments 2 and 3. Conscious access typically reflects a relatively early stage of visual processing, which appears to be less susceptible to later stage of cognitive control mechanisms (Cohen et al., 2020; Koivisto & Revonsuo, 2008; Schlossmacher et al., 2021). Previous eye-tracking studies using various metrics that reflect early stage of visual processing have found that non-prioritized memory items do influence early visual processing. Specifically, it was observed that items matching non-prioritized memory content received more attended times (Carlisle & Woodman, 2019), had a higher first fixation proportion (Zhang et al., 2018), and triggered more micro-saccades (van Loon et al., 2017) compared to memory-unrelated items. Similarly, several studies have reported that stimuli matching non-prioritized memory content do not capture more attention compared to memory-unrelated stimuli (Downing & Dodds, 2004; Olivers et al., 2011). This may be because the attentional guidance effect reflects a relatively later stage of perceptual processing, which is more susceptible to cognitive control mechanisms (Han & Kim, 2009; Sawaki and Luck, 2011) and, therefore, more vulnerable to strategic factors that can affect and potentially mask the phenomenon under investigation. For instance, Zhang et al. (2018, Experiment 1) found a higher first fixation proportion for stimuli matching non-prioritized memory items compared to memory-unrelated items, while observing no difference in manual RTs (which including post-perceptual processing, like decision-making) between these two categories. Taken together, our findings suggest that certain types of perceptual tasks used to measure the effect of visual working memory on early visual processing are more sensitive than others, particularly those that assess the relatively early stages of visual processing. It should be stressed, however, that we found no evidence that the influence of non-prioritized memory items on early visual processing reliably differed between the various experimental paradigms that we employed. Thus, any conclusions about non-prioritized memory items differentially impacting different perceptual processes are premature.

Interestingly, we observed that uncued memory items in Delay 2 (i.e., items that were no longer relevant to the memory task) continued to influence early visual processing. This finding is surprising, given prior studies involving a single memory delay, where uncued (i.e., discarded) items do not typically affect concurrent perceptual tasks (Gayet et al., 2013; Olivers et al., 2006). Why, then, would discard items in the second delay behave differently? Previous research suggests that when memory items prioritized in delay 1 become non-prioritized in Delay 2, they may resist decay or be effortful to discard, remaining active in the brain (van Moorselaar et al., 2015b; Rerko & Oberauer, 2013). When we split the match with the uncued condition in delay 2 based on whether the VWM-matching stimuli were previously prioritized, we indeed found that only items cued (prioritized) in delay 1 continued to influence early visual processing. These findings also align with a study showing that memory content could be decoded from an object-selective visual region (posterior fusiform cortex) across two consecutive delays (van Loon et al., 2018). In their design, participants memorized two items as templates for two consecutive visual searches. The cued (prioritized) memory items were relevant to the immediate visual search, while the uncued (non-prioritized) memory items were relevant to a future visual search. Notably, items cued in delay 1 were uncued in delay 2, and vice versa. Even under these conditions, uncued memory items in delay 2 (previously prioritized in delay 1) yielded better decoding performance than uncued items in delay 1 (although the uncued items in delay 1 would soon become relevant, while the uncued memory items in delay 2 could be discarded). These findings suggest that, once VWM content has been maintained in a prioritized memory state for a prolonged duration, deprioritizing this VWM content may take longer or may be more effortful. Consequently, memory items that were maintained in a prioritized state before, exert a lasting influence on early visual processing, even after those items are no longer directly relevant to the task.

There have been ongoing debates on whether multiple memorized items stored in different states can influence early visual processing. The single-item template hypothesis suggests that only memory items in a prioritized (active) state can act as template to interact with visual input, while non-prioritized (passive) state cannot (Olivers et al., 2011). In contrast, the multiple-item template hypothesis argues that multiple memory items, including those in a non-prioritized state, can interact with visual input (Beck et al., 2012). A more recent perspective proposes that the representational fidelity of memory items determines their influence on early visual processing (Hollingworth & Hwang, 2013; Salahub & Emrich, 2016; Williams et al., 2022). In our study, we found a correlation between working memory recall errors for prioritized items and perceptual performance, suggesting that better memory performance is associated with a greater influence of memory items on early visual processing. This extends earlier work showing that higher memory resolution increases the likelihood of influencing concurrent visual processing (Salahub & Emrich, 2016; Williams et al., 2022). Moreover, this link between recall performance of VWM content and its influence on visual processing also provides an alternative interpretation of the difference between prioritized and non-prioritized items in influencing early visual processing. Across all experiments, we observed memory loss for non-prioritized items. This weaker influence of non-prioritized items on concurrent perception may reflect a temporary loss of precision for non-prioritized items, which reduced their influence on early visual processing. From this perspective, the difference between prioritized and non-prioritized memory items in their ability to affect visual input might not be discrete but gradual and may directly relate to the representational strength (or precision) of the memory content. Framed differently, then, the finding that non-prioritized memory items impacted early visual processing in the current study, may reflect that these items were not fully deprioritized; some attentional resources were still allocated to these items, thus, some influence on early visual processing persisted. The difference between prioritized and non-prioritized memory items, then, would not reflect discrete representational states, but reflects differences along a continuum of attentional resources that participants can allocate to their VWM content.

Our study found a significant result of non-prioritized memory items on visual awareness in Experiment 1 but did not on attention allocation in Experiments 2 and 3. One potential explanation for this discrepancy may involve differences in the extent to which non-prioritized items were deprioritized across tasks. Specifically, in Experiment 1, the non-prioritized item may not have been fully deprioritized, as it retained the potential to become a target, thereby receiving more attentional resources compared to Experiments 2 and 3. However, our analysis showed that the priority states of memory items were consistent across all experiments, with no significant differences between experiments or interactions between perceptual task and experiment. These findings suggest that the observed effects are unlikely to result from differences in the extent of de-prioritization. Instead, they may reflect a more general mechanism by which non-prioritized memory items interact with early visual processing, a process that appears consistent across different perceptual contexts.

Finally, we consider an alternative account for the finding that non-prioritized (i.e., uncued) memory items also influenced early visual processing, albeit to a lesser extent than prioritized (i.e., cued) memory items. We consider the possibility of swap errors; that is, participants may have mistakenly prioritized the uncued memory items during a subset of trials, leading to a (small but consistent) influence of non-prioritized memory items on early visual processing, when averaged across all trials. We deem this unlikely, however, as we excluded all trials with memory recall errors above 45 degrees; that is, memory responses that are closer to one of the other items presented on a trial than to the cued memory item. Although the contribution of such swap errors cannot be fully excluded, the exclusion of categorical errors (viewed in light of the observed recall precision of participants) makes it unlikely that they fully explain the effect of non-prioritized memory items on early visual processing.

7. Conclusion

In sum, the present study showed how participants can flexibly alter the priority state of their VWM content, at minimal loss of precision. This allows participants to exert control over the extent to which VWM content influence concurrent early visual processing, and which items barely do so. This is beneficial for all kinds of VWM-guided behavior (such as top-down visual search) in a dynamic visual environment, where task goals change on a moment-to-moment basis.

CRediT authorship contribution statement

Dan Wang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Samson Chota:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Luzi Xu:** Writing – review & editing, Validation, Supervision, Software, Resources, Methodology, Conceptualization. **Stefan Van der Stigchel:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Surya Gayet:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The raw data and analysis code for all three experiments are publicly available at https://osf.io/x2uzh/.

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