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RESEARCH ARTICLE

Prioritization mechanisms in working memory modulate perceptual interference

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ABSTRACT

Working memory provides temporary storage of information needed for immediate responses. Within this system, individuals can also prioritize certain items, enhancing the representation of those items. An ongoing debate concerns whether prioritized information is protected from or vulnerable to external stimuli remains debated. The present study examined how prioritization mechanisms of working memory interact with perceptual interference from external stimuli. Participants performed a working memory task in which item priority was manipulated using either value-based cues or spatial cues, presented either before encoding or during maintenance. Following the memory display, a to-be-ignored suffix item (a geometric shape) was either presented or omitted. In this way, we examined whether the extent of suffix interference would vary depending on the type and timing of prioritization. The results showed that the interference effect of suffix items on prioritized information is not consistent but is observed only under specific conditions. In particular, prioritized items were more susceptible to suffix interference only when high value was assigned before encoding. By contrast, when value-based prioritization was applied during maintenance, no such interference was observed. Similarly, spatial cueing-based prioritization protected prioritized items from suffix interference regardless of whether cues were given before encoding or during maintenance. These findings suggest that different forms and timings of prioritization in working memory interact distinctly with perceptual interference from irrelevant stimuli.

Keywords: Prioritization; Working memory; Suffix interference

1. Introduction

The visual environment contains a substantial amount of information to process at a given time. Hence, people need to be capable of prioritizing behaviorally relevant information for further processing. Specifically, directing attention to a stimulus in the visual environment helps preferential encoding of the attended stimulus into working memory, which enables information to be momentarily maintained for immediate use in ongoing processing [1] (Cowan, 2017). Such prioritization can be implemented in at least two primary ways: spatial cueing-based and value-based.

In spatial cueing-based prioritization, Individuals can prioritize the information of working memory by using visual cues at encoding [2-5] or during maintenance [6-9]. Specifically, in the studies, participants were

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informed that a visual item, whose location was pointed by a visual cue, is more likely to be tested than un-cued items. The visual cue guides attention to one of the information, thereby tagging the information as the most relevant for an upcoming memory test. Memory recall performance for the cued item was found to be enhanced (cueing advantages), whereas the performance for an un-cued item suffered (cueing costs). This pattern of results suggests that a subset of items can be prioritized over others at encoding, as well as during maintenance of working memory.

Besides the cueing manipulation, there is also evidence that an item associated with higher potential value or reward is preferentially processed [10-12]. Specifically, participants were presented with visual items to remember. They were informed that a particular item is worth a higher reward than the other items. For instance, participants may be told that correct response of the higher value item will gain them four points, whereas correct response to one of low value items will gain them one point. Although the reward points were purely notional, and unrelated to any monetary compensation [13], previous studies have reported consistently enhanced memory probe accuracy for a high-value item than items worth low value [14-17]. From this, previous research has concluded that more valuable information is more likely to be maintained in the focus of attention, rendering it more accessible (value-based prioritization [18]).

While it is generally accepted that prioritized information is maintained in the focus of attention, the extent to which such information is affected by an external, irrelevant stimulus is a matter of ongoing debate. On the one hand, it has been proposed that prioritization enhances the robustness of working memory, shielding it from interference. Evidence for this view comes from studies showing that prioritized information can resist interference from task-irrelevant stimuli or temporal decay [19-24]. The observation that prioritized information is less susceptible to distraction aligns with the conceptualization of the focus of attention as a privileged state within working memory [25-27], in which information is protected from interference [28-30].

On the other hand, it has been shown that information maintained in the focus of attention is not immune to distractor interference [14, 31-33]. This susceptibility is often found in value-based procedure. In such cases, the high-reward item assumed to be in the focus of attention shows greater susceptibility to performance impairment when a task-irrelevant suffix is presented between working memory encoding and retrieval, despite overall higher recall accuracy [14, 31-32, 34; See also 6, 35]. These findings suggest that prioritized information may be in a highly accessible but labile state.

Recent studies have noted that the inconsistent findings in the literature regarding distractor susceptibility may be attributable to methodological differences across studies [18, 35-37], such as the prioritization strategy employed (spatial cueing vs. reward), the mode of memory item presentation (simultaneous vs. sequential), and the timing of the prioritization cue (before encoding vs. during maintenance of working memory). Among these several factors, we focused in particular on the mechanisms through which information is prioritized, i.e., prioritization strategy, as differences in prioritization strategy may be especially consequential for distractor susceptibility. We also figured that spatial or value-based cues often involved a mixture of exogenous and endogenous cues, yet these cue types have been shown to elicit qualitatively different cognitive and neural effects [38-40], highlighting the need for applying a consistent cueing approach. This reasoning is supported by recent review emphasizing that internal attention mechanisms operate differently than external ones in working memory [41].

In the present study, we adopted endogenous cues for both prioritization strategies, considering that working memory representations are inherently internal in nature. Specifically, spatial cueing-based prioritization was achieved through central arrow cues, whereas reward-based prioritization was operationalized via numerical cues. In addition, to control for differences arising from the mode of item presentation, all memory items were presented simultaneously. Furthermore, the inconsistent findings in previous studies may be attributable to the fact that cueing-based prioritization has typically been applied during working memory maintenance via retrocues [7-8, 21-22, 24, 42-43], whereas value-based prioritization has generally been applied via precues prior to working memory encoding [14, 16, 32, 34]. To eliminate this discrepancy, the present study applied both prioritization timings (precue and retrocue) to each prioritization method [18]. Importantly, although prior research has implemented prioritization cues at different time points, it has rarely examined whether the effects of cue timing are directly comparable. Thus, it remains unclear whether prioritization applied before encoding and during maintenance results in representations being in an equivalent prioritized state. To address this issue, the present study first assessed whether prioritization strategies (cueing-based and value-based) applied at these two time points produced comparable prioritization effects, and subsequently examined the distractor susceptibility of the prioritized information.

2. Experiment 1 (1A and 1B)

Experiment 1A and B were conducted to examine whether working memory prioritization exerts a significant effect both at encoding and during maintenance. To do this, a spatial cue or values were presented either before the presentation of memory items (precue) or after the offset of memory items (retrocue). The precue and retrocue were physically identical and only differed in timing of application. These cues allowed us to establish whether the prioritization of information during maintenance of memory items is as effective as the prioritization before encoding of memory items. These procedures serve as a baseline to verify that both methods reliably induce prioritization effects, which is a prerequisite for subsequently examining their susceptibility to suffix interference in Experiment 2.

2.1. Methods

2.1.1. Participants

A total of twenty-two volunteers (13 women, 9 men; age range: 20-27 years) participated in Experiment 1A (value-based prioritization), and twenty volunteers (11 women, 9 men; age range: 20-25 years) participated in Experiment 1B (spatial cueing-based prioritization). All participants had normal or corrected-to normal vision and received monetary compensation for participation. The sample size was estimated based upon previous studies showing value-based or spatial cueing-based prioritization in working memory. Specifically, in a previous study reporting value-based prioritization [16] and another study showing cueing-based prioritization [7], the partial eta-squared related to the probe value was .63 and .92, respectively. A G*Power analysis [47] indicated that a minimum of $N = 5$ for value-based prioritization and $N = 3$ for spatial cueing-based prioritization would be sufficient to achieve a power of .90 with a type-I error rate of 5%. However, given concerns about replicability and potential performance-based exclusion (memory probe error rate over 50%), and our additional aim of examining effects of cue timing, we decided to collect data from 20 people for each prioritization strategy. In experiment 1A, data collection was stopped after we had recruited twenty-two participants, of whom two were excluded based on predefined performance criteria, resulting in a final sample of twenty. In experiment 1B, no participants met the exclusion criteria, yielding a final sample of twenty. All data were collected in person, with participants visiting the laboratory to complete the tasks. Written informed consent was obtained from all participants, and all experimental procedures were approved by the Chungnam National University Institutional Review Board.

2.1.2. Apparatus and Stimuli

The experiment was programmed and run using Psychopy3 [48]. The stimuli were presented on a 21-in. LCD monitor with a gray background. Viewing distance was set to about 60 cm.

Each trial comprised a fixation display, a cue display, a memory display, a placeholder display, and a response display. In Experiment 1A (value-based prioritization), four numbers in white color appeared in the cue display. In Experiment 1B (spatial cueing-based prioritization), a white arrow instead of numbers was presented in the cue display. The memory display included four colored shapes. In each trial, the shapes of memory stimuli were randomly selected from a pool of five shapes (star, square, triangle, circle, or a hexagon) without replacement, while for the colors of the memory stimuli, seven colors were drawn from a 360° color wheel in CIELAB color space (L = 70, a = 20, b = 38, radius = 60). On the color wheel, each different color occupied 1° of the color wheel. Hence, a total of 360 colors constituted the wheel. For each trial, selected colors were distanced at least 42° from each other. The placeholder display had four white outlined squares. The visual stimuli in the cue, placeholder, and memory display were presented at four locations, occupying four corners of an imaginary square with radius of 3.0°.

2.1.3. Procedure and design

To encourage participants to heed the cue-types, the precue and retrocue conditions were conducted on separate sessions in both experiments. Each session day was separated by two days on average. Experimental procedures were varied depending on the session. On the precue session, each trial started with a 500-ms fixation display, followed by a 1000-ms cue display (Figure 1). After a blank interval of 500-ms, during which only the fixation cross was presented, a memory display was presented for 2000 ms. Participants were required to memorize the four visual items. Specifically, they had to encode both the color and shape of the items. Following a 250-ms blank interval a placeholder display was presented for 1000 ms.

Then, a response display appeared until a response was registered (Max 2000 ms). In this display, a single probe stimulus was presented. Participants had to indicate whether the color of the test probe was the same as the memory item by pressing '.' for same and '/' for different. Participants were instructed to respond as accurately as possible while keeping in mind that the maximum response time was limited to 2 seconds. Each of the responses (same or different) occurred in an equal proportion of the trials. In a half of the different response trials, the color of test probe was selected from the other colors in the memory display. For the other half, the probe color was selected from the remaining color list. On the retrocue session, the placeholder display appeared prior to the memory display and the memory display was followed by the cue display. Importantly, the overall timing structure of the retrocue session was identical to that of the precue session, with the only difference being the order of the placeholder and cue displays. We included the placeholder display to control for visual interference induced by the value numbers or a spatial cue during the memory retention interval across sessions.

The instructions were provided differently depending on the prioritization method. In Experiment 1A, participants were informed that the numbers in the cue display represented the points they would earn for correctly recalling the memory item at the corresponding spatial location. Participants were also told to try to earn as many points as possible, even though the points were not associated with monetary reward. There were two different types of cue displays: the equal-cue display contained four '1', whereas the other, unequal-cue display included three '1' and one '4'. This provided three probe types: equal value (all memory items were worth 10 points and one of the items was probed), low value (i.e., one memory item was worth 40 points, but one of the 10 points value memory items was probed), and high value (the memory item probed was worth 40 points). We selected the 10 vs. 40 points to maximize the effect of value. Participants were presented with the total points earned at the end of each run, and we reasoned that using larger absolute values would elicit a more robust value-based effect than the smaller differences typically used in previous studies (e.g., 1 vs. 4 or 1 vs. 8) [35]. Participants were also informed that the points of the items did not predict which item would be probed [14, 16, 31-32]; the spatial location of the probed item was selected with equal probability (25% chance).

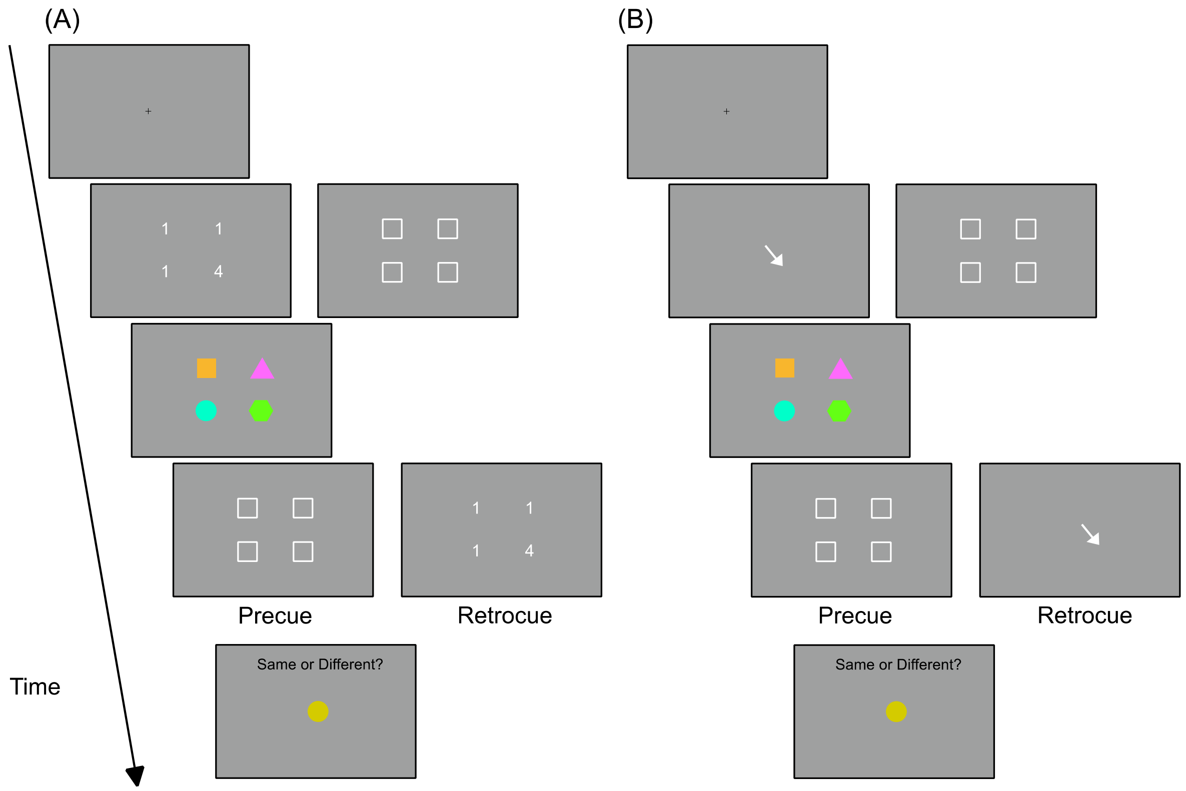

Figure 1. Example trial sequence of Experiment 1A (A) and 1B (B). The cue display is depicting low probe type in Experiment 1(A) and invalid trial in Experiment 1(B).

In Experiment 1B, a white arrow instead of numbers was presented in the cue display. There were three different types of cues: neutral, valid, and invalid cues. In the neutral trials, only a fixation cross was presented at the center of the display. In the valid trials, the cue indicated the location where the memory item to-be-probed would be presented. In the invalid trials, the location indicated by a cue and the memory item to-be-probed location did not match. Importantly, the proportions of the neutral, invalid, valid trials were 25%, 25%, and 50%, respectively. Hence, the probability that the cue indicated the location of to-be-probed memory item was above-chance, rendering the cue informative of the to-be-probed item location. Participants were informed about the informativity of the cue stimulus.

The experimental design of each experiment consisted of a 3 x 2 factorial design with probe type (low, equal, high in Experiment 1A; invalid, neutral, valid in Experiment 1B) and session (precue and retrocue) as within-subject factors. In Experiment 1A, for each session, participants performed 4 experimental blocks, each of which included 80 trials. In Experiment 1B, participants performed 6 experimental blocks, each of which included 80 trials. The order of sessions was counterbalanced across participants, each lasing approximately 60 minutes. Prior to the main experiment on each session, participants completed 20 practice trials to become familiar with the task.

2.2. Results

The main dependent variable was the proportion of correct memory probe responses. Data analyses were done using the base system libraries of R (version 4.4.2). For both Experiment 1A and 1B, we applied a repeated measures two-way ANOVA with probe type (low, equal, high in Experiment 1A; invalid, neutral, valid in Experiment 1B) and session (precue and retrocue) as factors to accuracy data. The results are shown in Figure 2.

In Experiment 1A, the analysis revealed significant main effect of probe type, $F(2,38) = 36.58$, $p < .001$, $\eta^2 = .66$. The main effect of session was not significant, $F(1,19) = .19$, $p = .669$, $\eta^2 = .01$. The interaction between factors was not significant, $F(2,38) = .17$, $p = .848$, $\eta^2 = .01$. To explore whether benefit and cost from prioritization occurred, we ran planned t-tests. Given the non-significant interaction between factors we collapsed data across the sessions for analysis. A comparison demonstrated that memory probe accuracy was significantly greater when high value memory item was probed than when all the memory items were given equal value, $t(19) = 3.94$, $p < .001$, $d = .88$. This result reflects that selective focusing via value-prioritization benefits working memory performance. The other t-test showed that memory probe accuracy was significantly lower for low-value trials than that of equal-value trials, $t(19) = 5.85$, $p < .001$, $d = 1.31$. This result reflects costs of value-based prioritization.

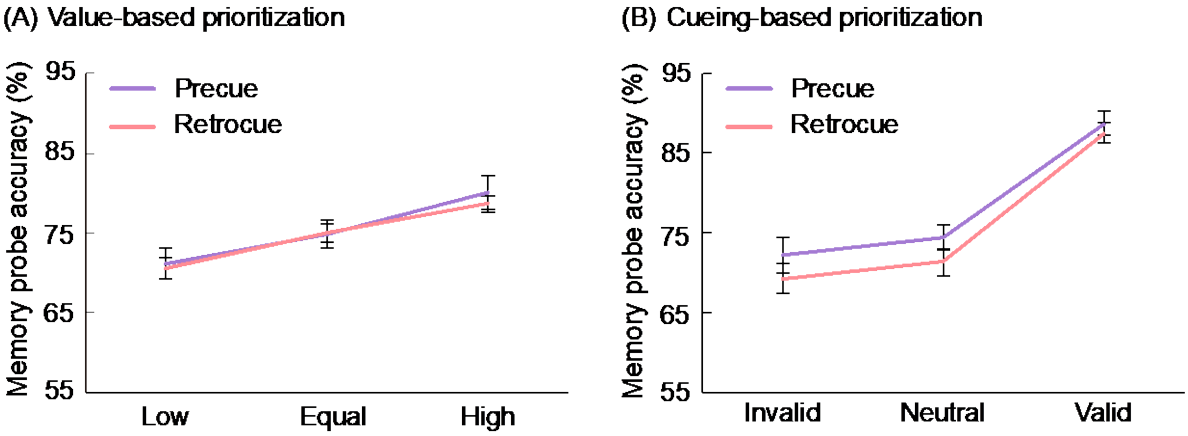

Figure 2. Memory probe accuracy rates of Experiment 1A (A) and 1B (B). Error bars denote within-subject standard error.

In Experiment 1B, the accuracy analysis revealed significant main effect of probe type, $F(2,38) = 67.96$, $p < .001$, $\eta^2 = .78$. The main effect of session was also significant, $F(1,19) = 8.67$, $p = .008$, $\eta^2 = .31$, with memory probe accuracy being greater when the spatial cue was presented prior to the memory items. The interaction between factors was not significant, $F(2,38) = .45$, $p = .644$, $\eta^2 = .02$. As in the Experiment 1A, we examined the benefit and cost of prioritization via spatial cueing. Considering that interaction between factors was not significant, we collapsed data across the sessions. Participants exhibited greater memory probe performance in valid trials, compared to the neutral trials, $t(19) = 11.26$, $p < .001$, $d = 2.52$. Another t-test showed that memory probe accuracy was significantly greater for valid trials than that of invalid trials, $t(19) = 8.45$ $p < .001$, $d = 1.89$. Finally, the difference between neutral trials and invalid trials was not significant, $t(19) = 1.52$, $p = .144$, $d = .34$.

We assume that no difference between invalid and neutral trials might be because memory items were over-prioritized than expected. In the present study, four memory items were presented for relatively extended durations (2000 ms). Given that approximately four items can be represented in working memory, participants might be capable of prioritizing at least some of un-cued items in addition to a cued memory item. Several previous studies also reported similar findings [44-46]. In those studies, there was no significant difference between neutral and invalid trials.

The accuracy results of Experiment 1B are mostly similar with those of Experiment 1A. A notable difference is that significant main effect of session was found only in Experiment 1B. Hence, we compared the effect of session across the experiments. This between-experiment ANOVA revealed no significant difference of session across experiments, $F(1,38) = .93$, $p = .337$, $\eta^2 = .01$.

To analyze the reaction time data, we applied the same analysis used for the accuracy data. The results are presented in Figure 3. In Experiment 1A, the main effect of probe type was significant, $F(2,38) = 6.30$, $p = .004$, $\eta^2 = .25$. Neither main effect of session, $F(1,19) = .26$, $p = .615$, $\eta^2 = .01$, nor interaction between factors, $F(2,38) = .52$, $p = .599$, $\eta^2 = .03$, was significant. In Experiment 1B, the main effect of probe type was significant, $F(2,38) = 47.70$, $p < .001$, $\eta^2 = .72$. The main effect of session was not significant, $F(1,19) = 1.89$, $p = .185$, $\eta^2 = .09$. The two-way interaction between factors was significant, $F(2,38) = 16.19$, $p < .001$, $\eta^2 = .46$.

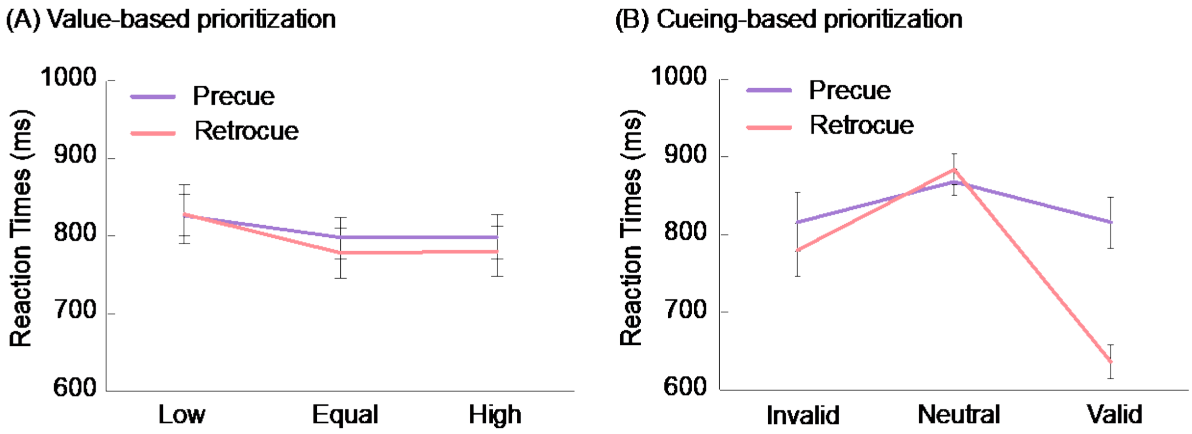

Figure 3. Memory probe reaction times (RTs) of Experiment 1A (A) and 1B (B). Error bars denote within-subject standard error.

Taken together, we confirmed a significant effect of value-based and spatial cuing-based prioritization of working memory, both before encoding of memory items as well as during maintenance of memory items. Moreover, the present results suggest that value-based and spatial cueing-based prioritization during maintenance is as effective as before encoding. Having established that retro-prioritizing cues were as effective as pre-prioritizing cues, we further examined how the suffix interference interacts with the different strategies of prioritizations in working memory in Experiment 2A and 2B.

3. Experiment 2 (2A and 2B)

3.1. Methods

The methods were mostly identical to those of Experiment 1A and 1B, with the following exceptions. A total of twenty-two volunteers (14 women, 8 men; age range: 20-27 years) participated in Experiment 2A (value-based prioritization), and twenty-two volunteers (12 women, 10 men; age range: 20-25 years) participated in Experiment 2B (spatial cueing-based prioritization). In Experiment 2A and 2B, no participants met the exclusion criteria, yielding a final sample of twenty-two participants in each experiment. In half of the total trial, a blank display was presented for 1000 ms before a response display, which are referred to as suffix-absent trials. For the other half, suffix-present trials, a 250-ms blank display was followed by a suffix display, in which a white shape presented at the center of the display for 250 ms. Then, a blank display was presented for 500 ms. The shape of the suffix was selected from the shape pool without a feature overlap with the memory items. Participants were informed that the suffix was entirely task-irrelevant and instructed to ignore the suffix. Unlike Experiments 1A and 1B, Experiment 2A and 2B incorporated two probe types. Specifically, Experiment 2A included high- and low-value trials in Experiment 2A, whereas Experiment 2B consisted of valid and invalid trials.

The experimental design of each experiment consisted of a within subject 2 x 2 x 2 design with probe type (low vs. high in Experiment 2A; valid vs. invalid in Experiment 2B), suffix (present vs. absent), and session (precue vs. retrocue) as factors. Probe type (high vs. low or valid vs. invalid) and suffix (present vs. absent) were randomly intermixed within blocks. For each session, participants performed 6 experimental blocks, each of which included 80 trials, for 480 trials (960 trials in total). The order of sessions was counterbalanced across participants, each lasting approximately 70 minutes.

3.2. Results

To analyze memory probe accuracy data, we applied a repeated measures three-way ANOVA with probe type (high vs. low or valid vs. invalid), suffix (present vs. absent), and session (precue vs. retrocue) as factors. The results of Experiment 2A and 2B are shown in Figure 4.

In Experiment 2A, this analysis revealed a significant main effect of probe type, $F(1,21) = 16.32$, $p < .001$, $\eta^2 = .44$, with higher memory probe accuracy for high-value trials than low-value trials. The main effect of suffix was also significant, $F(1,21) = 29.10$, $p < .001$, $\eta^2 = .58$, with lower accuracy in suffix-present than in suffix-absent trials. The two-way interaction between suffix and session was significant, $F(1,21) = 4.89$, $p = .038$, $\eta^2 = .19$, with stronger suffix interference in the precue session. Importantly, the three-way interaction between factors was also significant, $F(1,21) = 4.94$, $p = .037$, $\eta^2 = .19$. Given the significant three-way interaction, we separately examined the precue and retrocue session data to further explore the suffix interference across sessions.

In the precue session data, a repeated measures two-way ANOVA with probe type and suffix as factors revealed a significant main effect of probe type, $F(1,21) = 12.21$, $p = .002$, $\eta^2 = .37$, such that memory probe accuracy was higher for high-value trials than for low-value trials. The main effect of suffix was also significant, $F(1,21) = 26.85$, $p < .001$, $\eta^2 = .56$, with lower accuracy in suffix-present than in suffix-absent trials. Importantly, the interaction between factors was also significant, $F(1,21) = 5.13$, $p = .034$, $\eta^2 = .20$, with greater suffix interference for high-value than low-value trials. In the retrocue session data, the same analysis to the precue session data revealed a significant main effect of probe type, $F(1,21) = 7.14$, $p = .014$, $\eta^2 = .25$, with higher accuracy for high-value than for low-value trials. Neither the main effect of suffix, $F(1,21) = 2.67$, $p = .117$, $\eta^2 = .11$, nor the interaction between factors, $F(1,21) = 2.27$, $p = .147$, $\eta^2 = .10$, was significant. Even though the main effect of suffix was not significant, we ran exploratory analysis to further confirm whether the two trial types (low value and high value) did not show susceptibility to suffix interference. Subsequent pairwise t-tests revealed suffix interference on low-value trials, $t(21) = 2.90$, $p = .009$, $d = .62$. On the contrary, the suffix interference was not found on high-value trials, $t(21) = .15$, $p = .882$, $d = .03$.

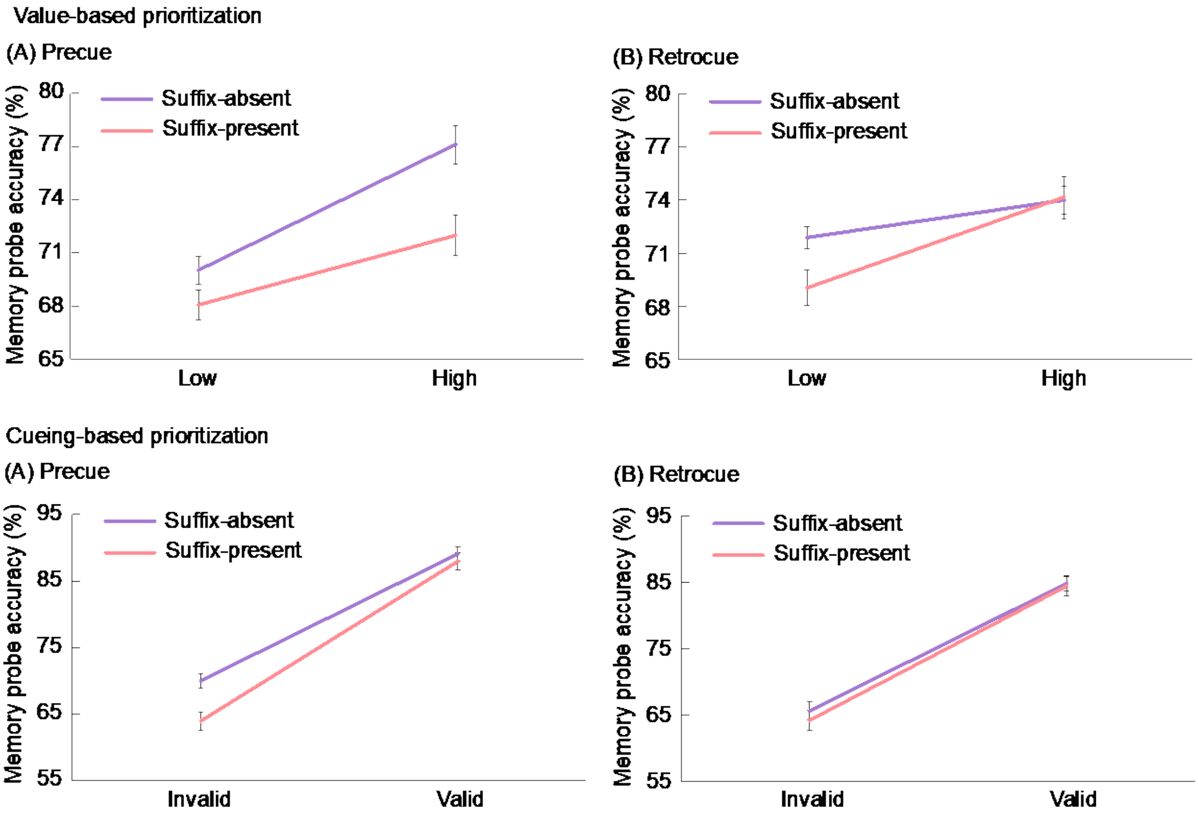

Figure 4. Memory probe accuracy rates of Experiment 2A (top panel) and 2B (bottom panel). Error bars denote within-subject standard error.

In Experiment 2B, the accuracy analysis revealed a significant main effect of probe type, $F(1,21) = 90.02$, $p < .001$, $\eta^2 = .81$, with higher accuracy for valid than for invalid trials. The main effect of suffix was also significant, $F(1,21) = 23.70$, $p < .001$, $\eta^2 = .53$, with lower accuracy in suffix-present than in suffix-absent trials. The main effect of session was also significant, $F(1,21) = 13.82$, $p = .001$, $\eta^2 = .40$, with higher accuracy when the spatial cue was presented before encoding. The two-way interaction between probe type and suffix was significant, $F(1,21) = 7.67$, $p = .012$, $\eta^2 = .27$, with stronger suffix interference for invalid than for valid trials . Importantly, the three-way interaction between factors was also significant, $F(1,21) = 4.65$, $p = .043$, $\eta^2 = .18$. Given the significant three-way interaction, we separately examined the precue and retrocue session data to further explore the suffix interference across sessions.

In the precue session data, a repeated measures two-way ANOVA with probe type and suffix as factors revealed a significant main effect of probe type, $F(1,21) = 94.09$, $p < .001$, $\eta^2 = .82$, with higher accuracy for valid than for invalid trials. The main effect of suffix was also significant, $F(1,21) = 28.52$, $p < .001$, $\eta^2 = .58$, with lower accuracy in suffix-present than in suffix-absent trials. Importantly, the interaction between factors was also significant, $F(1,21) = 15.38$, $p < .001$, $\eta^2 = .42$, with greater suffix interference for invalid than for valid trials. In the retrocue session data, the same analysis to the precue session data revealed a significant main effect of probe type, $F(1,21) = 63.23$, $p < .001$, $\eta^2 = .75$, with higher memory probe accuracy for valid trials than invalid trials. Neither the main effect of suffix, $F(1,21) = 1.04$, $p = .320$, $\eta^2 = .05$, nor the interaction between factors, $F(1,21) = .44$, $p = .513$, $\eta^2 = .02$, was significant.

To analyze the reaction time data, we applied the same analysis used for the accuracy data. The results are presented in Figure 5. In Experiment 2A, the RT analysis revealed no significant main effects, *ps* > .388, or interactions, *ps* > .145. In Experiment 2B, the analysis revealed significant main effect of probe type, $F(1,21) = 37.55$, $p < .001$, $\eta^2 = .64$, with shorter RTs for valid than for invalid trials. No main effects or interactions were significant except for the main effect of probe type, *ps* > .086

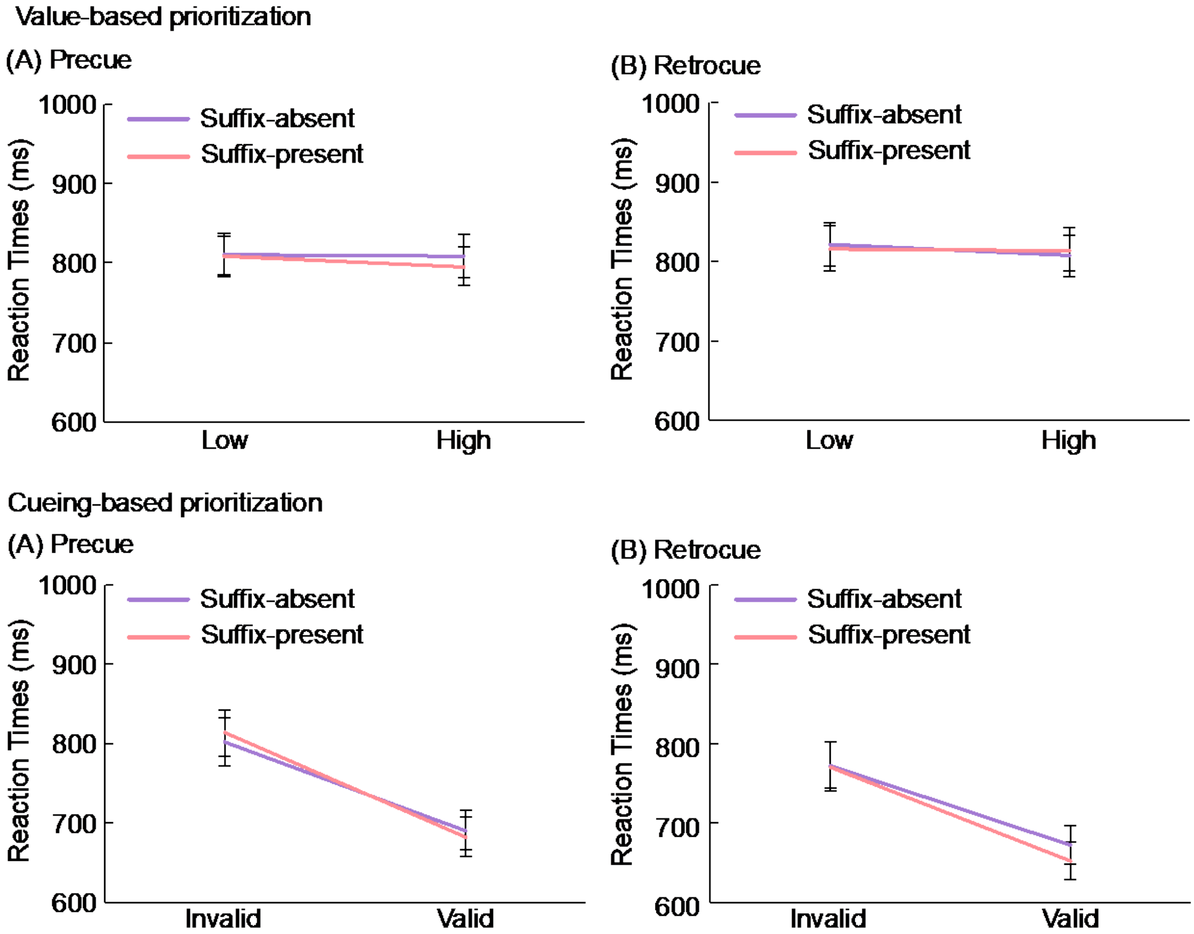

Figure 5. Memory probe reaction times (RTs) of Experiment 2A (top panel) and 2B (bottom panel). Error bars denote within-subject standard error.

4. General discussions

The present study examined how two forms of working memory prioritization, value-based and spatial cueing-based, differently affect task-irrelevant suffix interference, and how these effects depend on the timing of prioritization (precue vs. retrocue). Across experiments, we found that the memory representations in the privileged status could be susceptible to or protected from perceptual interference exerted by a presented suffix, depending on the types and timings of prioritization.

Specifically, when a high-value item was prioritized with a precue, it was found to be more vulnerable to suffix interference, even though recall accuracy was enhanced. This pattern supports the vulnerability account [14, 31-33] and suggests that value-based prioritization via a precue brings the selected item into a state of high accessibility but greater susceptibility to interference. In contrast, high-value items prioritized by a retrocue were unaffected by suffix distractors, indicating a transition into a more stable state. By comparison, spatial cueing-based prioritized items consistently resisted suffix interference regardless of whether cues were given before encoding or during maintenance. These results aligned more closely with the protection account [8, 42]. Together, these findings contribute to resolving the ongoing debate about whether prioritized information in working memory is protected from or vulnerable to interference. The results showed that the status of prioritized information cannot be reduced to a simple claim of protection or vulnerability. Instead, susceptibility is shaped by both the strategy used to establish prioritization and the timing at which prioritization is applied.

In value-based precue conditions, prioritization is established during encoding [5, 22, 49-51], which enhances the accessibility of the selected item but leave its representation in a more labile state. Because prioritization occurs early, there is less opportunity to selectively refresh the high-value item during maintenance, making it more susceptible to interference. In contrast, retrocues identify the relevant item after all items have been encoded [52-53], enabling selective refreshing that occurs closer in time to the upcoming distraction [15-16, 51, 54-55]. This temporal proximity likely contributes to the greater stability observed under retrocue conditions.

For spatial cueing-based proiritization, both precues and retrocues conferred protection from suffix interference. These results are consistent with prior findings in which interference was absent under retrocue conditions with spatial cues [19, 21-22, 24, 43]. However, in the present study, interference effects by suffix stimuli were evident for invalid items under precue conditions. One interpretation is that precues lead participants to allocate most attentional resources to the cued item during encoding, leaving uncued items in a more fragile state. As a result, these items are especially vulnerable to subsequent distraction. In contrast, when retrocues are presented after encoding, all items are initially encoded in a comparable manner, reducing the likelihood that uncued items are selectively fragile and explaining why interference was absent in the retrocue condition.

In addition to the accuracy-based findings, the RT data also revealed an interesting pattern. The validity effect (valid vs. invalid trials or high vs. low trials) on RTs appeared weaker for numerical/reward cues than for arrow cues. Although this difference was not the primary focus of the present study, it may nonetheless provide additional insights into the mechanisms of prioritization. One possible explanation is that arrow cues act as direct spatial cues, guiding attention explicitly to a location and thereby producing a stronger validity effect on RTs. By contrast, reward cues signal which items should be prioritized based on reward or numerical information, and these items are subsequently linked to specific locations. Although such cues can ultimately have spatial consequences, the prioritization mechanism is indirect, relying on value-based selection rather than direct spatial signaling. This distinction may help explain why the RT validity effect was relatively weaker for reward cues. In this way, the observed pattern aligns with ongoing debates about whether spatial cueing and value-based forms of prioritization rely on distinct attentional processes [18]. At the same time, because the present study was not designed to test this distinction directly, these interpretations should be treated as tentative. Future research examining RT effects more directly could strengthen our understanding of how different forms of prioritization modulate performance in visual working memory.

The present study primarily compared reward-based and spatial cueing-based prioritization. It is also possible that the level of prioritization in working memory varies depending on the order in which items are presented, and previous studies have shown that under sequential presentation prioritized information can still be susceptible to external perceptual stimuli [31-32, 35, 57]. In the present study, to avoid variability arising from differences in presentation format, we presented all items simultaneously. Future research that incorporates additional prioritization methods (e.g., sequential presentation) alongside those used here would be valuable for further advancing the theoretical debate on the susceptibility of prioritized information to distraction.

To conclude, the present study demonstrated that the susceptibility of prioritized information in working memory determined jointly by how and when prioritization is implemented. Under value-based precues, prioritized items became highly accessible yet more vulnerable to distraction, whereas retrocues stabilized both reward-based and spatially cued items, shielding them from interference. Thus, although we found evidence that prioritized information can be susceptible to external interference, such vulnerability was observed only under restricted conditions. These findings underscore that the focus of attention in working memory is not a single, uniform state but a dynamic construct whose susceptibility to interference is shaped by both the strategy and the timing of prioritization. Taken together, these findings help reconcile previously inconsistent results in the literature and clarify that prioritization in working memory is not a monolithic process. Beyond theoretical implications, this framework may also inform applied contexts that require selective protection against distraction, such as interface design, educational and attentional training programs, and environments in which stable memory maintenance under interference is essential.

Data Accessibility Statement

The data that support the present findings are available through the Open Science Framework (https://osf.io/k68w5/).

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Ethics and Consent

All experimental procedures were approved by the Chungnam National University Institutional Review Board. The study was conducted according to the Convention of Helsinki. Participants provided informed consent before participating in the study.

Competing Interests

No potential conflict of interest was reported by the authors.

Authors' contributions

K.J. and S.W.H. conceived and designed the study. K.J. programmed the experiment, collected data, and analyzed data. K.J. and S.W.H. wrote the paper. All authors contributed editing, and interpretations of the data. All authors approved the final version of the manuscript for submission.

Conflict of interest

The authors declare no conflict of interest

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