Journal of Memory and Language 146 (2026) 104702

Contents lists available at ScienceDirect

Journal of Memory and Language

journal homepage: www.elsevier.com/locate/jml

Asymmetric interaction effects of information with varying priorities in visual working memory

Jing Ni, Jiayi Fu, Ruotong Wang, Can Yang, Ying Cai *

Department of Psychology and Behavioral Sciences, Zhejiang University, Hangzhou 310028, China

ARTICLE INFO

Keywords:
Visual working memory
Prioritized memory items
Unprioritized memory items
Interaction effects

ABSTRACT

Visual working memory (VWM) is the ability to temporarily maintain and manipulate visual information, with individuals adjusting the priority of information processing based on task demands. However, the nature of the interactions between information of varying priorities in VWM remains debated, which is the focus of the current study. In Experiment 1, participants performed a delayed recall task for colors under different loads of prioritized memory items (PMIs) and unprioritized memory items (UMIs). The results indicated that the recall for PMIs deteriorated as the load of UMIs increased, and vice versa. Crucially, recall for UMIs was more significantly affected by the load of PMIs, indicating an asymmetric interaction between PMIs and UMIs. Experiments 2 and 3 examined whether such an interaction pattern was influenced by the presentation order of PMIs and UMIs. we reversed and randomized the presentation sequence and replicated the findings. Experiments 4 and 5 further validated these findings in delayed recall tasks for orientations and locations, confirming that the asymmetric interactions were consistent across stimulus types. Moreover, Experiments 6 and 7 tested the cognitive mechanism underlying this pattern. Experiment 6 introduced an interference task during the delay, revealing that the sustained attention to PMIs contributed to the asymmetry interaction; Experiment 7 added a test condition without recall of PMIs, demonstrating the prioritized retrieval of PMIs was responsible for the asymmetry interaction as well. Overall, this study enhances our understanding of how information with different priorities interacts during VWM and offers valuable insights for future studies.

Introduction

Visual working memory (VWM) is the ability of individuals to temporarily maintain and manipulate visual information and is the foundation for advanced cognitive processes (Baddeley & Hitch, 1974). Researchers have demonstrated that individuals can adjust the priority of information processing depending on ongoing task demands (Myers et al., 2017). However, the nature of interactions between information of varying priorities in VWM remains debated.

Some earlier studies have suggested a resource-based model, where more cognitive resources are devoted to prioritized memory items (PMIs) than to unprioritized memory items (UMIs) (Bays & Husain, 2008; Ma et al., 2014). For example, the items associated with higher reward (Hitch et al., 2018; Hu et al., 2016) or with higher probability to recall (Hollingworth & Maxcey-Richard, 2013; W. Zhang & Luck, 2008) could be maintained as PMIs, resulting in better recall performance. In contrast, recent researchers have proposed a state-based model, positing PMIs and UMIs are maintained in distinct states: PMIs are directly related to the ongoing task and require real-time processing, and their representations are always active, while UMIs are not necessary for the ongoing task and are kept in a more passive storage state (Cowan, 2001; Olivers et al., 2011). Compared with the resource-based model, the state-based model prefers fewer interactions between items of varying priorities and dissociated neural basis underlying them. This independent storage view has been strengthened by an earlier behavioral study, which required participants to remember two rows of numbers and perform an arithmetic operation on specific numbers in one row (PMIs in the active row) but just to store numbers in the other row (UMIs in the passive row) during the interval, and reported all numbers at the end (Oberauer, 2002). They found that only the recall for UMIs became poorer with increased delay duration and interference. Additionally, reaction times during arithmetic operations were affected only by the load of PMIs but not UMIs. Some other studies established recall-order prioritization, designating first-recalled items as PMIs and later-recalled items as UMIs (Z. Li et al., 2021; Nee & Jonides, 2011). For example, the recent study employed a double *retro*-cue design, requiring

* Corresponding author at: Department of Psychology and Behavioral Sciences, Zhejiang University, Hangzhou 310028, Zhejiang, China.
E-mail address: yingcai@zju.edu.cn (Y. Cai).

https://doi.org/10.1016/j.jml.2025.104702
Received 27 January 2025; Received in revised form 30 September 2025; Accepted 1 October 2025
Available online 8 October 2025

participants to make change detection judgments sequentially on two memorized items(Z. Li et al., 2021). They demonstrated that increasing the memory load of the first-recalled PMIs did not affect the performance of the later-recalled UMIs, and vice versa.

Moreover, this independent storage view has been supported by neuroimaging studies, where the prioritization was also identified by the recall order. Some researchers have noted that the PMI and UMI can be stored in different brain areas. For example, a functional magnetic resonance imaging (fMRI) study revealed stronger activations in the posterior parietal cortex and inferior temporal cortex during PMI retrieval, whereas the lateral prefrontal cortex was more active during UMI retrieval (Nee & Jonides, 2011); Another study investigated their neural representations and reported that PMIs can be decoded from a wide range of areas, including visual, parietal, and prefrontal regions, whereas UMIs can be decoded from only limited areas, such as the intraparietal sulcus and the frontal eye field (Christophel et al., 2018). However, some other researchers have suggested that the PMI and UMI can be stored in the same area but in different formats (Lewis-Peacock et al., 2012; Van Loon et al., 2018; Wan et al., 2020; Yu et al., 2020; Yu & Shim, 2017; J. Zhang et al., 2022). For example, studies have shown that in the occipital region, the neural representation of the PMI can be continuously decoded during maintenance, whereas the UMI representation rapidly returns to baseline levels (Lewis-Peacock et al., 2012; Yu & Shim, 2017). Moreover, recent research has shown that the PMI and UMI reveal opposite neural representational patterns in posterior areas during VWM maintenance (Van Loon et al., 2018; Wan et al., 2020; Yu et al., 2020). Additionally, recent electroencephalography (EEG) studies have shown that the amplitude of contralateral delay activity (CDA), which is thought to reflect the storage capacity, is related to the number of PMIs but not UMIs (J. Zhang et al., 2022).

However, there is accumulating evidence against the independent storage view, suggesting that information with varying priorities interacts during VWM. For example, a recent study using a more sensitive orientation delayed estimation task revealed that the recall of both PMIs and UMIs was influenced by each other (Bae & Luck, 2017). The authors found that PMIs and UMIs repelled each other when the angular difference between PMIs and UMIs was small while attracted each other when the angular difference became larger. Researchers have suggested that lateral inhibition occurs between PMIs and UMIs. Moreover, Bae's study noted that the recall of PMIs was less influenced by UMIs, and posited a potential explanation that sustained attention to PMIs reduced their susceptibility to UMI interference. However, in this study, PMIs and UMIs were presented in the same location, which could introduce perceptual-level interference (Shepherdson et al., 2022) and confound the VWM-level interaction conclusions. Meanwhile, the total memory load was under the memory capacity (around 4 items) and left the influence of memory load unclear. In addition, another study challenged these findings by revealing that only the neural representations of UMIs recovered to the original levels after a distracting stimulus was presented. Researchers have argued that the inactivity of a UMI's neural representation makes it less susceptible to interference (Mallett & Lewis-Peacock, 2019). Moreover, a series of recent neuroimaging studies also have revealed that during PMI recall, the memory representations of UMIs are reactivated (Muhle-Karbe et al., 2021; Pietrelli et al., 2022; Yu et al., 2020), providing another perspective for understanding the underlying mechanism of their interactions. In sum, this evidence suggests that studies supporting the independent storage view may be due to their insensitive experimental designs or mistakenly linking dissociated neural activities to absent behavioral interference. Meanwhile, although preliminary behavioral results indicated asymmetrical interaction between PMIs and UMIs, key questions like modulating factors and underlying mechanisms remain unelucidated.

In the current study, we operationalized the state of memory items based on their recall priorities: PMIs were the first-recalled items and would be processed in an active state for the upcoming response, while UMIs were the later-recalled items and would be stored in a relatively passive state. In Experiment 1, participants performed a delayed recall task for colors under different loads of PMIs and UMIs. We assessed the interaction effects by comparing recall changes of the PMIs and UMIs when the memory load of the other state increased. Next, we confirmed that the interaction pattern was consistent across different sequence orders (Experiments 2 and 3) and stimulus types (Experiments 4 and 5). Finally, we verified that the sustained attention allocated to PMIs during maintenance (Experiment 6) and the prioritized retrieval of PMIs (Experiment 7) were responsible for the observed interaction patterns between PMIs and UMIs. In these two experiments, although the manipulations introduced temporal state changes, we made the definitions consistent given the core information flow were kept same and it would be crucial to preserve the continuity across the study.

Experiment 1

Experiment 1 aimed to examine whether the PMIs and UMIs interacted during VWM by testing whether the memory load of the PMIs affected UMI recall and vice versa. The participants completed a delayed recall task for colors, where they were required to recall two sequentially presented color arrays. First, we tried to replicate that recall performance of PMIs and UMIs decreased as their own load increased (i.e., the self-state load effect, Lewis-Peacock et al., 2012; Z. Li et al., 2021); More importantly, we tested whether recall performance of the PMI and UMI would deteriorate when the load of items in the other state increased (i.e., another-state load effect). Furthermore, we examined if the another-state load effect was different in PMIs and UMIs.

Participants

To determine the sample size, we entered the effect size of the interaction effect between priority status and item load on recall performance in a previous study ($\eta_p^2 = 0.545$; Experiment 3 in Li et al., 2021) into MorePower software (Campbell & Thompson, 2012), and a sample size of 8 participants would provide power greater than 90 % for detecting interaction of priority status and item load ($\alpha = 0.05$). Based on the results in power analysis and number of participants in previous study with a similar design (Li et al., 2021, $n = 30$ in Experiment 3; Myers et al., 2018, $n = 24$ in Experiment 1), we further increased the sample size to 24 in the experiment to ensure the reliability of our experiment.

Twenty-seven undergraduate and graduate students from Zhejiang University participated in Experiment 1 (11 males; age: $M = 19.13$ years, $SD = 1.62$). All of the participants were right-handed, had normal or corrected-to-normal vision, and had no color blindness or color weakness. We excluded participants whose recall errors exceeded 3 standard deviations from the group mean, and 24 participants were included. A unique set of participants was recruited for each experiment. This study was approved by the Institutional Review Board at Zhejiang University (2021–025), and participants provided informed consent prior to the experiment and received monetary compensation (30 RMB/hour) for the experiment.

Stimuli and procedure

The participants completed a delayed recall task for colors (Fig. 1; Li et al., 2021; W. Zhang & Luck, 2008). In each trial, a 500 ms white fixation (length = 0.75°, width = 0.05°) appeared in the center of the screen, and then the first color array was presented. The color array consisted of 1, 2, or 3 colored dots (radius = 0.5°). Three hundred and sixty color values were sampled around a color circle in the CIE L*a*b space, with the center at [50, 20, 20] and a radius of 60. In each trial, six colors were randomly selected from these 360° color values, with a minimum difference of 20°. Two sets of six positions from an invisible ring centered at the screen (radius = 6°; first set: 60°, 180°, 300°; second set: 120°, 240°, 360°) were selected. On the basis of the number of items

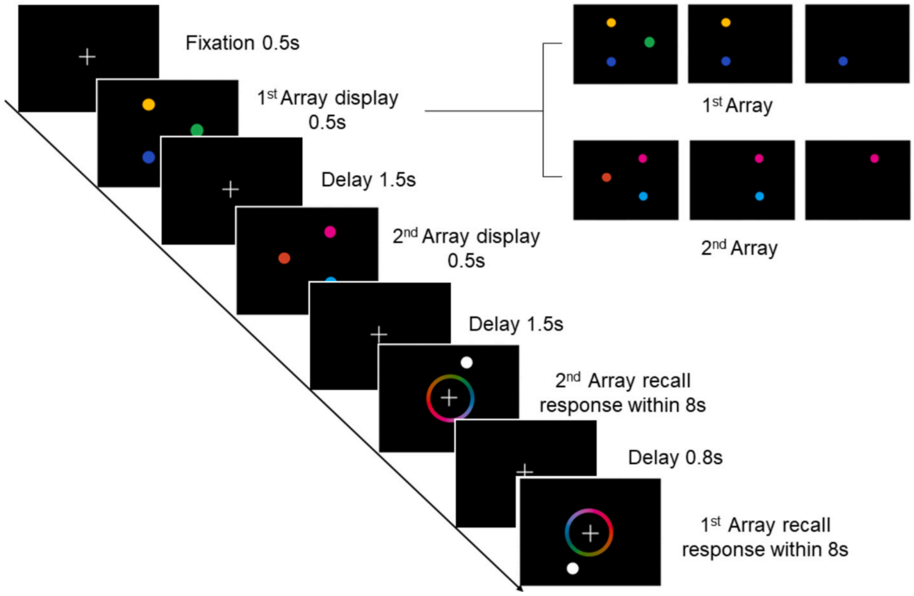


Fig. 1. In the delayed estimation task for colors in the Experiment 1, participants were required to remember two subsequently-presented color arrays. The memory load in the first and second color arrays was 1, 2, or 3. In the first probe display, participants always recalled the color at the targeted location in the second color array; then they recalled another targeted color in the first color array. The figure showed an example where the memory loads in both the first and second color arrays were 3.

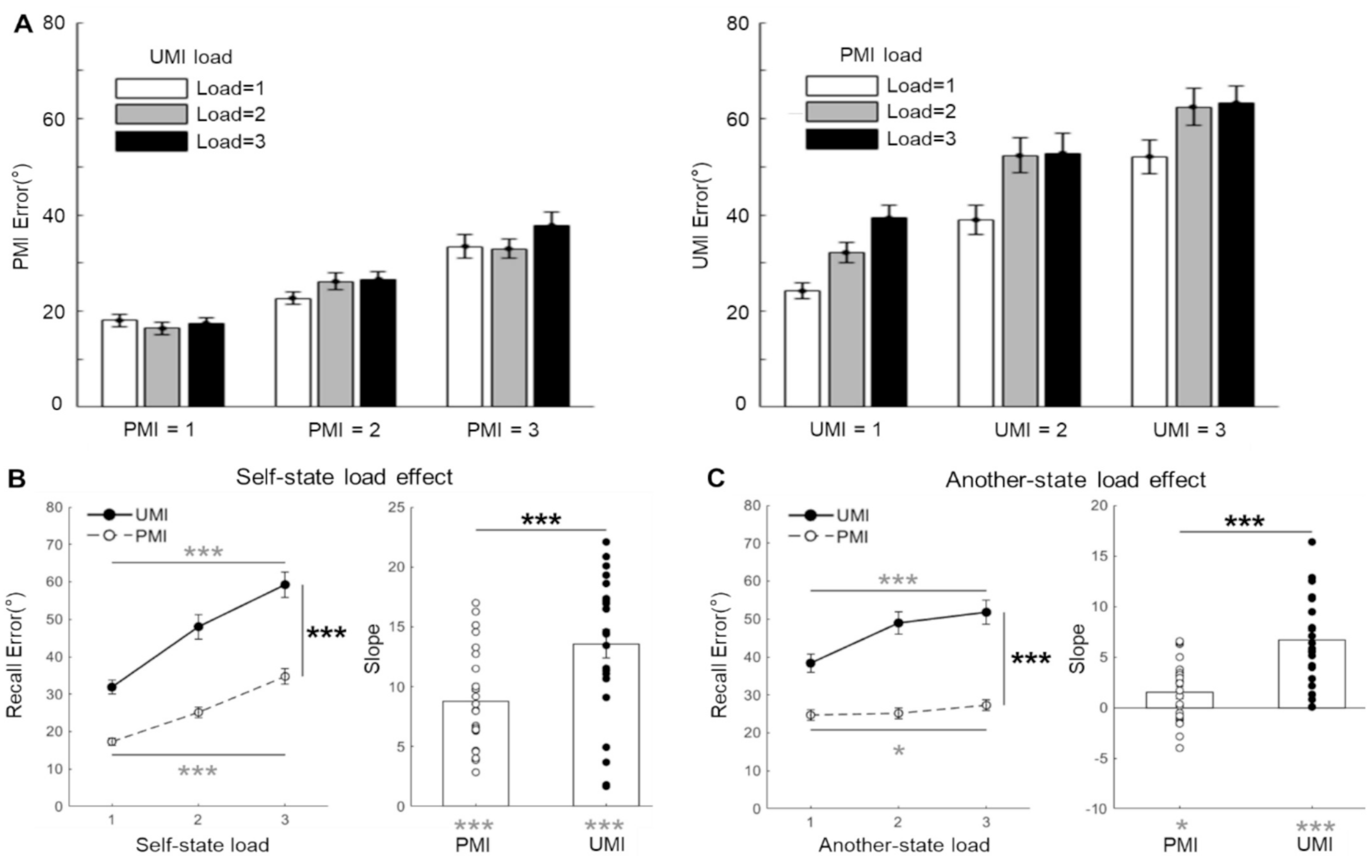


Fig. 2. A. Recall errors for PMIs and UMIs under different memory load conditions of Experiment 1. B. The self-state load effects on PMI and UMI recall. C. The another-state load effects on PMI and UMI recall. In the left figures in panel B and C, black asterisks represent two-way interaction effects and gray asterisks represent one-way ANOVA effects; In the right figures in panel B, the PMI label along the x axis indicates the influence of PMI load on PMI recall, and the UMI label indicates the influence of UMI load on UMI recall; In the right figures in panel C, the PMI label along the x axis indicates the influence of UMI load on PMI recall, and the UMI label indicates the influence of PMI load on UMI recall. Each point in the right figures of panel B and C represents the fitting slope value for each participant. Black asterisks indicate significance in paired t-tests and gray asterisks indicate significance in one-sample t-tests (compared to zero). Error bars represent standard errors (SE). ***p < 0.001; **p < 0.01; *p < 0.05.

in each color array, we then determined the colors and their presented positions from the candidate colors and positions. Colors and positions in the same trial were not repeated. Each color array lasted for 500 ms, followed by an interval of 1500 ms where a fixation was centered on the screen. Next, two probe displays were presented sequentially with an interval of 800 ms, requiring participants to recall the colors of the cued positions in the second and first color arrays. The probe display included a color wheel, which was 0.5° thick, had a radius of 3° and was centered on the screen. The participants were instructed to recall the targeted color by moving the mouse and clicking the specific color along the color wheel within a maximum response time of 8 s. The color distribution on the wheel was randomized in each trial to prevent participants from preparing their responses in advance.

The experiment included three memory loads for the PMI and UMI (1, 2, or 3 items), and there were 40 trials per condition. All of the trials were evenly and randomly divided into 10 blocks. At the beginning of each block, a random four-digit number was presented, and the participants were asked to verbally repeat it during the task to prevent potential verbalization strategies (Shaffer & Shiffrin, 1972). The entire experiment lasted for approximately 70 min. Before the formal experiment began, each participant completed 36 practice trials to ensure that they were familiar with the procedure.

The experimental program was written using MATLAB scripts in combination with Psychtoolbox-3. All stimuli were presented on a 19-inch LCD monitor (60 Hz refresh rate, 1920 × 1080 pixels) using MATLAB R2020a software. The participants viewed the screen from a distance of 80 cm, and the background color of the screen was set to black (RGB = [0, 0, 0]) throughout the experiment to avoid potential visual distractions.

Data analysis

The recall error was estimated by the angular difference on the color wheel between the selected color and the target color (in degrees). The errors in the first and second recalls indicated the performance of the PMI and UMI, respectively (Fig. 2A).

To examine whether the recall performance for the PMI and UMI was influenced by the memory load of the same and different priority states, we conducted a 2 (recall priority: UMI vs. PMI) × 3 (self-state load: 1 vs. 2 vs. 3 items) × 3 (another-state load: 1 vs. 2 vs. 3 items) three-way repeated-measures ANOVA. If the three-way interaction was significant, we would examine the interaction effects between the self-state load and another-state load on PMI and UMI recall separately via two-way repeated-measures ANOVA. If the three-way interaction was not significant, we would specifically examine the interactions between recall priority and self-state load, as well as interactions between recall priority and another-state load. In the case of significant two-way interactions, we further conducted simple effect analyses and post hoc tests. All post hoc tests in this study were corrected via Bonferroni adjustments. Moreover, we performed parallel Bayesian analyses via standard priors, as implemented in JASP Version 0.16.3. All of the statistical analyses were performed in MATLAB and JASP software.

Previous studies have reported that recall errors for PMIs are lower than those for UMIs (Bae & Luck, 2017; Z. Li et al., 2021; Oberauer, 2005; Peters et al., 2012). To rule out the possibility that recall baselines influenced interaction patterns between PMIs and UMIs, we assessed the overall magnitude of their interaction effects using linear regression analysis. To achieve this, at the individual level, we conducted linear regression analyses with PMI and UMI recall errors as dependent variables and self-state load and another-state load as independent variables. The slope values of the linear fits indicated the degree to which the PMIs and UMIs were affected by the self-state load or another-state load. Next, we tested the significance of the slopes via one-sample t tests and compared the degree to which the PMI and UMI were affected by the self-state load and another-state load using paired t tests.

Results

Three-way repeated-measures ANOVA revealed no three-way interaction ($F(4,92) = 1.846$, $p = 0.110$, $\eta_p^2 = 0.078$, BF = 0.994), but significant two-way interactions between the priority state and self-state load ($F(2,46) = 15.354$, $p < 0.001$, $\eta_p^2 = 0.400$, BF > 1000), as well as between the priority state and another-state load ($F(2,46) = 20.570$, $p < 0.001$, $\eta_p^2 = 0.472$, BF > 1000). To examine the interaction between the priority state and self-state load, further one-way repeated measures ANOVAs and post hoc test results indicated that as the self-state load increased, the recall errors for both PMIs and UMIs worsened (one-way ANOVAs: $Fs > 89.043$, $ps < 0.001$, $\eta_p^2s > 0.795$, BFs > 1000; post hoc tests: $ts > 7.680$ $ps < 0.001$, Cohen's $ds > 0.756$, BFs > 1000; Fig. 2B, left). Meanwhile, paired t tests on fitting slopes revealed that the degree of UMI influenced by the self-state load was significantly greater than that of PMI ($t(23) = 4.811$, $p < 0.001$, Cohen's $d = 0.982$, BF = 351.956; both slopes were greater than 0: $ts > 10.152$, $ps < 0.001$, Cohen's $ds > 2.072$, BFs > 1000; Fig. 2B, right). These results indicated that our sequential recall task effectively modulated the priority state.

More importantly, to clarify the interaction between the priority state and another-state load, one-way repeated-measures ANOVA revealed that there were significant differences in recall errors for both the PMI and UMI as the another-state load increased ($Fs > 3.230$, $ps < 0.049$, $\eta_p^2s > 0.123$, BFs > 1.244), and the post hoc test results revealed that the PMI recall errors significantly worsened under larger UMI loads (UMI load 1 vs. 2: $t(23) = 0.356$, $p = 1.000$, Cohen's $d = 0.062$, BF = 0.227; UMI load 2 vs. 3, $t(23) = 2.815$, $p = 0.029$, Cohen's $d = 0.296$, BF = 4.913), whereas the UMI recall errors significantly worsened under higher PMI loads (PMI load 1 vs. 2: $t(23) = 8.092$, $p < 0.001$, Cohen's $d = 0.760$, BF ≥ 1000; PMI load 2 vs. 3: $t(23) = 2.217$, $p = 0.110$, Cohen's $d = 0.204$, BF = 1.659; Fig. 2C, left). Consistently, paired t tests on slopes also revealed that the degree to which UMI was influenced by PMI was significantly greater than the degree to which PMI was influenced by UMI ($t(23) = 4.967$, $p < 0.001$, Cohen's $d = 1.014$, BF = 499.002; both fitted slopes were greater than 0: $ts > 2.477$, $ps < 0.021$, Cohen's $ds > 0.506$, BF > 2.613; Fig. 2C, right). These results demonstrated an asymmetrical interaction pattern between PMIs and UMIs. Moreover, additional paired t tests on the slopes revealed that for both the PMI and UMI recalls, the degrees of self-state load effects were significantly stronger than those of the another-state load effects ($ts > 5.679$, $ps < 0.001$, Cohen's $ds > 1.159$; BF > 1000), confirming that PMIs and UMIs were stored in different formats, with the distinction being qualitative rather than quantitative.

Summary of Experiment 1

Experiment 1 replicated previous findings that recall errors for both PMIs and UMIs are influenced by self-state load (Lewis-Peacock et al., 2012; Z. Li et al., 2021). More importantly, we found that the recall errors for both the PMIs and UMIs deteriorated when the another-state load increased, indicating considerable interactions between items with varying priorities in VWM. Additionally, we found that these interactive effects were asymmetric, with UMI recall being more affected by PMI than the opposite. In the following experiments, we focused on the interaction patterns between PMIs and UMIs during VWM.

Experiments 2 and 3

Experiments 2 and 3 further examined whether the presentation order of PMIs and UMIs influenced the interaction between them. In Experiment 2, we reversed the presentation order of the PMIs and UMIs; in Experiment 3, we randomized the presentation order by introducing a post encoding cue. The other settings were the same as those in Experiment 1. If the interaction pattern was not influenced by the presentation order, we would observe similar results in Experiments 2 and 3.

Experiment 2

Participants and procedure

The sample size of participants and selection criteria were consistent with those in Experiment 1; Experiment 2 included 24 participants (10 males; age: M = 22.17 years, SD = 3.07). The stimulus materials and task procedures used in Experiment 2 were similar to those used in Experiment 1. In Experiment 2, the only difference was that the recall order of two color arrays was reversed, requiring participants to first recall one targeted color from the first array and then another from the second array (Fig. 3A).

Data analysis

The data analysis was identical to that in Experiment 1 while we only focused on the another-load effect (a.k.a. the interaction effect between priority state and another-state load). The recall error in the first recall reflects the performance of the PMI, and the recall error in the second recall reflects the performance of the UMI.

Results

Consistent with the results of Experiment 1, the three-way interaction effect between the priority state, self-state load and another-state load was not significant ($F(4,92) = 1.304$, $p = 0.274$, $\eta_p^2 = 0.054$, BF = 0.274). However, all two-way interactions were significant (*Fs* > 3.086, *ps* < 0.020, η_p^2s > 0.118, BFs > 1.662). Focusing on the interaction between priority state and another-state load, one-way repeated-measures ANOVA revealed that both the PMI and UMI recall errors changed significantly across the another-state loads (*Fs* > 8.259, *ps* < 0.001, η_p^2s > 0.264, BFs > 34.58; Fig. 3C, left). Post hoc tests revealed that as the another-state load increased, PMI recall errors significantly increased only between the lowest two UMI load levels (UMI load 1 vs. 2: $t(23) = 4.240$, $p = 0.003$, Cohen's $d = 0.295$, BF = 38.271; UMI load 2 vs. 3: $t(23) = 0.941$, $p = 1.000$, Cohen's $d = 0.066$, BF = 0.264), whereas UMI recall errors significantly increased as the PMI load gradually increased (*ts* > 6.776, *ps* < 0.001, Cohen's *ds* > 0.732, BFs > 1000). Moreover, a paired *t* test of the slopes indicated that the degree of the another-state load effect on the UMI was greater than that on the PMI ($t(23) = 6.847$, $p < 0.001$, Cohen's $d = 1.398$, BF > 1000; both slopes were greater than 0, *ts* > 3.339, *ps* < 0.003, Cohen's *ds* > 0.682, BFs > 14.120; Fig. 3C, right). These results replicated the asymmetrical interaction pattern and indicated a larger influence of PMIs on UMIs.

Experiment 3

Participants and procedure

The sample size of participants and selection criteria were consistent with those in Experiment 1; Experiment 3 included 24 participants (9 males; age: M = 20.58 years, *SD* = 2.28). The stimulus materials and task procedures used in Experiment 3 were similar to those used in Experiment 1. The only difference was that the recall order was determined by a numerical cue presented after the second color array, with "1″ indicating that participants first recalled colors from the first color array and then from the second array, whereas ″2″ indicating the opposite recall order. The numerical cue was presented for 200 ms, and the

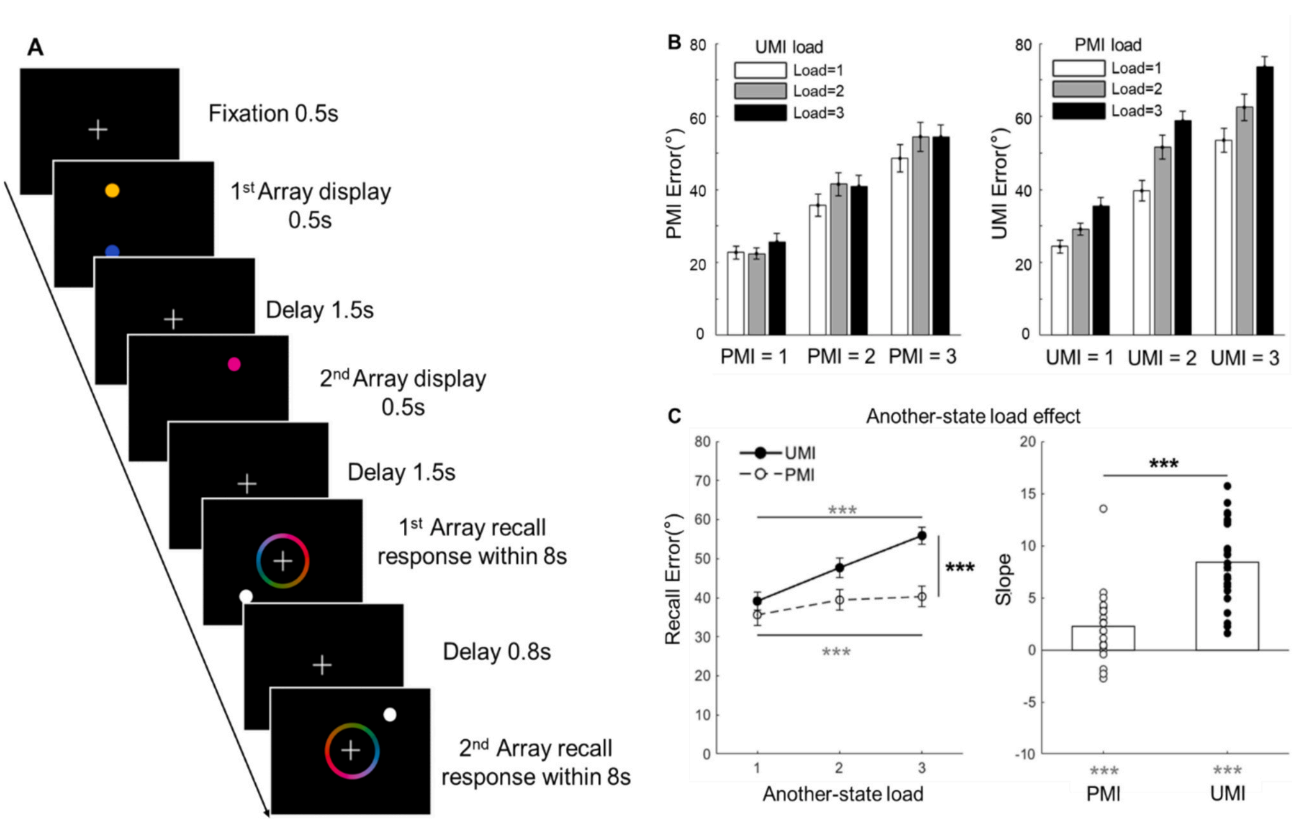


Fig. 3. A. The delayed estimation task for colors in Experiment 2. In all trials, participants were required to recall one targeted color in the first array, and then recall another targeted color in the second array. B. Recall errors for PMIs and UMIs under different memory load conditions. C. Another-state load effects on PMI and UMI recall. In panel C, the left figures show changes in PMI and UMI recall errors under different another-state memory load conditions. Black asterisks represent significant interaction effect and gray asterisks represent significant one-way ANOVAs. The right figures show the fitted slopes of the another-state memory load effects on PMI and UMI recall. Black asterisks represent significant paired t-tests, and gray asterisks represent significant single-sample t-tests. Error bars represent standard errors (SE). ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

probabilities of the two recall orders were equal (Fig. 4A).

Data analysis

The data analysis was identical to that in Experiment 2. Furthermore, we performed an analysis to further assess the asymmetric interaction effects across Experiments 1 to 3. Based on the three-way repeated-measures ANOVAs, we add a between-subject factor presentation order of PMIs and UMIs (Experiment 1-backward recall vs. Experiment2-forward recall vs. Experiment 3- random recall order) into this analysis.

Results

Similar three-way ANOVA results with Experiment 1 were observed: There was no three-way interaction effect ($F(4,92) = 1.994$, $p = 0.102$, $\eta_p^2 = 0.080$, BF = 1.371), but all two-way interactions were significant ($Fs > 17.505$, $ps < 0.001$, $\eta_p^2s > 0.432$, BFs > 1000). Focusing on the interaction effect between priority state and another-state load, further one-way repeated-measures ANOVA revealed that both the PMI and UMI recall errors changed across the another-state loads ($Fs > 9.982$, $ps < 0.001$, $\eta_p^2s > 0.303$, BFs > 99; Fig. 4C, left). Post hoc tests revealed that as the another-state load increased, PMI recall errors increased only between lower UMI loads (UMI load 1 vs. 2: $t(23) = 3.130$, $p = 0.014$, Cohen's $d = 0.363$, BF = 9.180; UMI load 2 vs. 3: $t(23) = 1.139$, $p = 0.799$, Cohen's $d = 0.123$, BF = 0.383), whereas UMI recall errors significantly increased as the another-state load gradually increased ($ts > 2.739$, $ps < 0.035$, Cohen's $ds > 0.320$, BFs > 4.251). Moreover, a paired t test of the slopes revealed that UMI recall errors were more significantly influenced by the PMI load than vice versa ($t(23) = 5.300$, $p < 0.001$, Cohen's $d = 1.082$, BF ≥ 1000; both slopes were greater than 0, $ts > 4.188$, $ps < 0.001$, Cohen's $ds > 0.855$, BF > 87.911; Fig. 4C, right).

Additionally, there was no significant three-way interaction between priority states, another-state loads, and presentation orders ($F(4,138) = 2.126$, $p = 0.081$, $\eta_p^2 = 0.058$, BF = 0.260), suggesting comparable interaction effects across three experiments with varying presentation orders of PMIs and UMIs.

Summary of Experiments 2 and 3

Both Experiments 2 and 3 replicated the main findings of Experiment 1: the interactive effects between the PMI and UMI memory were significant, and the UMI was more significantly affected by the PMI than was the opposite. These results suggested that the representation order of the PMI and UMI did not affect the pattern of their interactions. The different interactive effects between PMI and UMI under low and high memory loads in Experiments 2 and 3 are discussed further in the general discussion section.

Experiments 4 and 5

To investigate whether the interaction pattern between different types of priority information is consistent across different stimulus types, Experiments 4 and 5 employed delayed estimation tasks for orientations and locations, and we expected similar PMI and UMI interaction patterns.

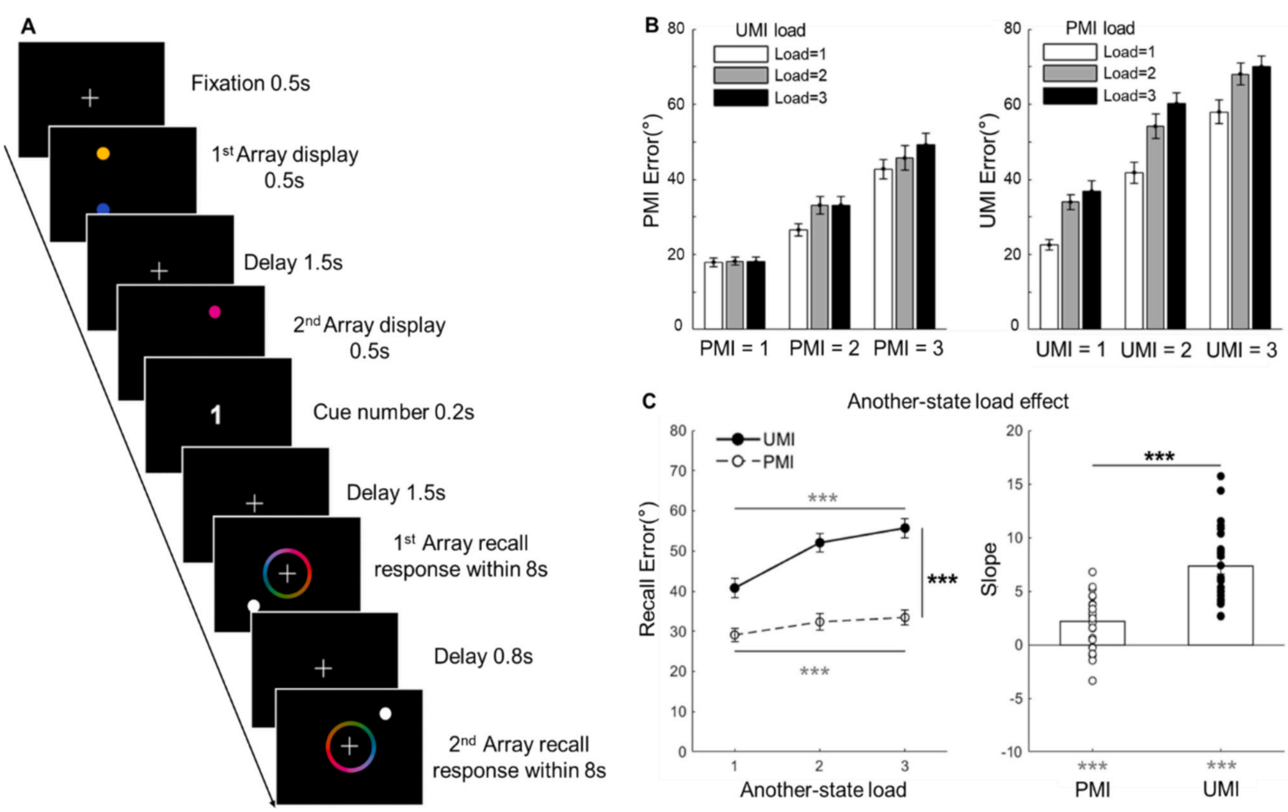


Fig. 4. A. The delayed estimation task for colors in Experiment 3. A post-encoding number cue indicates the recall order in each trial. The number "1″ indicates that participants recall the first color array and then the second array, and it will be presented in half of the randomized trials. B. Recall errors for PMIs and UMIs under different memory load conditions. C. Another-state load effects on PMI and UMI recall. In panel C, the left figures show changes in PMI and UMI recall errors under different another-state memory load conditions. Black asterisks represent significant interaction effect and gray asterisks represent significant one-way ANOVAs. The right figures show the fitted slopes of the another-state memory load effects on PMI and UMI recall. Black asterisks represent significant paired t-tests, and gray asterisks represent significant single-sample t-tests. Error bars represent standard errors (SE). ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

Experiment 4

Participants and procedure

The sample size of participants and selection criteria were consistent with those used in Experiment 1. Experiment 4 included 24 participants (12 males; age: M = 21.92 years, *SD* = 2.69). Participants completed a delayed recall task for orientations. In each trial, six orientations were randomly selected from 0° to 180°, with a minimum difference of 10°. The orientations were presented as white lines (1.5° in length, 0.1° in width). The positions where the orientations were presented were the same as those in Experiment 3. In the two test phases, participants were required to recall the orientation at the cued positions. On the probe display, a randomly oriented white line was presented at the center of the screen, and participants adjusted its orientation using the mouse and then confirmed the response by clicking the left button. The initial angle of the white line was randomized in each trial to prevent advance preparation (Fig. 5A).

Data analysis

The recall errors for orientations were defined as the different angles (in degrees) between the selected values and the targeted values. The data analysis procedure was the same as that in Experiment 3.

Results

The orientation task revealed a similar interaction pattern as the three experiments above. Three-way ANOVA revealed significant interaction effect between the priority state and the another-state load (F(2,46) = 22.431, $p < 0.001$, $\eta_p^2 = 0.494$, BF > 1000), with no three-way interaction or other two-way interactions (Fs < 1.267, ps > 0.289, η_p^2s < 0.052, BFs < 0.246). Accordingly, the following one-way repeated measures ANOVAs and post hoc tests revealed that both the PMI and UMI recall errors increased as the another-state load gradually increased (one-way ANOVAs: Fs > 20.071, ps < 0.001, η_p^2s > 0.466, BFs > 1000; post hoc tests: ps < 0.035, Cohen's ds > 0.227, BFs ≥ 4.290; Fig. 5C, left). Additionally, a paired t test of the slopes revealed that the UMI was more strongly affected by the PMI than vice versa (t(23) = 5.971, p < 0.001, Cohen's d = 1.219, BF ≥ 1000; both slopes were greater than 0: ts > 5.590, ps < 0.001, Cohen's ds > 1.141, BFs > 1000; Fig. 5C, right).

Experiment 5

Participants and procedure

The sample size of participants and selection criteria were consistent with those used in Experiment 1. Experiment 5 included 24 participants (7 males, M = 22.08 years, *SD* = 2.21).

Participants completed a delayed estimation task for locations. The only difference from Experiment 3 was that participants had to recall the previously presented locations during the test phase on the basis of the colored cues. To achieve this, the colors and positions of the stimuli were adjusted accordingly. In all of the trials, the colors of the two memory arrays were fixed and selected from the same color wheel: 60°, 180°, and 300° for one array and 120°, 240°, and 360° for the other; then, the positions were randomly selected from the same invisible circle, with a minimum difference of 20°. During the test phases, colored cues were

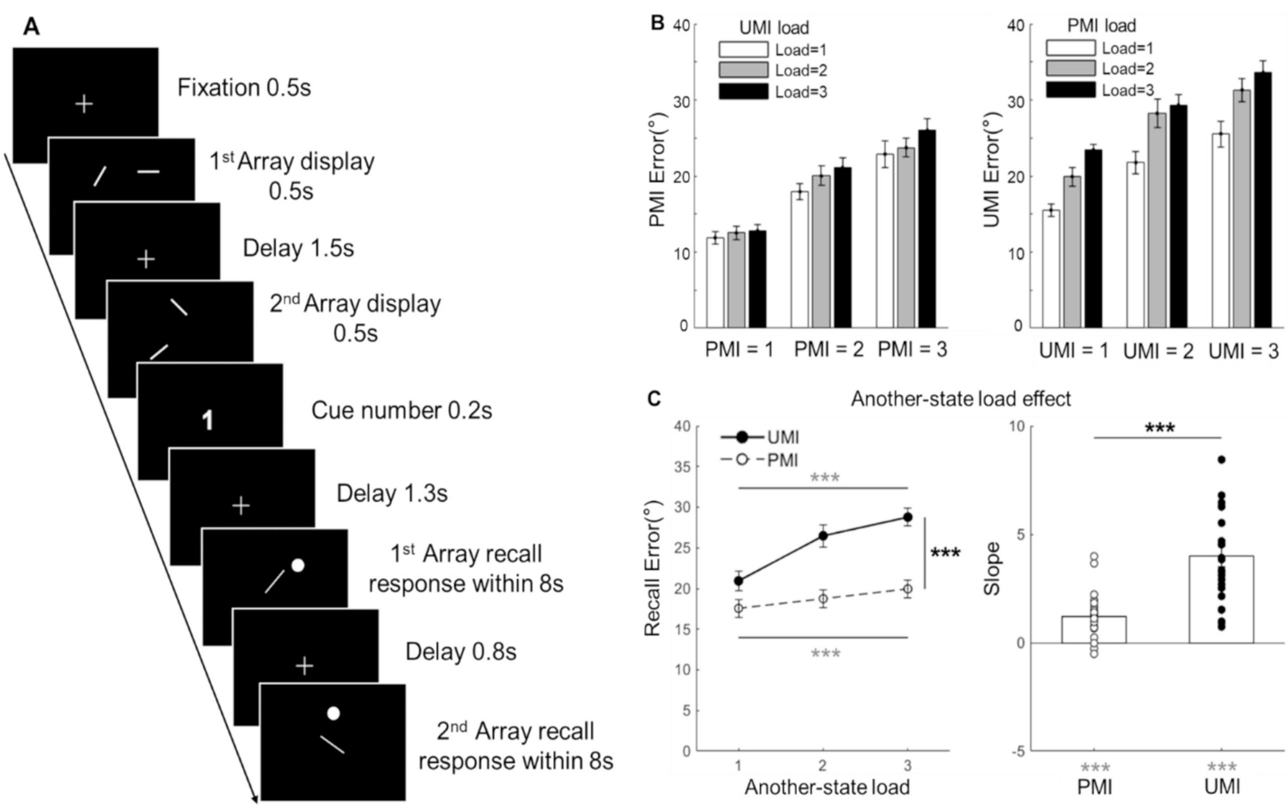


Fig. 5. A. The delayed estimation task for orientations in Experiment 4. After two orientation arrays, a number indicates the order of recalls: "1″ indicates participants recall the targeted orientation from the first array first, and "2″ indicates the opposite condition; B. Recall errors for PMIs and UMIs under different memory load conditions. C. Another-state load effects on PMI and UMI recall. In panel C, the left figures show changes in PMI and UMI recall errors under different another-state memory load conditions. Black asterisks represent significant interaction effect and gray asterisks represent significant one-way ANOVAs. The right figures show the fitted slopes of the another-state memory load effects on PMI and UMI recall. Black asterisks represent significant paired t-tests, and gray asterisks represent significant single-sample t-tests. Error bars represent standard errors (SE). ***p < 0.001; **p < 0.01; *p < 0.05.

presented in the center of the screen (radius = 0.5°), and a white response wheel was displayed (radius = 3°, width = 0.5°). The participants recalled the position of the cued colors by moving the mouse around the response wheel, with a white dot indicating the mouse's corresponding position (radius = 0.5°). The participants confirmed their selection by clicking the left mouse button. The initial position of the white dot was randomly set in each trial to prevent advance preparation (Fig. 6A).

Data analysis

The recall errors for locations were defined as the different angles (in degrees) between the selected values and the targeted values. The data analysis procedure was the same as that in Experiment 3. Furthermore, we performed a four-way repeated-measures ANOVA to compare the another-state load effects across Experiments 3 to 5. To achieve this, based on the three-way repeated-measures ANOVAs in each experiment, we added a between-subject factor stimuli type (Experiment 3: color recall vs. Experiment 4: orientation recall vs. Experiment 5: location recall). Given the non-uniform error scales (color/location errors ranged 0–180° due to unique dot values, while orientation errors ranged 0–90° due to circular angle representation), color/location errors were divided by two to ensure cross-experimental consistency and mitigate statistical biases.

Results

The location task also replicated the main findings of the three experiments above, although there was a slight difference. Three-way repeated-measures ANOVA revealed a significant interaction effect between the priority state, self-state load and another-state load ($F(4,92) = 3.915$, $p = 0.006$, $\eta_p^2 = 0.145$, BF = 17.435). Since we focused on the another-state load effect, at each self-load level, we conducted two-way repeated measures ANOVAs to test the interaction effects between the priority state and another-state load. The results revealed that when the self-state load was 1, although the main effects of the priority state and the another-state load were significant (*Fs* > 16.496, *ps* < 0.001, η_p^2s > 0.418, BFs > 100), there was no interaction effect between them ($F(2,46) = 0.957$, $p = 0.392$, $\eta_p^2 = 0.040$, BF = 0.297; Fig. 6C, left). One-way repeated measures ANOVAs revealed that both the PMI and UMI recall errors changed as the another-state load increased (*Fs* > 7.491, *ps* < 0.002, η_p^2s > 0.246, BFs > 35.366). Post hoc tests revealed that PMI recall errors tended to increase with increasing UMI load but were not statistically significant (load 1 vs. load 2: $t(23) = 2.514$, $p = 0.058$, Cohen's $d = 0.486$, BF = 2.793; load 2 vs. load 3: $t(23) = 1.786$, $p = 0.262$, Cohen's $d = 0.485$, BF = 0.845), and UMI recall errors followed a similar pattern (load 1 vs. load 2: $t(23) = 2.246$, $p = 0.104$, Cohen's $d = 0.487$, BF = 1.743; load 2 vs. load 3: $t(23) = 3.124$, $p = 0.014$, Cohen's $d = 0.638$, BF = 9.060). Consistently, paired t tests revealed no difference between the influences of the PMI on the UMI and those of the UMI on the PMI ($t(23) = 1.893$, $p = 0.071$, Cohen's $d = 0.387$, BF = 0.990; both slopes greater than 0: *ts* > 2.922, *ps* < 0.008, Cohen's *ds* > 0.597, BFs ≥ 6.058).

In contrast, when the self-state load was 2 or 3, the interaction patterns between the PMI and UMI were consistent with those of previous experiments, showing significant interaction effects between the priority state and the other-state load (*Fs* > 5.907, *ps* < 0.005; η_p^2s > 0.204; BFs > 15.486). Simple effects analysis and post hoc tests revealed that both PMI and UMI recall errors significantly increased as the another-state load gradually increased (one-way ANOVA: *Fs* > 17.610, *ps* < 0.001, η_p^2s > 0.434, BFs > 1000; post hoc *t* test: *ts* > 2.639, *ps* < 0.044, Cohen's $d > 0.492$; BFs ≥ 3.514; except for PMI recall errors, the PMI load was 2, UMI load 2 vs. load 3: $t(23) = 2.161$, $p = 0.124$, Cohen's $d = 0.525$, BF = 1.512). Additionally, a paired *t* test of the slopes revealed that the UMI was significantly more affected by the PMI than the opposite way was (*ts* > 3.204, *ps* < 0.004, Cohen's *ds* > 0.654, BFs ≥

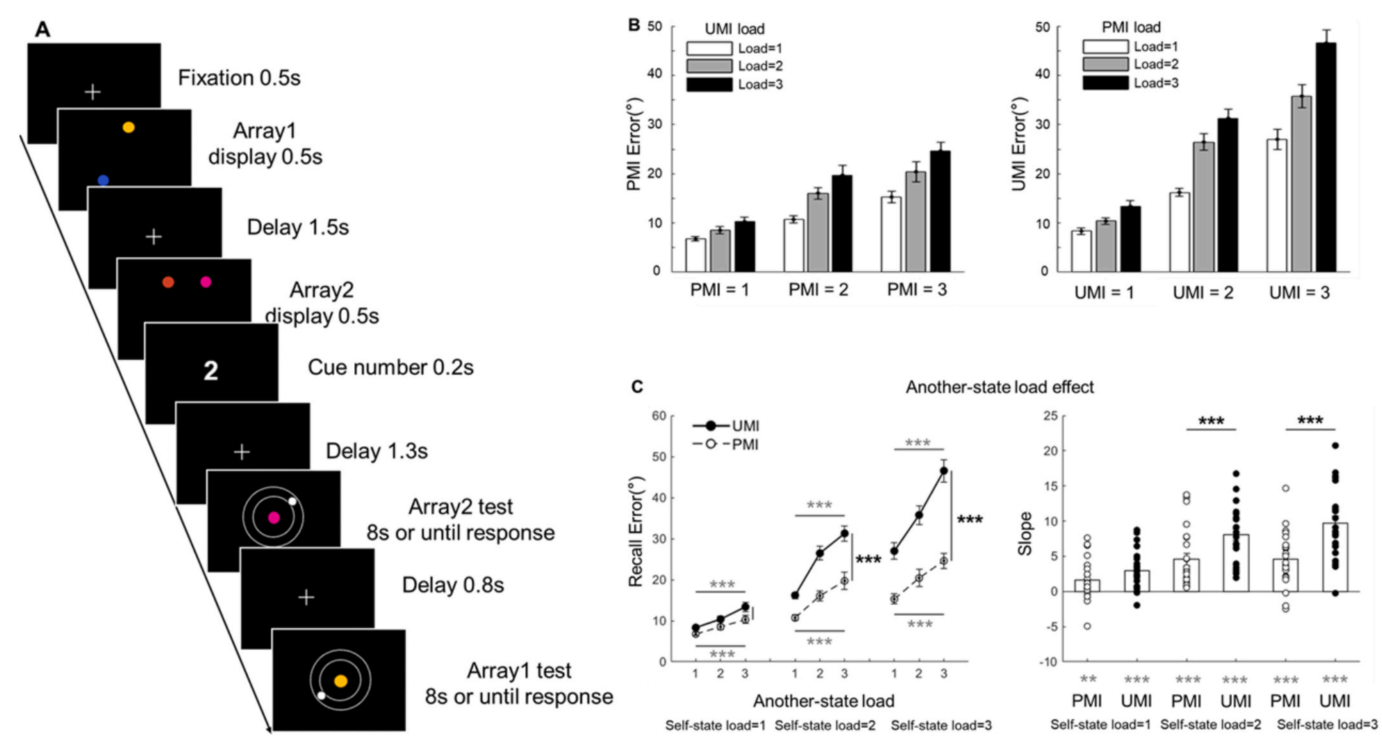


Fig. 6. A. The delayed estimation task for locations in Experiment 5. The procedure is similar with that in Experiment 4. B. Recall errors for PMIs and UMIs under different memory load conditions. C. Another-state load effects on PMI and UMI recall. In panel C, the left figures show changes in PMI and UMI recall errors under different another-state memory load conditions. Black asterisks represent significant interaction effect and gray asterisks represent significant one-way ANOVAs. The right figures show the fitted slopes of the another-state memory load effects on PMI and UMI recall. Black asterisks represent significant paired t-tests, and gray asterisks represent significant single-sample t-tests. Error bars represent standard errors (SE). ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

10.673; all slopes greater than 0: $ts > 5.265$, $ps < 0.001$, Cohen's $ds > 1.075$, BFs ≥ 971.071; Fig. 6C, right).

Finally, there was no significant three-way interaction between priority states, another-state loads, and stimuli types ($F(4,138) = 0.682$, $p = 0.606$, $\eta_p^2 = 0.019$, BF = 0.032), suggesting comparable interaction effects across the experiments with varying stimuli types.

Summary of Experiments 4 and 5

Experiments 4 and 5 verified that the asymmetry interaction pattern between PMIs and UMIs is consistent across different stimulus types. Notably, this pattern was similar across memory loads in color and orientation recalls but became more pronounced under higher loads in location recall. We explore potential reasons for these differences in the discussion section.

Experiments 6 and 7

Through the above experiments, we have provided strong evidence of the asymmetric interaction effects between PMIs and UMIs during VWM. However, the underlying cognitive mechanisms remain unclear. One view proposed that the asymmetry interactions occurred since more attentional resources were allocated to PMIs during the delay phase, reducing its susceptibility to interference (Bae & Luck, 2017). Another view suggested that the reactivation of UMI representations during PMI retrieval affects UMI recall, leading to a unidirectional influence (Muhle-Karbe et al., 2021). We tested these two hypotheses in Experiment 6 and Experiment 7 separately. The experimental designs leveraged that in Experiment 1, which showed the strongest interaction between priority status and another-state load.

Experiment 6

In Experiment 6, participated need to complete a math distracting task during the maintenance. This attention-shift manipulation temporally withdraws both PMIs and UMIs out of attention and introduces similar passive states. If the sustained attention to PMIs drives the asymmetric interactions, comparing with the attention-stay condition without distractors, we would expect an increased influence of UMIs on PMIs under the attention-shift condition and thus a less asymmetrical interaction, we kept the terms of PMIs and UMIs across experimental conditions since the recall priorities did not change and the comparisons between conditions would be clearer.

Participants

To determine the sample size, we entered the effect size of the interaction effect between priority status and the another-state load in Experiment 1 ($\eta_p^2 = 0.421$) into MorePower software, and a sample size of 18 participants would provide power greater than 90 % to replicate the interaction effect ($\alpha = 0.05$). The inclusion and screening criteria for participants were consistent with those of the previous experiments. Eighteen participants were included in Experiment 6 (5 males; age: M = 22.56 years, $SD = 4.23$).

Procedure

The procedure was similar to that in Experiment 1 except that we included two attention conditions (Fig. 7A). In half of the trials, consistent with the regular experimental procedure in Experiment 1, during the 2 s delay after the second color array, the participants only needed to look at the fixation at the center of the screen ("attention stay"). In the other half of the trials, the participants were required to complete a single-digit addition or subtraction task during this delay period ("attention switch"). In these attention switch trials, the participants judged whether the presented equation was correct by pressing the A or D key, with a maximum response time of 2 s. The keys were counterbalanced across participants. Moreover, the memory loads of PMIs and UMIs could be 1 or 2. Thus, in the Experiment 6, we included 8 conditions, and each condition included 40 trials. All trials were evenly and randomly distributed into 10 blocks. The experiment lasted for approximately 80 min.

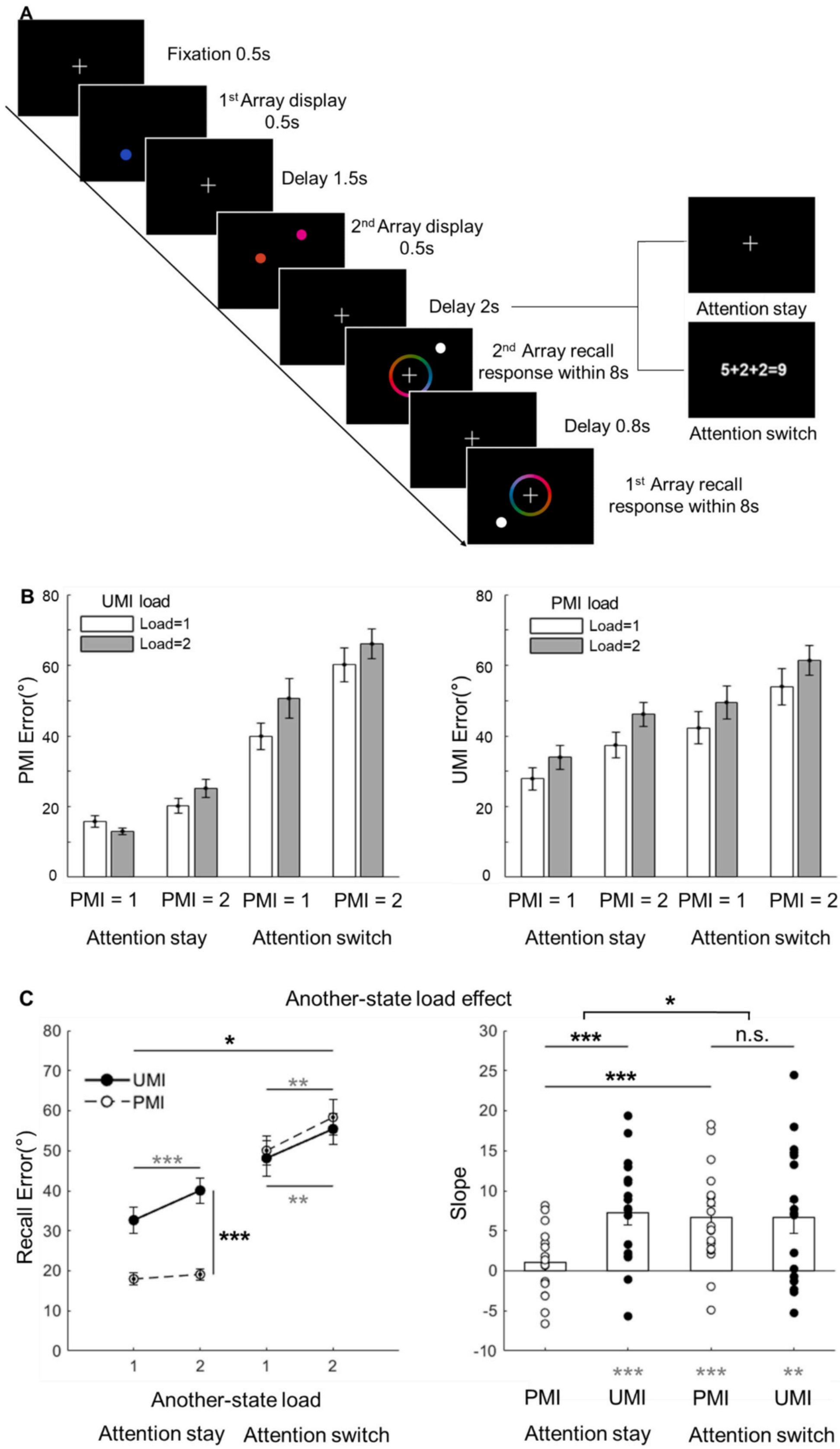
Data analysis

The accuracy rate in arithmetic judgments validated the attention-switching manipulation (mean accuracy = 70.90 %, $SD = 7.37$ %, one sample t-test versus chance level is significant, $t(17) = 12.023$, $p < 0.001$, Cohen's $d = 2.834$; BF ≥ 1000). The color recall error reflects the VWM performance. First, we performed similar three-factor repeated measures ANOVAs and statistical procedures in the attention-stay and attention-switch conditions separately. We still focused on the interaction between priority states and another-state load, and paired t-tests were conducted in each priority state if it was significant (since only two memory loads were included in this experiment). If different interaction patterns between the PMI and UMI were observed in the two attention conditions, we would then conduct a four-way repeated-measures ANOVA [2 (attention condition: attention stay vs. attention switch) × 2 (priority state: UMI vs. PMI) × 2 (self-state load: 1 vs. 2) × 2 (another-state load: 1 vs. 2)] to further confirm whether the differences were significant. Moreover, we performed a similar linear fit analysis of recall errors and further conducted a two-way ANOVA [2 (attention condition: attention stay vs. attention switch) × 2 (another-load effect: PMI affected by UMI vs. UMI affected by PMI)] to examine whether the interaction effects differed significantly between attention conditions.

Results

We replicated the results of Experiment 1 under the attention stay condition. The three-way ANOVA revealed significant two-way interactions between the priority state and another-state load, as well as between another-state load and self-state load ($Fs > 6.243$, $ps < 0.023$, $\eta_p^2s > 0.269$, BFs > 2.602), but no three-way interaction or two-way interaction between the priority state and self-state load ($Fs < 2.943$, $ps > 0.104$, $\eta_p^2s < 0.104$, BFs < 1.392). Then, further paired t tests revealed that UMI recall error significantly increased when the PMI load increased ($t(17) = 5.032$, $p < 0.001$, Cohen's $d = 1.186$; BF = 275.714), but no difference was detected in the opposite condition ($t(17) = 1.088$, $p = 0.292$, Cohen's $d = 0.257$, BF = 0.407; Fig. 7C, left). Consistently, paired t tests on the slopes revealed that the another-load effect on UMI was significantly greater than that on PMI ($t(17) = 3.839$, $p = 0.001$, Cohen's $d = 0.905$, BF = 29.533; the UMI slope was greater than 0:$t(17) = 4.695$, $p < 0.001$, Cohen's $d = 1.107$, BF = 147.313; and the PMI slope was not different from 0: $t(17) = 1.032$, $p = 0.317$, Cohen's $d = 0.243$, BF = 0.387; Fig. 7C, right). In contrast, as expected, under the attention switch condition, there were no three-way interaction or two-way interactions ($Fs < 2.087$, $ps > 0.167$, $\eta_p^2s < 0.108$, BFs < 0.729; Fig. 7C, left), but significant main effects of self-state load and another-state load ($Fs > 15.900$, $ps < 0.001$, $\eta_p^2s > 0.483$, BFs > 21.418). Paired t tests revealed that both the PMI and UMI recall errors increased when the another-state memory load increased ($ts > 2.937$, $ps < 0.009$, Cohen's $ds > 0.692$, BFs > 5.662; Fig. 7C, right). Similarly, paired t tests on the slopes revealed no difference in the degrees of the another-state loads on the PMIs and UMIs ($t(17) = 0.017$, $p = 0.987$, Cohen's $d = 0.004$, BF = 0.243; the slopes were all greater than 0: $ts > 3.297$, $ps < 0.004$, Cohen's $ds > 0.777$, BFs > 10.819; Fig. 7C, right).

More importantly, the four-way repeated-measures ANOVA revealed significant three-way interactions between attention condition, priority state and another-state load, as well as attention condition, another-state load and self-state load ($Fs > 4.779$, $ps < 0.043$, $\eta_p^2s > 0.219$, BFs > 1.677, no other interactions were significant: $Fs < 4.008$, $ps > 0.062$, $\eta_p^2s > 0.191$, BFs < 1.109). Additionally, a two-way ANOVA of the



(caption on next page)

Fig. 7. A. The procedure of Experiment 6. In Experiment 6, participants only needed to look at the fixation during the delay phase under the attention stay condition, while they are required to complete an arithmetic judgment task during the delay phase under the attention switch condition. Two types of trials were equally and randomly presented during the task. The loads of PMIs and UMIs are 1 or 2. B. Recall errors for PMIs and UMIs under different memory load conditions. C. Another-state load effects on PMI and UMI recall. In panel C, the left figures show changes in PMI and UMI recall errors under different another-state memory load conditions. Black asterisks represent significant interaction effect and gray asterisks represent significant one-way ANOVAs. The right figures show the fitted slopes of the another-state memory load effects on PMI and UMI recall. Black asterisks represent significant paired t-tests, and gray asterisks represent significant single-sample t-tests. Error bars represent standard errors (SE). ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

slopes revealed a significant interaction between the attention condition and the another-load effect ($F(1,17) = 5.765$, $p = 0.028$, $\eta_p^2 = 0.253$, BF $= 5.472$; Fig. 7C, right). Further paired t tests revealed that, compared with the attention stay condition, the another-load effect on the PMI specifically increased under the attention switch condition ($t(17) = 4.084$, $p < 0.001$, Cohen's $d = 0.963$, BF $= 46.780$; the another-load effect on the UMI did not change: $t(17) = 0.203$, $p = 0.842$, Cohen's $d = 0.048$; BF $= 0.248$). These results confirmed that the asymmetry interaction effects were a result of sustained attention to the PMI and that the PMI was less affected by UMI.

Experiment 7

In Experiment 7, participated completed an additional single-recall condition where only PMIs or UMIs were recalled. If the prioritized retrieval of PMIs contributed to the asymmetrical interaction, we would expect that the influence of the PMI on the UMI specifically decrease when PMI recall was not needed. As a result, the asymmetry interaction effects reduced.

Participants

The sample size of participants and selection criteria were consistent with those used in Experiment 6. Eighteen participants were included in Experiment 7 (4 males, age: M = 21.61 years, *SD* = 2.20).

Procedure

The procedure was similar to that of Experiment 1 except that we included two recall conditions. In both conditions, participants encoded two memory arrays with the instructions that the second memory array was always first-recalled (PMIs) and the first memory array would be later-recalled (UMIs). Then, after the delay following the second memory array display, different types of recall trials were randomly presented: In the double recall condition, consistent with previous experiments, participants recalled the PMI and UMI sequentially ("double recall: PMI & UMI"). In the single recall condition, participants needed to recall only the PMI or UMI ("single recall: PMI" or "single recall: UMI" in 50 % chance). In the single recall PMI trials, the participants recalled the targeted colors from the second memory array when the probe display appeared, and no responses were required in the following waiting display, where a white dot (radius $= 0.5°$) was presented for 2 s; In the single recall UMI trials, the same white dot waiting display was first presented for 2 s, and then the participants needed to recall the targeted colors from the first memory array when the following probe display appeared (Fig. 8A). Notably, the 2 s interval was based on the mean recall RT of PMIs in Experiment 1 to minimize the potential influence of different delay durations (the actual RTs for PMIs in two conditions were comparable to, and not significantly different from, 2 s, $ps > 0.05$); and the waiting display omitted the response wheel to prevent potential spontaneous retrieval processes.

Data analysis

The data analysis in Experiment 7 was similar to that of Experiment 6, and we examined whether the interaction patterns differed between the double-recall and single-recall conditions.

Results

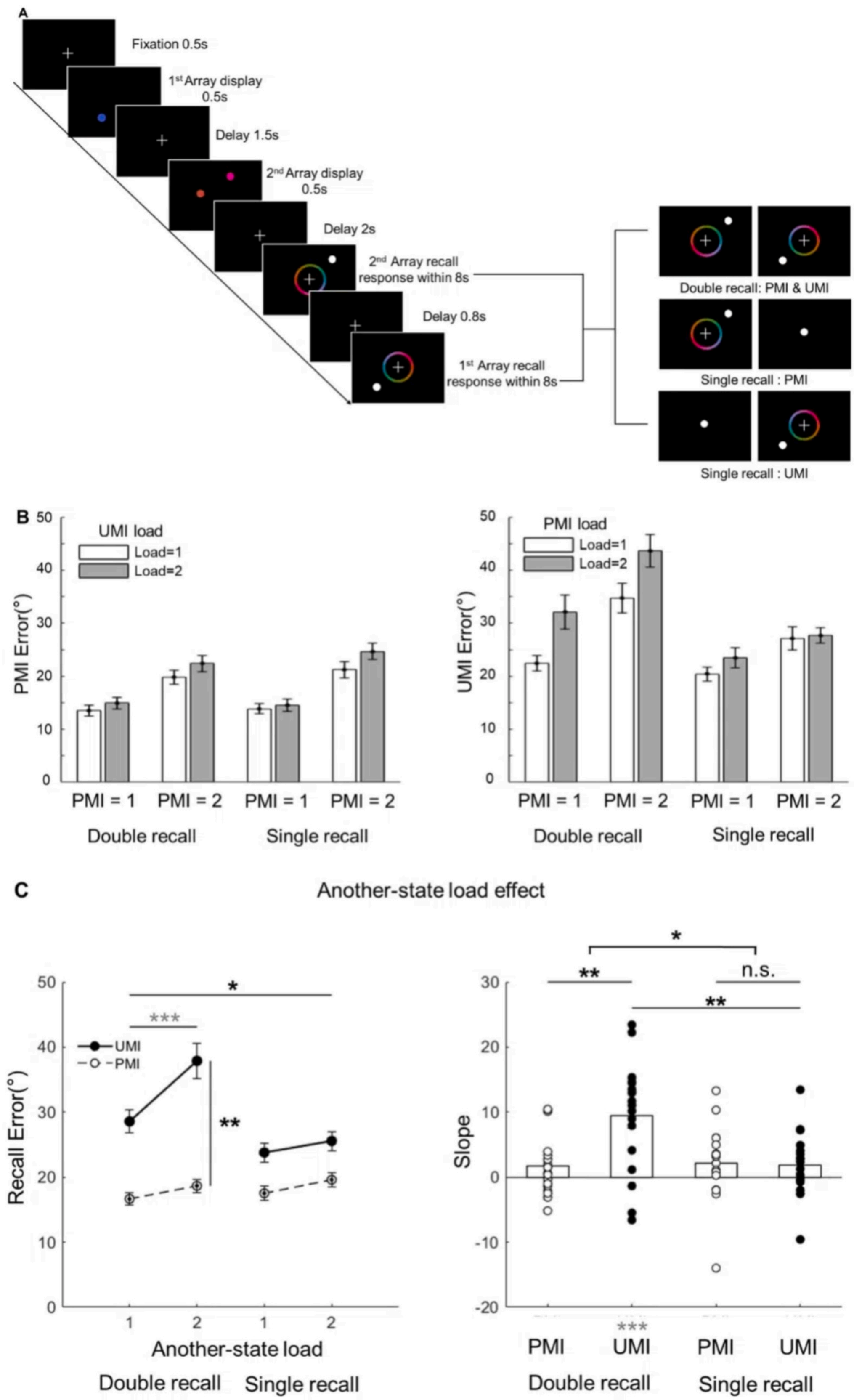
Similarly, we replicated the results of Experiment 1 in the double-recall trials. A three-factor repeated-measures ANOVA revealed that two-way interactions between priority state and another-state load ($F(1,17) = 12.848$, $p = 0.002$, $\eta_p^2 = 0.430$, BF $= 12.516$), as well as those between priority state and self-state load, were significant ($F(1,17) = 8.595$, $p = 0.009$, $\eta_p^2 = 0.336$, BF $= 1.424$; other interaction effects: $Fs < 0.107$, $ps > 0.748$, $\eta_p^2s < 0.006$, BFs < 0.332). Further paired t tests revealed that the UMI recall error significantly increased with increasing PMI load ($t(21) = 4.532$, $p < 0.001$, Cohen's $d = 1.068$; BF $= 129.626$), whereas the PMI recall error did not change when the UMI load increased ($t(17) = 1.859$, $p = 0.080$, Cohen's $d = 0.438$, BF $= 0.538$; Fig. 8C, left). Similarly, paired t tests on the slopes revealed that the another-load effect on UMI was significantly greater than that on PMI ($t(17) = 3.644$, $p = 0.002$, Cohen's $d = 0.859$, BF $= 20.496$; on UMI: $t(17) = 4.821$, $p < 0.001$, Cohen's $d = 1.136$, BF $= 186.412$; on PMI: $t(17) = 1.555$, $p = 0.138$, Cohen's $d = 0.366$, BF $= 0.672$; Fig. 8C, right). In contrast, in the single-recall condition, except for a significant two-way interaction between priority state and self-state load ($F(1,17) = 6.849$, $p = 0.018$, $\eta_p^2 = 0.287$, BF $= 1.344$), the other interaction effects were not significant ($Fs < 2.017$, $ps > 0.174$, $\eta_p^2s < 0.106$, BFs < 1.849). Further paired t tests revealed that neither the PMI nor the UMI recall errors changed when the another-state load increased ($ts < 1.577$, $ps > 0.133$, Cohen's $d < 0.356$, BFs < 0.691; Fig. 8C, left). Similarly, the comparison of slopes revealed that there were no significant another-load effects on the PMI or UMI ($ts < 1.630$, $ps > 0.121$, Cohen's $ds < 0.384$, BFs < 0.738; difference: $t(17) = 0.136$, $p = 0.894$, Cohen's $d = 0.032$, BF $= 0.245$; Fig. 8C, right).

Moreover, the four-way repeated-measures ANOVA revealed significant three-way interactions between the recall condition, priority state and another-state load, as well as between the recall condition, priority state and self-state load ($Fs > 6.112$, $ps < 0.024$, $\eta_p^2s > 0.264$, BFs > 3.240; other interaction effects: $Fs < 0.981$, $ps > 0.336$, $\eta_p^2s < 0.055$, BFs < 0.510). Moreover, two-way ANOVA of the slopes revealed a significant interaction effect ($F(1,17) = 5.790$, $p = 0.028$, $\eta_p^2 = 0.254$, BF $= 24.087$). Further paired t tests revealed that the another-load effect on UMI specifically decreased in the double-recall condition compared with that in the single-recall condition ($t(17) = 3.189$, $p = 0.005$, Cohen's $d = 0.752$, BF $= 8.879$; no changes in the another-load effect on PMI were detected: $t(17) = 0.272$, $p = 0.789$, Cohen's $d = 0.064$, BF $= 0.251$; Fig. 8C, right). These results suggested that the priority retrieval of the prioritized set contributes to the greater influence of the PMI on the UMI than that of the UMI on the PMI.

Summary of Experiments 6 and 7

The results of Experiment 6 indicated that the smaller influence of UMI on PMI was due to the protective effect of sustained attention on PMI during the delay phase, which reduced its susceptibility to UMI. Moreover, the results of Experiment 7 indicated that the greater influence of the PMI on the UMI was due to the prioritized retrieval of the PMI, which increased the interference from the PMI unidirectionally. Together, both the sustained attention to PMIs and the prioritized retrieval of PMIs were responsible for the asymmetric interaction effects between the PMI and UMI during VWM.

Notably, Experiment 6 revealed comparable recall performance between PMIs and UMIs following the distractor task, alongside



(caption on next page)

Fig. 8. A. The procedure of Experiment 7. In Experiment 7, participants sequentially recall colors from two memory arrays under the double recall condition, whereas participants only recall one memory array under the single recall condition. Three types of trials are equally and randomly presented during the task, and the PMIs and UMIs are 1 or 2. B. Recall errors for PMIs and UMIs under different memory load conditions. C. Another-state load effects on PMI and UMI recall. In panel C, the left figures show changes in PMI and UMI recall errors under different another-state memory load conditions. Black asterisks represent significant interaction effect and gray asterisks represent significant one-way ANOVAs. The right figures show the fitted slopes of the another-state memory load effects on PMI and UMI recall. Black asterisks represent significant paired t-tests, and gray asterisks represent significant single-sample t-tests. Error bars represent standard errors (SE). ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

comparable another-load effects of PMIs and UMIs — a pattern seemingly inconsistent with Experiment 7′s demonstration that PMI retrieval evoked extra interference on UMIs. We reconcile these outcomes through differential pre-recall states of PMIs: In Experiment 6, the arithmetic task disrupted sustained attention to PMIs, inducing temporally pre-recall passive states and resulting in a passive-state retrieval for PMIs. In contrast, in Experiment 7, PMIs sustained in active states before retrieval, leading to an active-state retrieval. This dissociation demonstrates that, although PMI retrievals occur in both experiments, only active-state retrieval of PMIs interferes with UMIs and drives the asymmetric interaction pattern. Aligning with this interpretation, studies have demonstrated that only PMIs could be reactivated by visual impulses (Wolff et al., 2015) and neural modulations (Rose et al., 2016) during the maintenance before recall, indicating that pre-recall storage states lead to different retrieval processes. Critically, recent evidence supported the interference effect of active-state retrieval: neural reactivations of UMIs during PMI recall were observed (Muhle-Karbe et al., 2021), and PMI reactivations after visual impulses correlated with impaired UMI recall (Yang et al., 2025). Nevertheless, the consequences of retrieval from (temporally) passive states remain underexplored and warrant further investigation.

General discussion

Our study revealed asymmetrical interactions between PMIs and UMIs during VWM and clarified its underlying cognitive mechanism. That is, the degree to which PMIs affected UMIs during VWM was greater than the opposite, and this pattern was consistent across presentation orders and stimulus types. Moreover, the sustained attention allocation to PMIs during maintenance and the prioritized PMI retrieval were responsible for the observed asymmetric interactions, with the former increased the influence of UMIs on PMIs and the latter decreased the influence of PMIs on UMIs.

First, we found that UMI recall deteriorated when the PMI load increased and vice versa, providing direct evidence for the interactions between information with varying priorities during VWM. These findings are consistent with previous studies (Bae & Luck, 2017). Compared with Bae's study, on the one hand, PMIs and UMIs in the current study did not overlap in terms of location, ruling out the potential explanation that the observed interaction effects were caused only by the shared locations at the perceptual level; on the other hand, we examined the interactions between the PMIs and UMIs by testing the another-load effects instead of by measuring the recall biases, which provided a novel perspective to understand the interaction from sharing general VWM resources in addition to the lateral inhibition. However, when a similar design but a change detection task was used, another study failed to detect such interactions (Z. Li et al., 2021). We proposed that the most likely reason could be the delayed estimation task in the current study was more sensitive in detecting small performance changes. In addition, another recent study noted that PMI loads affect UMI performance only if the interval duration is too short (<1 s) to consolidate memory(Z. Li et al., 2024). However, this view was not supported by our results and we still observed mutual influences when memory consolidation was completed (with a long interval of 1.5 s). Importantly, our results cannot be adequately accounted by a pure resource-based model since larger self-load effects were observed than another-state load effects, indicating more intensive resource competition within-state than between-states, and could be better predicted by the state-based model.

Furthermore, our study revealed that the interaction pattern was asymmetrical, with a greater influence of PMIs on UMIs. This asymmetric interaction pattern has been also noted by an earlier study (Bae & Luck, 2017), and our study advanced their findings from the perspective of larger another-state load effects, and extended the asymmetrical interaction to the memory load exceeding memory capacity. More critically, we demonstrated that shifting attention specifically increased the influence of UMIs on PMIs, directly verifying the attention allocation hypothesis. This result was also consistent with previous findings that items allocated more attention would experience less interference. For example, one study reported that neither the performance of the PMI nor the VWM-related EEG indices (such as CDA) changed with UMI loads (Heuer & Schubö, 2016). However, these findings were challenged by other studies. For example, another study reported that a task-irrelevant stimulus during maintenance had a larger negative impact on the PMI than the UMI (Allen & Ueno, 2018; Hu et al., 2016). We proposed that these inconsistencies could be explained when we distinguished task-irrelevant interference on PMIs and UMIs from the mutual influence between PMIs and UMIs, which deserves more attention in future studies.

Besides, we confirmed that prioritized PMI retrieval was also responsible for the asymmetric interactions, which additionally increased the impacts of the PMI on the UMI. Since the priority of items was determined by response orders in most studies, the prioritized retrieval of PMIs may unidirectionally affect UMIs. Our study verified this hypothesis by demonstrating that the influence of PMIs on UMIs specifically decreased in trials where PMIs were not recalled. While other components of the testing window, such as test duration or probe interference, may also contribute to the worsened performance for UMI, the specific pattern of results observed in our study suggests that the prioritized retrieval of PMIs plays a critical role in the asymmetric interaction effects. Consistently, recent neuroimaging evidence has revealed neural representations of UMIs during PMI recall, confirming the "reactivation" of UMIs (Muhle-Karbe et al., 2021). Moreover, the latest study revealed that, visual impulses evoked neural reactivations of VWM, and larger reactivations were correlated with worse recall for both PMIs and UMIs (Yang et al., 2025). These researchers proposed that the neural reactivations weakened the neural dynamic representations, which have been proven to be beneficial for VWM, impairing the VWM performance (Liu et al., 2020). Moreover, our findings were consistent with studies that reported output interference in previous studies. For example, WM studies demonstrated large primacy effects in the serial recall for verbal stimuli (Cowan et al., 2002; Cowan & Elliott, 2023), and another study reported similar effects in long-term memory recall tasks (Bartsch & Oberauer, 2023). Notably, although both retrieval interference and attention allocation bias contribute to the asymmetrical interaction between PMIs and UMIs, they operate in separated ways.

Finally, although the overall interactions between PMIs and UMIs were consistent across presentation orders and stimuli, there were some distinctions. Regarding different presentation orders, when PMIs were first encoded, PMIs were more affected by UMIs when UMI loads were high, whereas UMIs were more affected by PMIs when PMI loads were low. In contrast, when PMIs were encoded later or the encoded orders were randomized, PMIs were more affected when UMI loads were low, whereas UMIs were affected regardless of PMI loads. These inconsistencies may be explained by memory strategies. Specifically, when PMIs were presented first, the memory state of both PMIs and UMIs underwent at least one priority shift (since UMIs must be in the focus of attention during their initial encoding). In this case, when the PMI load is low or the UMI load is high, individuals may tend to store them in the same active state to minimize the cost of state switching, leading to greater interactions; In the latter two conditions, individuals always encoded the first array as UMIs. Thus, as long as the load of the first array was small, individuals would be more likely to store all items in the same active state, resulting in stronger interactions. Regarding different stimuli, our study revealed that the asymmetric interactions in color and orientation recall tasks were consistent across memory loads but became more pronounced under high loads in the location task. We proposed two possibilities for this difference. First, it may reflect the dissociated processing between nonspatial and spatial WM. For example, compared with nonspatial WM, spatial WM processing could be more automatic (Postle et al., 2000; Ungerleider & Haxby, 1994). Second, it may just reflect the lower task difficulty in spatial WM (Cai et al., 2018; Wheeler & Treisman, 2002). In both conditions, we would predict only obvious asymmetrical interactions in high loads in spatial WM. Collectively, our results suggested a highly flexible storage process during VWM. We propose a specific account wherein items are tended to be stored in different states under high memory loads – a strategic adaption where the benefits of separated storage (e.g. reduced within-state interference) outweigh the costs of state-switching (e.g. dynamic changes of states). However, this account needs to be tested further in future studies.

There were several limitations in this study. For example, owing to the limited number of trials, we used recall error as an integrated index of VWM performance. Future studies could use model fittings to further elucidate the specific cognitive components of their interactions (e.g., recall precision and recall probability of targets) (Schneegans & Bays, 2016). In addition, future neuroimaging studies are needed to reveal the neural basis of the dynamics of such asymmetrical interactions. Furthermore, our study only focused on the condition where prioritization was identified by the recall order, future studies can further explore whether our conclusions could extend to prioritizations identified by other manipulations such as rewards, and so on.

Conclusions

This study revealed asymmetric interactions between PMIs and UMIs during VWM. Moreover, we clarified that the sustained attention to PMIs during maintenance and the prioritized retrieval of PMIs contributed to such interaction pattern separately. In summary, our findings clarified how the information with varying priorities interacts during VWM, extending our understanding of priority-based information processing during VWM.

CRediT authorship contribution statement

Jing Ni: Writing – original draft, Validation, Formal analysis, Data curation, Conceptualization. **Jiayi Fu:** Formal analysis, Data curation. **Ruotong Wang:** Formal analysis, Data curation. **Can Yang:** Writing – review & editing, Formal analysis. **Ying Cai:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

Funding

This work was supported by the STI 2030-Major Projects (2021ZD0200409, 2021ZD0200401), the Fundamental Research Funds for the Central Universities (226–2024-00118), and the National Natural Science Foundation of China (32100851).

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.

Data availability

I have shared the link to my data

References

Allen, R. J., & Ueno, T. (2018). Multiple high-reward items can be prioritized in working memory but with greater vulnerability to interference. *Attention, Perception, & Psychophysics, 80*(7), 1731–1743. https://doi.org/10.3758/s13414-018-1543-6

Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.), *Psychology of Learning and Motivation* (Vol. 8, pp. 47–89). Academic Press. https://doi.org/10.1016/S0079-7421(08)60452-1.

Bae, G.-Y., & Luck, S. J. (2017). Interactions between visual working memory representations. *Attention, Perception, & Psychophysics, 79*(8), 2376–2395. https://doi.org/10.3758/s13414-017-1404-8

Bartsch, L. M., & Oberauer, K. (2023). The contribution of episodic long-term memory to working memory for bindings. *Cognition, 231*, Article 105330. https://doi.org/10.1016/j.cognition.2022.105330

Bays, P. M., & Husain, M. (2008). Dynamic Shifts of Limited Working memory Resources in Human Vision. *Science, 321*(5890), 851–854. https://doi.org/10.1126/science.1158023

Cai, Y., Urgolites, Z., Wood, J., Chen, C., Li, S., Chen, A., & Xue, G. (2018). Distinct neural substrates for visual short-term memory of actions. *Human Brain Mapping, 39*(10), 4119–4133. https://doi.org/10.1002/hbm.24236

Campbell, J. I. D., & Thompson, V. A. (2012). MorePower 6.0 for ANOVA with relational confidence intervals and Bayesian analysis. *Behavior Research Methods, 44*(4), 1255–1265. https://doi.org/10.3758/s13428-012-0186-0

Christophel, T. B., Iamshchinina, P., Yan, C., Allefeld, C., & Haynes, J.-D. (2018). Cortical specialization for attended versus unattended working memory. *Nature Neuroscience, 21*(4). https://doi.org/10.1038/s41593-018-0094-4. Article 4.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24*(1), 87–114. https://doi.org/10.1017/S0140525X01003922

Cowan, N., & Elliott, E. M. (2023). Deconfounding serial recall: Response timing and the overarching role of grouping. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 49*(2), 249–268. https://doi.org/10.1037/xlm0001157

Cowan, N., Saults, J. S., Elliott, E. M., & Moreno, M. V. (2002). Deconfounding Serial recall. *Journal of Memory and Language, 46*(1), 153–177. https://doi.org/10.1006/jmla.2001.2805

Heuer, A., & Schubö, A. (2016). The focus of attention in visual working memory: Protection of focused representations and its individual variation. *PLoS One1, 11*(4), Article e0154228. https://doi.org/10.1371/journal.pone.0154228

Hitch, G. J., Hu, Y., Allen, R. J., & Baddeley, A. D. (2018). Competition for the focus of attention in visual working memory: Perceptual recency versus executive control. *Annals of the New York Academy of Sciences, 1424*(1), 64–75. https://doi.org/10.1111/nyas.13631

Hollingworth, A., & Maxcey-Richard, A. M. (2013). Selective maintenance in visual working memory does not require sustained visual attention. *Journal of Experimental Psychology: Human Perception and Performance, 39*(4), 1047–1058. https://doi.org/10.1037/a0030238

Hu, Y., Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2016). Executive control of stimulus-driven and goal-directed attention in visual working memory. *Attention, Perception, & Psychophysics, 78*(7), 2164–2175. https://doi.org/10.3758/s13414-016-1106-7

Lewis-Peacock, J. A., Drysdale, A. T., Oberauer, K., & Postle, B. R. (2012). Neural evidence for a Distinction between short-term memory and the Focus of attention. *Journal of Cognitive Neuroscience, 24*(1), 61–79. https://doi.org/10.1162/jocn_a_00140

Li, Z., Lei, M., & Liu, Q. (2024). Cognitive mechanisms underlying the formation of offline representations in visual working memory. *Acta Psychologica Sinica, 56*(4), 412. https://doi.org/10.3724/SP.J.1041.2024.00412

Li, Z., Liang, T., & Liu, Q. (2021). The storage resources of the active and passive states are independent in visual working memory. *Cognition, 217*, Article 104911. https://doi.org/10.1016/j.cognition.2021.104911

Liu, J., Zhang, H., Yu, T., Ni, D., Ren, L., Yang, Q., Lu, B., Wang, D., Heinen, R., Axmacher, N., & Xue, G. (2020). Stable maintenance of multiple representational formats in human visual short-term memory. *Proceedings of the National Academy of Sciences, 117*(51), 32329–32339. https://doi.org/10.1073/pnas.2006752117

Ma, W. J., Husain, M., & Bays, P. M. (2014). Changing concepts of working memory. *Nature Neuroscience, 17*(3), 347–356. https://doi.org/10.1038/nn.3655

Mallett, R., & Lewis-Peacock, J. A. (2019). Working memory prioritization impacts neural recovery from distraction. *Cortex, 121*, 225–238. https://doi.org/10.1016/j.cortex.2019.08.019

Muhle-Karbe, P. S., Myers, N. E., & Stokes, M. G. (2021). A hierarchy of functional states in working memory. *The Journal of Neuroscience, 41*(20), 4461–4475. https://doi.org/10.1523/JNEUROSCI.3104-20.2021

Myers, N. E., Chekroud, S. R., Stokes, M. G., & Nobre, A. C. (2018). Benefits of flexible prioritization in working memory can arise without costs. *Journal of Experimental Psychology: Human Perception and Performance, 44*(3), 398–411. https://doi.org/10.1037/xhp0000449

Myers, N. E., Stokes, M. G., & Nobre, A. C. (2017). Prioritizing Information during Working memory: Beyond Sustained Internal attention. *TRENDS IN COGNITIVE SCIENCES, 21*(6), 449–461. https://doi.org/10.1016/j.tics.2017.03.010

Nee, D. E., & Jonides, J. (2011). Dissociable contributions of prefrontal cortex and the hippocampus to short-term memory: Evidence for a 3-state model of memory. *NeuroImage, 54*(2), 1540–1548. https://doi.org/10.1016/j.neuroimage.2010.09.002

Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*(3), 411–421. https://doi.org/10.1037/0278-7393.28.3.411

Oberauer, K. (2005). Control of the Contents of Working Memory—A Comparison of two Paradigms and two Age groups. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*(4), 714–728. https://doi.org/10.1037/0278-7393.31.4.714

Olivers, C. N. L., Peters, J., Houtkamp, R., & Roelfsema, P. R. (2011). Different states in visual working memory: When it guides attention and when it does not. *Trends in Cognitive Sciences, 15*(7), 327–334. https://doi.org/10.1016/j.tics.2011.05.004

Peters, J. C., Roelfsema, P. R., & Goebel, R. (2012). Task-Relevant and Accessory items in Working memory have Opposite Effects on activity in Extrastriate Cortex. *JOURNAL OF NEUROSCIENCE, 32*(47), 17003–17011. https://doi.org/10.1523/JNEUROSCI.0591-12.2012

Pietrelli, M., Samaha, J., & Postle, B. R. (2022). Spectral distribution Dynamics across Different Attentional Priority States. *Journal of Neuroscience, 42*(19), 4026–4041. https://doi.org/10.1523/JNEUROSCI.2318-21.2022

Postle, B. R., Zarahn, E., & D'Esposito, M. (2000). Using event-related fMRI to assess delay-period activity during performance of spatial and nonspatial working memory tasks. *Brain Research Protocols, 5*(1), 57–66. https://doi.org/10.1016/S1385-299X(99)00053-7

Rose, N. S., LaRocque, J. J., Riggall, A. C., Gosseries, O., Starrett, M. J., Meyering, E. E., & Postle, B. R. (2016). Reactivation of latent working memories with transcranial magnetic stimulation. *Science, 354*(6316), 1136–1139. https://doi.org/10.1126/science.aah7011

Schneegans, S., & Bays, P. M. (2016). No fixed item limit in visuospatial working memory. *Cortex, 83*, 181–193. https://doi.org/10.1016/j.cortex.2016.07.021

Shaffer, W., & Shiffrin, R. M. (1972). Rehearsal and storage of visual information. *Journal of Experimental Psychology, 92*(2), 292–296. https://doi.org/10.1037/h0032076

Shepherdson, P., Hell, L., & Oberauer, K. (2022). How does visual working memory solve the binding problem? *Journal of Experimental Psychology: Human Perception and Performance, 48*(10), 1137–1152. https://doi.org/10.1037/xhp0001044

Ungerleider, L. G., & Haxby, J. V. (1994). 'What' and 'where' in the human brain. *Current Opinion in Neurobiology, 4*(2), 157–165. https://doi.org/10.1016/0959-4388(94)90066-3

Van Loon, A. M., Olmos-Solis, K., Fahrenfort, J. J., & Olivers, C. N. (2018). Current and future goals are represented in opposite patterns in object-selective cortex. *eLife, 7*, Article e38677. https://doi.org/10.7554/eLife.38677

Wan, Q., Cai, Y., Samaha, J., & Postle, B. R. (2020). Tracking stimulus representation across a 2-back visual working memory task. *Royal Society Open Science, 7*(8), Article 190228. https://doi.org/10.1098/rsos.190228

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General, 131*(1), 48–64. https://doi.org/10.1037/0096-3445.131.1.48

Wolff, M. J., Ding, J., Myers, N. E., & Stokes, M. G. (2015). Revealing hidden states in visual working memory using electroencephalography. *Frontiers in Systems Neuroscience, 9*. https://doi.org/10.3389/fnsys.2015.00123

Yang, C., He, X., & Cai, Y. (2025). Reactivating and reorganizing activity-silent working memory: Two distinct mechanisms underlying pinging the brain. *Cerebral Cortex*. , Article bhae494. https://doi.org/10.1093/cercor/bhae494

Yu, Q., & Shim, W. M. (2017). Occipital, parietal, and frontal cortices selectively maintain task-relevant features of multi-feature objects in visual working memory. *NeuroImage, 157*, 97–107. https://doi.org/10.1016/j.neuroimage.2017.05.055

Yu, Q., Teng, C., & Postle, B. R. (2020). Different states of priority recruit different neural representations in visual working memory. *PLOS Biology, 18*(6), Article e3000769. https://doi.org/10.1371/journal.pbio.3000769

Zhang, J., Ye, C., Sun, H.-J., Zhou, J., Liang, T., Li, Y., & Liu, Q. (2022). The passive state: A protective mechanism for information in working memory tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 48*(9), 1235–1248. https://doi.org/10.1037/xlm0001092

Zhang, W., & Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature, 453*(7192), 233–235. https://doi.org/10.1038/nature06860