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The modulatory mechanism of spatial distance on the role of internal attention in unattended working memory representations

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ABSTRACT
Visual working memory (VWM) temporarily stores visual information, supporting higher cognition. Internal attention selectively prioritizes VWM representations, influencing both cued and uncued items. This study examined how spatial distance modulates internal attention's effect on unattended representations. Two experiments using a lateralized change detection task assessed retro-cue effects. Experiment 1 revealed that uncued items closer to the cued item exhibited less memory decline, supporting an attentional spatial proximity effect. Experiment 2, with reduced memory load and controlled spatial configurations, confirmed that proximity to the cued item mitigates memory loss, independent of intervening items. Moreover, increasing spatial distance gradually reduced VWM performance, reinforcing a graded attentional effect. These findings indicate that internal attention extends its benefits beyond the cued representation, illuminating how spatial distance helps manage limited VWM capacity. Overall, this work advances our understanding of the flexible and spatially sensitive mechanisms governing attentional processes in VWM.

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Visual short-term memory; internal attention; spatial distance; retro-cue effect; attentional spatial proximity

Visual working memory (VWM) is understood as a cognitive system that stores and processes visual information when external stimuli are absent (Luck & Vogel, 1997). This ability is essential for higher cognitive functions, as shown by research highlighting its key role (Fukuda et al., 2010; Luck & Vogel, 2013). In daily life, we face tasks that require us to constantly update what is important to remember. VWM is known to hold only about three to four simple items perfectly at a time (Vogel & Awh, 2008). However, it can adjust by focusing on important information and ignoring what is not needed, which helps overcome its limited capacity (Vogel et al., 2005). Recent research has explored how VWM works, showing that it is flexible and adaptive, not fixed (Emrich et al., 2017; Lorenc et al., 2018; Ma et al., 2014; Myers et al., 2018; Wolff et al., 2017; Ye et al., 2017; Ye et al., 2019; Ye et al., 2020). During the maintenance phase, VWM resources can be shifted to focus on specific items or specific feature via the internal attention (Fu et al., 2022; Griffin & Nobre, 2003; Landman et al., 2003; Liu et al., 2023; Liu et al., 2024; Park et al., 2017; Rerko et al., 2014; Souza, Rerko, Lin, et al., 2014; Souza, Rerko, & Oberauer, 2014, 2015; Souza & Oberauer, 2016; Ye et al., 2016; Ye et al., 2021). Therefore, internal attention mechanisms are crucial for controlling what gets into VWM and for prioritizing the stored information for use in behavior.

The influence of internal attention on VWM has been widely studied using retro-cues. In a typical retro-cue experiment, participants are asked to remember a set of items. During the interval between the memory items and test/probe array, a retro-cue indicates which item is most likely to be tested. Researchers have found that participants can use the retro-cue to enhance VWM performance (Griffin & Nobre, 2003; Landman et al., 2003). This effect of using retro-cue on VWM performance is called the retro-cue effect (RCE), which includes retro-cue benefit (RCB) and retro-cue cost (RCC). RCB means that in the valid retro-cue condition (where the cue indicates the item to be tested),

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memory performance is better than in the no-cue or neutral-cue condition. RCC means that in the invalid retro-cue condition (where the cue points to an item that will not be tested), memory performance for the uncued item is worse than in the no-cue or neutral-cue condition. Over the past twenty years, more and more studies have examined how people use internal attention to prioritize information already in VWM. This research has given us a deeper understanding of the cognitive processes involved in maintaining VWM.

In previous studies on the mechanisms of RCE, researchers have also focused on the fate of unattended representation in VWM. In perceptual attention research, if participants focus their perceptual attention on the location of a cued visual item, this may lead to an attentional spatial proximity effect, where attention is preferentially allocated to the location of the cued item with a gradual fall-off over space to nearby locations of uncued items (Schmidt et al., 2002). However, it may also lead to an attentional surround suppression effect, where attending to a visual stimulus enhances processing in the cued location and suppresses processing in adjacent uncued locations (Cutzu & Tsotsos, 2003; Mounts, 2000a, 2000b). Recently, researchers have begun to investigate how prioritizing a cued item stored in VWM using internal attention affects the maintenance of uncued items located near the cued item. In the study by Souza et al. (2018), participants were asked to remember eight colors for a VWM task (change detection task), with a pre-cue condition to examine perceptual attention and a retro-cue condition to examine internal attention. In the pre-cue condition, participants saw an arrow before the memory array appeared, while in the retro-cue condition, they saw an arrow after the memory array disappeared. The arrow pointed to the location of a color, and participants were told that the cued stimulus had a higher probability of being tested (65% valid). In the invalid cue condition, where tested item was an uncued item, the researchers systematically manipulated the distance between the tested uncued item and the cued item to examine how VWM performance for uncued locations changed with their distance from the cued location. Their results showed that in both pre-cue and retro-cue conditions, the spatial distance between uncued and cued locations modulated the cuing costs: items close to the cued location were insulated from cuing costs. VWM performance for uncued items decreased monotonically with increasing distance from the cued item. Their evidence supports the idea that when internal attention prioritizes a cued item stored in VWM, it also prioritizes uncued items near the cued item, protecting them from cuing costs. However, uncued items far from the cued item suffer significant cuing costs. Thus, their study supports the existence of an attentional spatial proximity effect when internal attention prioritizes items maintained in VWM.

However, another study by Fang et al. (2019) found different evidence from the study by Souza et al. (2018). They asked participants to remember six colors and perform a VWM task (delayed-estimation task). They also included pre-cue and retro-cue conditions, with a spatial cue presented before the memory array appeared or after it disappeared, indicating which item was more likely to be tested (50% valid). They systematically manipulated the distance between the probed uncued item and the cued item in the invalid cue condition. Their results showed that in both pre-cue and retro-cue conditions, VWM performance for uncued items followed a Mexican-hat profile as a function of the distance between the test item and the cued item. Their results suggest that when internal attention prioritizes a cued item stored in VWM, it further suppresses the memory maintenance of uncued items near the cued item, exerting a significant cost on uncued item performance at intermediate locations, while uncued items both very close to and far from the cued item also experience a numerical trend of suppression. Thus, the study by Fang et al. (2019) supports the existence of an attentional surround suppression effect when internal attention prioritizes items maintained in VWM. Fang et al. (2019) proposed that these seemingly inconsistent results may be due to the greater distance between memory stimuli and fixation in the study by Souza et al. (2018) and the subtle differences in VWM performance detected in their experimental task.

Although there is still some debate about how internal attention prioritization of cued items in VWM affects the maintenance of nearby uncued items, this study does not aim to simply replicate the studies by Souza et al. (2018) or Fang et al. (2019) to test which conclusion is correct. Instead, we aim to build on their findings and further investigate the mechanisms by which retro-cues affect uncued representations around the cued item, providing new evidence from a different perspective.

We noted two similar setups in the studies by Souza et al. (2018) and Fang et al. (2019). First, both studies used a number of items that exceeded the typical memory capacity limit of individuals. Previous research has shown that memory performance significantly declines when participants are asked to remember more than 3–4 simple color stimuli. In the studies by Souza et al. (2018) and Fang et al. (2019), participants were required to remember 8 and 6 color stimuli, respectively. As a result, in the retro-cue task, participants may not have been able to adequately consolidate and maintain all the memory stimuli from the memory array. They may have only selectively maintained a subset of stimuli (e.g., 3–4 simple colors) in VWM (Vogel & Awh, 2008). This could also explain why the benefit RCB was significantly higher in the pre-cue condition compared to the retro-cue condition. In the pre-cue condition, participants can use the pre-cue to selectively store the cued item in VWM, while in the retro-cue task, it is possible that the item indicated by the retro-cue had not been successfully consolidated into VWM for maintenance. Therefore, using a number of items that exceed the VWM capacity limit may introduce larger individual differences and random noise unrelated to the retro-cue mechanism, making it more difficult to explore the effects of the retro-cue on uncued representation without interference from other factors unrelated to internal attention.

Secondly, both studies set up positions for far distant items always presenting these distant items in the contralateral visual field (the farthest possible distance on the screen. e.g., Souza et al. (2018) used uncued stimuli located four positions away from the cued item; Fang et al. (2019) used stimuli three positions away). Previous research has shown that resource allocation for VWM in the two visual fields might be somewhat independent. For example, previous studies have demonstrated that VWM performance is better when visual items are allocated in both the left and right visual fields than within only one hemifield (Delvenne, 2005; Umemoto et al., 2010). This phenomenon, called the bilateral field advantage, is likely due to the allocation of more attentional resources when items are presented in both visual fields (Zhang et al., 2018). Additionally, when individuals memorize stimuli in a single visual field, greater negative activity is often observed in the contralateral parietal-occipital cortex. The ERP component CDA (contralateral delay activity), which tracks VWM load, was calculated based on this characteristic (Luria et al., 2016; Vogel et al., 2005; Vogel & Machizawa, 2004). Therefore, many VWM studies (especially ERP studies) often restrict the stimuli to be remembered to a single visual field. However, in the studies by Souza et al. (2018) and Fang et al. (2019), the far distant items set in the contralateral visual field could exceed the range of influence by internal attention on nearby items. This might explain why Fang et al. (2019) found that memory performance for uncued stimuli located two positions away from the cued item was the worst, while performance for stimuli located three positions away was numerically better than for those located two positions away. Thus, presenting cued and uncued items in different visual hemifields might introduce additional potential issues when exploring the mechanism of internal attention on uncued items.

In our study, we aim to examine the effects of internal attention on VWM representations of uncued items (unattended representations) at varying distances from the cued item under moderate memory load and within a single visual hemifield. This setup not only allows our results to validate the findings of Souza et al. (2018) and Fang et al. (2019), but also enables us to establish an effective paradigm for further exploration of this issue. If the memory performance of uncued items shows a monotonic relationship with their distance from the cued item, we would expect to observe a decline in performance with increasing distance. This result would support the existence of an attentional spatial proximity effect when internal attention prioritizes items maintained in VWM. However, if the relationship is non-monotonic (e.g., a curvilinear relationship), we might find that performance is worse for adjacent items and better for more distant stimuli. This result would support the existence of an attentional surround suppression effect when internal attention prioritizes items maintained in VWM. Alternatively, it is possible that in our experimental setup, the memory performance of uncued items will not be modulated by their distance from the cued item.

Experiment 1

The aim of Experiment 1 was to investigate how the RCE of uncued items is modulated by their distance from the cued item in a VWM task. We designed a lateralized change detection task with a memory load of four colors, including both retro-cue and no-cue conditions. The choice of four colors as the memory load is based on previous research showing that participants can effectively maintain 3–4 colors, with memory performance declining sharply beyond this number. This ensures that participants in our experiment can maintain the stimuli well during the encoding phase, ensuring that the observed results are not due to insufficient initial VWM representation.

Additionally, unlike the studies by Souza et al. (2018) and Fang et al. (2019), we did not include a pre-cue condition, as our research focuses on the mechanism of internal attention on uncued items in a VWM task rather than the effects of perceptual attention. Our previous research indicates that the validity of the cue affects the strategy participants use to prioritize the cued item with a retro-cue. Higher cue validity increases participants' motivation to use the retro-cue and is more likely to lead to the suppression/forgetting of uncued representations (Fu et al., 2022; Liu et al., 2024). Therefore, we used a higher cue validity than that used by Souza et al. (2018) and Fang et al. (2019) to enhance participants' motivation to utilize the retro-cue.

Materials and methods

Participants

To ensure sufficient statistical power for our comparisons, we conducted an a priori power analysis using G*Power 3.1.9.2 (Faul et al., 2007), guided by the effect sizes (Cohen's $d = 0.87–3.14$) reported in the study by Fang et al. (2019). Anticipating a similar effect size (Cohen's $d = 0.87$) in our experimental design, we targeted a statistical power of $(1 - \beta) = 0.80$, with a significance level of 0.05. This analysis indicated a minimum required sample size of 13 participants. Additionally, we considered the sample sizes used in previous research: the study by Fang et al. (2019) involved 12 participants per experiment, while the study by Souza et al. (2018) used 50–60 participants per experiment. Taking these factors into account, we set our recruitment goal at approximately 28 participants per experiment.

Thirty volunteers, comprising undergraduate and graduate students, participated after being briefed about the experiment. Except for one, all participants were right-handed, with normal or corrected-to-normal vision, free from color vision deficiencies, and had no history of mental illness. However, one participant was excluded from the analysis due to a significantly lower-than-chance accuracy rate (below 40%) under certain conditions. Consequently, data from the remaining 29 participants (22 females and 7 males, aged 18–23 years, with a mean age of 19.93 ± 1.53 years) were analyzed. All participants provided informed consent and were compensated with 30 Chinese Yuan upon completion. The study received ethical approval from the Ethics Committee of Sichuan Normal University.

Stimuli

The experiment was programmed in Matlab using the Psychophysics Toolbox 3. The memory array consisted of 8 evenly distributed colored circles, each with a radius of 0.83 degree of visual angle (dva), positioned on a virtual circle with a radius of 6 dva centered on the screen. These eight circles were located on both sides of the screen, four on each side, spaced 3.6 dva apart. The eight locations were fixed at angles of 17.5°, 52.5°, 127.5°, 162.5°, 197.5°, 232.5°, 307.5°, and 342.5°, starting from the right horizontal meridian. Within each hemifield, adjacent circles were separated by 35°. The colors of the 8 circles in each presentation were randomly selected from 12 colors, each chosen from a color wheel containing 360 hues. The colors were uniformly distributed in the HSV color space, with $s = 0.7$ and $\mathbf{v} = 0.9$. All colors had the same saturation and brightness, differing only in hue. The memory tasks were presented on a 23.8-inch monitor with a visible size of 52.71× 29.65 cm and a refresh rate of 60 hz, against a uniform gray background (128, 128, 128). Throughout the experiment, participants were seated 70 cm from the screen in a quiet, distraction-free environment.

To provide a clear comparison between the present study and previous studies (Fang et al., 2019; Souza et al., 2018), we include a detailed summary table (Table 1) highlighting the similarities and differences in stimulus parameters. The table encompasses key attributes such as the set size of memory items, retro-cue validity rate, stimulus size,

Table 1. Comparison of stimulus parameters across studies.

	Set Size of Memory Items	Validity Rate of Retro-Cues (%)	Size of Each Stimulus (dva × dva)	Eccentricity (dva)	Minimum stimulus-to-stimulus distance between two adjacent stimuli (dva)	Minimum Angular Separation (Degrees)
Our study	4	73%	0.83 × 0.83	6	3.6	35°
Experiment 1 (Souza et al., 2018)	8	65%	0.83 × 0.83	5	3.83	45°
Experiment 2 (Souza et al., 2018)	8	60%	0.83 × 0.83	5	1.95	22.5°
Fang et al. (2019)	6	50%	0.45 × 0.45	2.8	2.8	60°

This table summarizes key stimulus parameters used in the present study and previous studies by Souza et al. (2018) and Fang et al. (2019). Parameters include the set size of memory items, the validity rate of retro-cues, the size of each stimulus (in degrees of visual angle, dva), the eccentricity of stimuli, the minimum stimulus-to-stimulus distance between adjacent stimuli, and the minimum angular separation between adjacent stimuli (defined as the angle formed by the lines connecting two stimuli to the central fixation point).

eccentricity, the minimum stimulus-to-stimulus distance between adjacent stimuli, and the minimum angular separation between adjacent stimuli.

It is worth noting that the eccentricity values used in these studies vary considerably, particularly between Fang et al. (2019) and the studies by Souza et al. (2018) and ours. Since eccentricity greatly influences the actual extent of attentional focus, direct comparisons based on the physical distance between stimuli (measured in degrees of visual angle, dva) may not fully capture the differences in attentional mechanisms across studies. Therefore, in subsequent analyses, we will primarily use angular separation to differentiate between stimuli rather than relying on their physical distances. This approach provides a more appropriate basis for comparing our findings with those of previous research.

Procedure and design

Participants were first presented with a white fixation point, accompanied by black arrows pointing left or right, with the direction randomized in each trial (each direction representing 50% of the total trials). After displaying the fixation point and arrows for 200 ms, a blank screen with the fixation point appeared for 300 ms, followed by a 500 ms memory array. The memory array contained 4 stimuli on each side, totaling 8 colored circles per trial, randomly chosen from 12 colors. Participants were instructed to remember all four colors on the side indicated by the arrows and ignore the other side, focusing only on the 4 items on the indicated side. Following the memory array, the screen went blank again, displaying the fixation point for 800 ms to allow sufficient time for processing and consolidating the memory items. Then, either a retro-cue or a neutral cue was presented in the center of the screen for 300 ms, followed by another 600 ms blank screen with the fixation point, after which the probe item appeared (As shown in Figure 1A). The retro-cue was an arrow placed in the center pointing to a specific memory target, whereas the neutral cue was a cross. The probe item was a colored circle appearing in one of the memory target positions. The probe item had a 50% chance of matching the color of the memory target at that position and a 50% chance of being a new color not present in the memory array. Participants were asked to determine whether the color of the probe item matched the memory at that position without a time constraint but were encouraged to respond as quickly as possible after making their judgment. To maintain balance, half of the participants were instructed to press the "F" key for a match and the "J" key for a non-match, and the other half the opposite. After each trial, the next trial began following a 1000-ms blank screen. Participants were instructed not to vocalize or subvocally rehearse the memory items to prevent the influence of verbal memory between the disappearance of the memory array and the appearance of the probe array.

By manipulating the cue and the position of probed item, our experiment included four conditions, as illustrated in Figure 1B. Following Souza et al. (2018), the retro-cue conditions were categorized based on the angular separation between the cued location and the probed item. The conditions were defined as follows: (1) *Neutral cue condition*, where the cue was a neutral cue, and the probed item could be at any memory target location. (2) *0° separation* (*Valid cue) condition*, where the cue was a retro-cue, and the position of the probed item matched the location indicated by the retro-cue. (3) *35° separation* (*Near-distance invalid cue) condition*, where the cue was a retro-cue, but the probed item was an adjacent non-cued item (being the

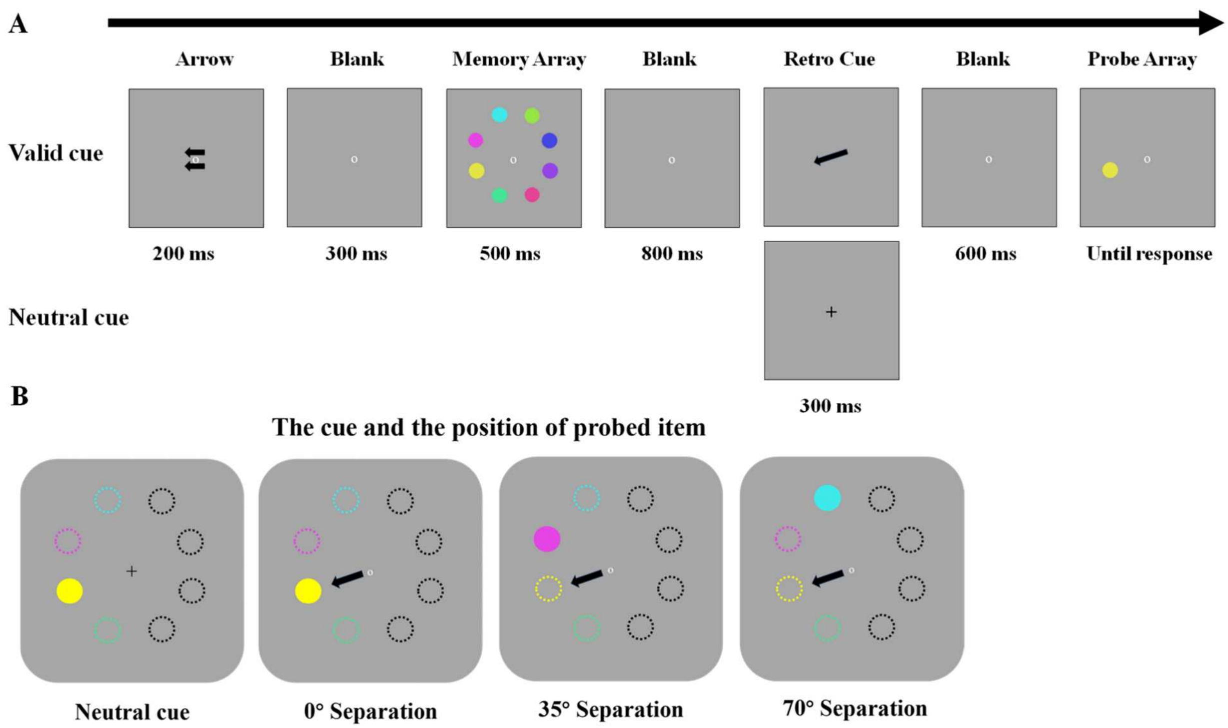

Figure 1. A: The flowchart for Experiment 1; B: The cue and the position of probed item. The arrows represent the retro-cue. The item pointed to by the arrow is the cued item, the solid circle indicates the probed item, and the other two are items presented in the memory array that were neither cued nor probed.

location 35° away from cued item). (4) *70° separation (Middle-distance invalid cue) condition*, where the cue was a retro-cue, but the probed item was one position away from the cued location (being the location 70° away from cued item). Experiment 1 consisted of 12 blocks, each with 57 trials, totaling 684 trials in the formal experiment. Each participant completed 24 practice trials before the formal experiment, resulting in a total of 708 trials per participant. There were 396 trials with valid retro-cues, 144 with invalid retro-cues, and 144 with neutral cues, meaning retro-cues were valid 73% in the whole experiment. The number of trials for the 35° separation (near-distance invalid cue) condition and the 70° separation (middle-distance invalid cue) condition was the same, with 72 trials each. The four conditions were randomly presented in each block. Participants were given at least a 1-min break after each block to prevent fatigue effects. The entire experiment lasted approximately 65–75 min.

Data analysis

We conducted data analyses on the mean accuracy and mean reaction time under different conditions for each participant. For calculating mean reaction time for each participant, we averaged the reaction times of correct response trials for each condition. Separate one-way repeated measures ANOVAs were conducted for accuracy and reaction time, with condition (neutral cue vs. 0° separation vs. 35° separation vs. 70° separation) as a within-subjects factor. To further explore differences between conditions, follow-up pairwise comparisons across four conditions using two-tailed t-tests were performed. Partial eta squared (η^2) measures were used to estimate effect sizes for the ANOVAs, while Cohen's d was employed to estimate the effect sizes of significant results in the t-tests. A significance level of $p < 0.05$ was applied for all statistical tests. Bayes factor analyses were used to show whether the t-test results supported the alternative hypothesis or the null hypothesis (Rouder et al., 2009). The Bayes factor (BF_{10}) was used to provide an odds ratio for null versus alternative hypotheses (values > 1 favor the alternative hypothesis, and values < 1 favor the null hypothesis). For example, a BF_{10} of 3 indicates that the alternative hypothesis is three times more likely than the null hypothesis.

Results

The accuracy and reaction time results are presented in Figure 2. For accuracy, a significant main effect of condition on accuracy was observed, $F(3,84) = 48.968$, $p < 0.001$, $\eta^2 = 0.636$. Follow-up comparisons showed that the accuracy was significantly higher in the 0° separation (valid cue) condition ($M = 0.845$, SD = 0.046) than in the neutral cue condition ($M = 0.753$, SD = 0.066), $t(28) = 8.107$, $p < 0.001$, Cohen's $d = 1.505$, $BF_{10} > 1000$, in 35° separation (near-distance invalid cue) condition ($M = 0.735$, SD = 0.073), $t(28) = 8.574$, $p < 0.001$, Cohen's $d = 1.592$, $BF_{10} > 1000$, and in 70° separation(middle-distance invalid cue) condition ($M = 0.711$, SD = 0.090), $t(28) = 9.456$, $p < 0.001$, Cohen's $d = 1.765$, $BF_{10} > 1000$. These findings suggest that memory performance was significantly better in the valid cue condition than in both the neutral cue and invalid cue conditions. Additionally, accuracy was significantly higher in the neutral cue condition than in the 70° separation (middle-distance invalid cue) condition, $t(28) = 3.639$, $p = 0.001$, Cohen's $d = 0.676$, $BF_{10} = 30.802$, but no significant difference was found between the

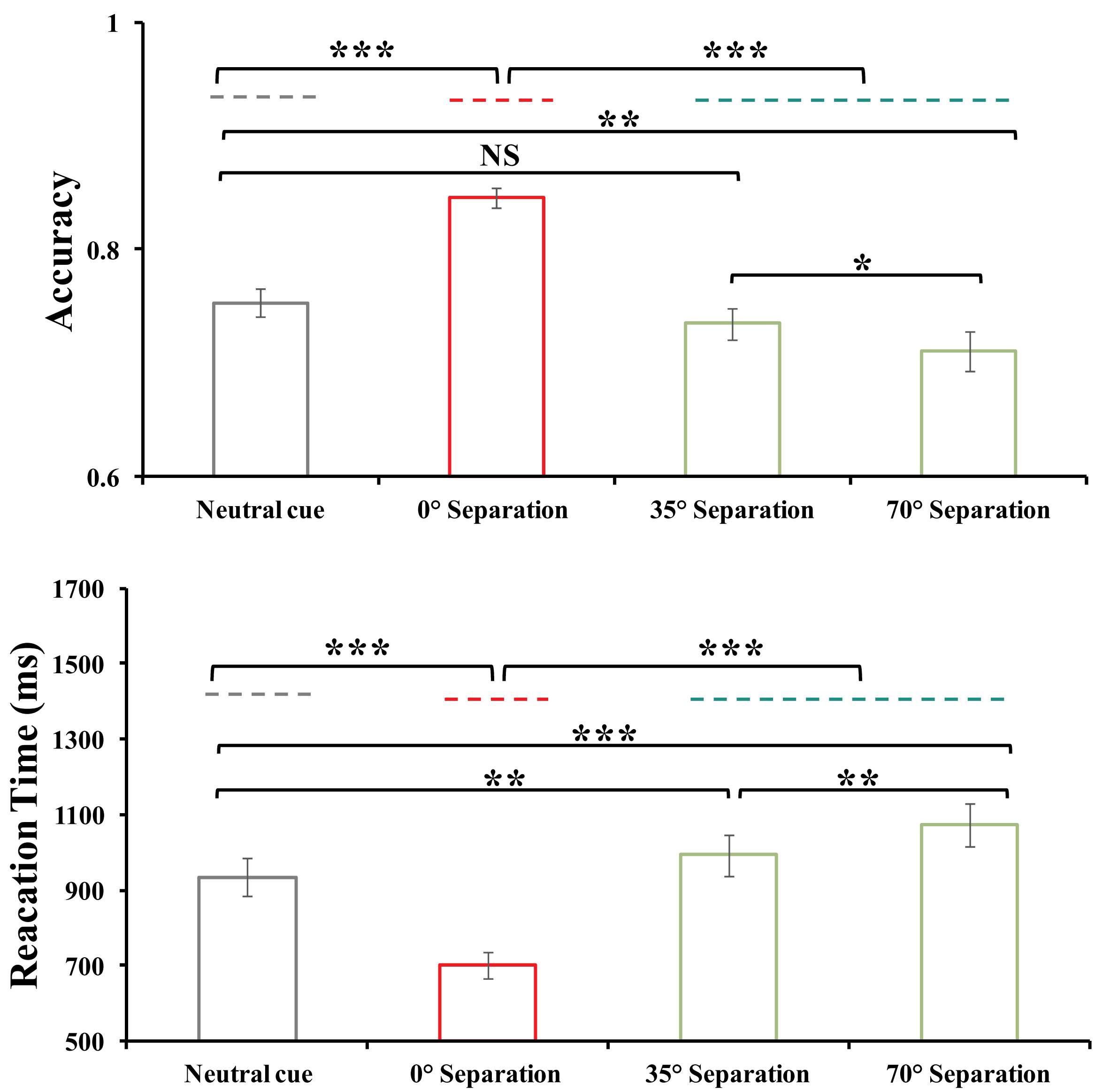

Figure 2. Accuracy and reaction time in each experimental condition in Experiment 1. The upper panel displays the accuracy results across the neutral cue condition (grey), 0° separation (valid cue) condition (red), 35° separation (near-distance invalid cue) condition (green), and 70° separation (middle-distance invalid cue) condition (green). The lower panel shows the reaction times for the same conditions. Note that the dashed lines at the top of the figure indicate comparisons between the neutral cue (grey) and the 0° separation (red), as well as between 35° separation (green) and the 70° separation (green) conditions, respectively. Error bars represent the standard errors of the mean. NS: non significance, *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

neutral cue condition and the 35° separation (near-distance invalid cue) condition, $t(28) = 1.730$, $p = 0.095$, Cohen's $d = 0.321$, $BF_{10} = 0.738$. This suggests better memory performance in the neutral cue condition compared to only when a probed uncued item was farther from the cued item. The accuracy was significantly higher in the 35° separation (near-distance invalid cue) condition than in the 70° separation (middle-distance invalid cue) condition, $t(28) = 2.396$, $p = 0.024$, Cohen's $d = 0.445$, $BF_{10} = 2.231$, suggesting that memory performance was better in the 35° separation (near-distance invalid cue) condition than in the 70° separation (middle-distance invalid cue) condition.

For reaction time, a significant main effect of condition on reaction time was observed, $F(3,84) = 76.277$, $p < 0.001$, $\eta^2 = 0.731$. Follow-up comparisons showed that the reaction time was significantly shorter in the 0° separation (valid cue) condition ($M = 701$ ms, $SD = 190$) than in the neutral cue condition ($M = 935$ ms, $SD = 280$), $t(28) = 10.248$, $p < 0.001$, Cohen's $d = 1.903$, $BF_{10} > 1000$, in 35° separation (near-distance invalid cue) condition ($M = 994$ ms, $SD = 294$), $t(28) = 12.042$, $p < 0.001$, Cohen's $d = 2.236$, $BF_{10} > 1000$, and in 70° separation (middle-distance invalid cue) condition ($M = 1073$ ms, $SD = 294$), $t(28) = 11.404$, $p < 0.001$, Cohen's $d = 2.118$, $BF_{10} > 1000$. These results indicate that reaction speed was significantly faster in the valid cue condition than in both the neutral cue and invalid cue conditions. The reaction time was significantly shorter in the neutral cue condition than in the 35° separation (near-distance invalid cue) condition, $t(28) = 3.468$, $p = 0.002$, Cohen's $d = 0.644$, $BF_{10} = 20.84$, and in 70° separation (middle-distance invalid cue) condition, $t(28) = 4.238$, $p < 0.001$, Cohen's $d = 0.787$, $BF_{10} = 127.80$, suggesting that the reaction speed in the neutral cue condition was significantly faster than in the invalid cue conditions. The reaction time was significantly shorter in the 35° separation (near-distance invalid cue) condition than in the 70° separation (middle-distance invalid cue) condition, $t(28) = 3.499$, $p = 0.002$, Cohen's $d = 0.650$, $BF_{10} = 22.38$, indicating that reaction speed was significantly faster in the 35° separation condition compared to the 70° separation condition.

Discussion

In Experiment 1, the results for accuracy showed that participants VWM performed better under the 0° separation (valid cue) condition compared to the neutral cue condition, exhibiting a significant RCB. Conversely, in the invalid cue conditions, VWM performance was worse than in the 70° separation condition compared to the neutral cue condition, indicating a significant RCC. However, no significant difference in accuracy was found between the neutral cue condition and the 35° separation condition. More importantly, we found that participants' VWM performance for uncued items located farther (i.e., 70° separation) from the cued item was worse than for those near to the cued item (i.e., 35° separation). This suggests that as the distance between the probed uncued item and the cued item increases, the RCC induced by the invalid cue also increases. Our findings align with the study by Souza et al. (2018), which found that items close in space to the cued location were partially insulated from cuing costs. Thus, even when participants were required to maintain a unilateral memory of visual stimuli, our results support the existence of an attentional spatial proximity effect when internal attention prioritizes items maintained in VWM.

Our reaction time results showed that participants' response times under retro-cue conditions increased as the distance between the cued item and the probed item grew. This pattern can be interpreted through the lens of the Posner cueing effect. In the classical Posner cueing paradigm, attentional cues direct focus to specific spatial locations, facilitating faster processing and shorter response times for stimuli presented at cued locations (Posner et al., 1980). Conversely, stimuli appearing at uncued locations necessitate attentional shifts, resulting in longer response times. In our study, the retro-cue likely guided participants' attention toward a particular location, analogous to spatial attention in the Posner task. When the probed item corresponded to the cued item, participants could access the relevant information more quickly, leading to the shortest response times. As the probed item was located farther from the rcued item, additional attentional shifts during the response stage were required, thereby increasing response times. Furthermore, the response time results confirm the effectiveness of our distance manipulation within invalid cue conditions, ranging from 0° to 70° separation.

It is noteworthy that in the 35° separation condition, there were no other uncued items between the cued item and the probed uncued item. In contrast, in the 70° separation condition, there was always an additional uncued item between the cued item and the probed uncued item. Similar setups were also present in the studies by Souza et al. (2018) and Fang et al. (2019). In their research, as the distance between the cued item and the probed uncued item increased, the number of uncued items between the cued item and the probed uncued item also increased. Therefore, the poorer VWM performance observed in the 70° separation condition in our Experiment 1 may be attributed to the interference caused by the additional uncued item between the cued item and the probed uncued item, rather than the distance itself. However, neither the studies by Souza et al. (2018) and Fang et al. (2019) nor our Experiment 1, independently controlled for two critical factors: the spatial distance between the cued item and the probed uncued item, and the presence of intervening uncued items between them. As a result, the effects attributed to increasing spatial distance may have been confounded by the presence of intervening distractors.

To address this issue, Experiment 2 was designed to disentangle the effects of spatial distance and the presence of intervening uncued items on the cuing costs associated with the probed uncued item. By manipulating these factors, we aimed to further investigate how spatial distance influences the role of internal attention in the representation of unattended items within VWM.

In addition, considering the findings by Fang et al. (2019), which demonstrated that VWM performance for probed items was most impaired when the spatial separation between the cued item and the probed item was as large as 120°, the distance settings in Experiment 1 of the present study may have been insufficient to capture the full range of effects. Therefore, in Experiment 2, we included a condition with a larger spatial separation (i.e., 105° separation) between the cued item and the probed uncued item to more thoroughly examine the potential impact of extreme spatial distances.

Experiment 2

Vogel and Awh (2008) used a change detection task to assess the VWM capacity of 170 undergraduate students, revealing an average capacity of 2.9 items. Thus, the memory set size of four in our Experiment 1 likely imposed a high VWM load for some participants with low VWM capacity. To mitigate potential issues arising from excessive memory load, in our Experiment 2, we reduced the number of colors participants needed to remember from four to three. This adjustment aimed to ensure that participants could more effectively consolidate each stimulus in the memory array. This change also allowed us to better control for the distance between the cued item and the probed uncued item, as well as the presence of any additional uncued items between them.

Experiment 2 had two main purposes. The first purpose was to investigate whether the observed decrease in VWM performance with increasing distance between the cued item and the probed uncued item was due to the distance itself or to the presence of additional uncued items between the cued item and the probed uncued item. The second purpose was to further investigate how greater angular separations between the cued and probed items impact performance under invalid cue conditions. To address this, we manipulated the distance between the cued item and the probed uncued item in invalid cue trials (35° separation vs. 70° separation vs. 105° separation). Additionally, in the 70° separation (middle-distance invalid cue) trials, we controlled for the presence or absence of an uncued item between the cued item and the probed uncued item. As a result, Experiment 2 included five different conditions: (1) 0° separation (valid cue) condition; (2) 35° separation (near-distance invalid cue) condition; (3) 70° separation without interference (middle-distance invalid cue without interference) condition (where no uncued item was present between the cued item and the probed item); (4) 70° separation with interference (middle-distance invalid cue with interference) condition (where an uncued item was present between the cued item and the probed item); (5) 105° separation (far-distance invalid cue) condition (where an uncued item was always present between the cued item and the probed item). Since our main focus in Experiment 2 was the comparison among different invalid cue conditions, we did not include neutral cue condition compared to Experiment 1, to ensure a high proportion of valid cue trials in the total number of trials.

Materials and methods

Participants

A total of 35 participants were recruited, all of whom were undergraduate or graduate students voluntarily participating in the experiment after being briefed on the task. All participants were right-handed, had normal or corrected-to-normal vision, had no history of color blindness or color weakness, and had no history of mental illness. However, three participants were excluded due to significantly lower-than-chance accuracy (below 40%) under certain conditions. Consequently, data from the remaining 32 participants (28 females and 4 males, aged 18–24 years, mean age 19.91 ± 1.65 years) were analyzed. All participants provided informed consent for the experiment and received a compensation of 35 Chinese Yuan upon completion. The research was conducted after obtaining ethical approval from the Ethics Committee of Sichuan Normal University.

Stimuli

The stimuli used in Experiment 2 were largely consistent with those in Experiment 1, with the primary difference being the number of items presented in the memory array. In Experiment 2, the memory array consisted of six colored circles, with three located on each side of the screen. The three colored circles on each side were randomly assigned to three of the four possible positions, which were identical to the positions used in the four-item array of Experiment 1.

Procedure and design

The experimental procedure was largely consistent with that of Experiment 1, with a few modifications. These included reducing the number of items in the memory array from eight to six and eliminating the neutral condition, as illustrated in Figure 3. By manipulating the position of the probed item, our experiment comprised five conditions: (1) *0° separation (Valid cue) condition*: The probed item's location matched the position indicated by the retro-cue. (2) *35° separation (Near-distance invalid cue) condition*: The probed item was an uncued item located close to the cued item (being the location 35° away from cued item). (3) *70° separation without interference (Middle-distance invalid cue without interference) condition*: The probed item was an uncued item adjacent to the cued item, with the distance between them being twice that of the near-distance invalid cue condition (being the location 70° away from cued item). (4) *70° separation with interference (Middle-distance invalid cue with interference) condition*: The probed item was an uncued item located at the same distance from the cued item as in the middle-distance invalid cue without interference condition (being the location 70° away from cued item), but with an additional uncued item positioned between the cued item and the probed item. (5) *105° separation (Far-distance invalid cue) condition*: The probed item was an uncued item, and the distance between it and the cued item was three times that of the near-distance invalid cue condition (being the location 105° away from cued item).

Experiment 2 consisted of 9 blocks, each containing 100 trials, for a total of 900 trials in the formal experiment. Of these, 660 trials involved valid retro-cues, and 240 involved invalid retro-cues, resulting in a 73% validity rate for retro-cues in Experiment 2. Due to the random distribution of memory array positions across trials, the 35° separation (near-distance invalid cue) condition was more likely to occur than other invalid cue conditions. Consequently, the near-distance invalid cue condition included 120 trials, while the 70° separation without interference (middle-distance invalid cue without interference) condition, the 70° separation with interference (middle-distance invalid cue with interference) condition, and the 105° separation (far-distance invalid cue) condition each included 40 trials. In this design, the number of trials for each invalid cue condition exceeded the 28 trials per condition used in the study by Souza et al. (2018). This ensured that, even with a memory load of three items, the experiment was not underpowered in terms of trial count. All conditions were randomly presented within each block. Each participant completed at least 24 practice trials before the formal experiment. Participants were given a minimum of a 1-minute break after each block to prevent fatigue. The entire experiment lasted approximately 80–90 minutes.

Data analysis

Similar to Experiment 1, we conducted data analyses on the mean accuracy and mean reaction time under different conditions for each participant. For

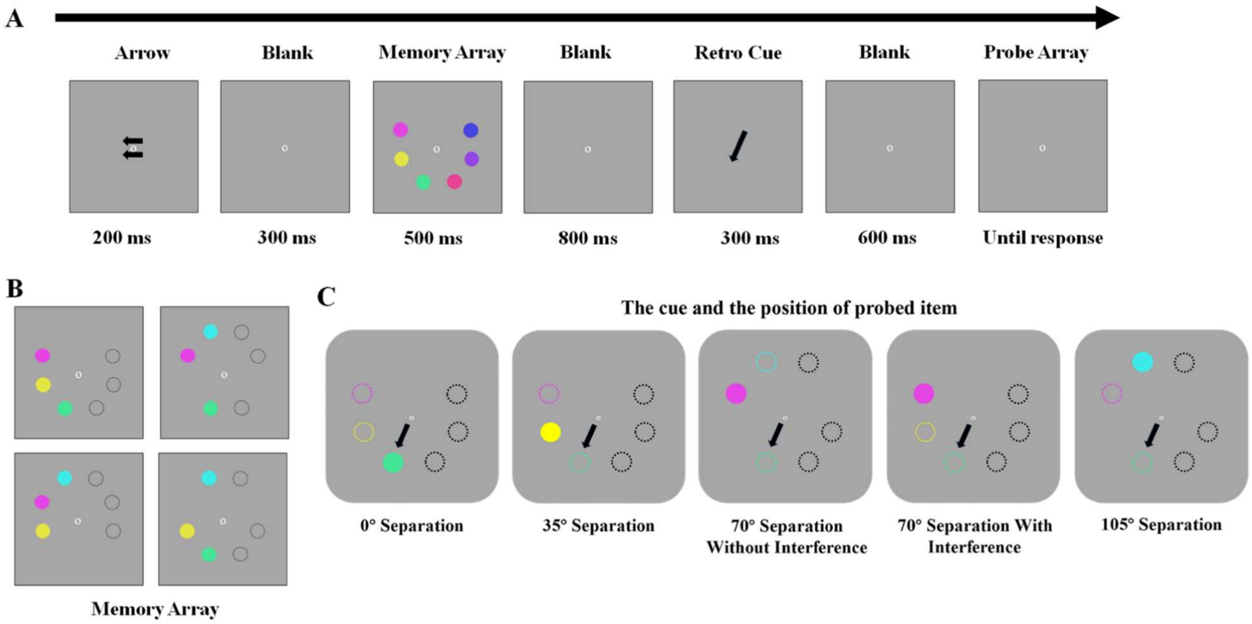

Figure 3. A: Flowchart for Experiment 2; B: Example of the memory array; C: The cue and the position of probed item. The arrows represent the retro-cue. The item pointed to by the arrow is the cued item, the solid circle indicates the probed item, and the rest of them are items presented in the memory array that were neither cued nor probed.

calculating mean reaction time for each participant, we averaged the reaction times of correct response trials for each condition. Separate one-way repeated measures ANOVAs were conducted for accuracy and reaction time, with condition (0° separation vs. 35° separation cue vs. 70° separation without interference vs. 70° separation with interference condition vs. 105° separation) as a within-subjects factor. To further explore differences between conditions, follow-up pairwise comparisons across five conditions using two-tailed t-tests were performed. Partial eta squared measures were used to estimate effect sizes for the ANOVAs, while Cohen's d was used to estimate the effect sizes of significant results in the *t*-tests. A significance level of $p < 0.05$ was applied for all statistical tests. Bayes factor analyses were used to show whether the t-test results supported the alternative hypothesis or the null hypothesis (Rouder et al., 2009).

Results

The results for accuracy and reaction time are displayed in Figure 4. Regarding accuracy, a significant main effect of condition was observed, $F(4,124) = 45.895$, $p < 0.001$, $\eta^2 = 0.597$. Post hoc comparisons revealed that accuracy was significantly higher in the 0° separation (valid cue) condition ($M = 0.877$, SD = 0.056) compared to the 35° separation (near-distance invalid cue) condition ($M = 0.726$, SD = 0.116), $t(31) = 8.650$, $p < 0.001$, Cohen's $d = 1.529$, $BF_{10} > 1000$, the 70° separation without interference (middle-distance invalid cue without interference) condition ($M = 0.711$, SD = 0.139), $t(31) = 8.021$, $p < 0.001$, Cohen's $d = 1.418$, $BF_{10} > 1000$, the 70° separation with interference (middle-distance invalid cue with interference) condition ($M = 0.689$, SD = 0.121), $t(31) = 10.449$, $p < 0.001$, Cohen's $d = 1.847$, $BF_{10} > 1000$, and the 105° separation (far-distance invalid cue) condition ($M = 0.709$, SD = 0.118), $t(31) = 9.347$, $p < 0.001$, Cohen's $d = 1.652$, $BF_{10} > 1000$. These results indicate that memory performance was significantly better in the valid cue condition than in all invalid cue conditions. Furthermore, accuracy in the 35° separation condition was significantly higher than in the 35° separation with interference condition, $t(31) = 3.034$, $p = 0.005$, Cohen's d = 0.536, $BF_{10} = 8.184$. However, no significant difference in accuracy was found between the 35° separation (near-distance invalid cue) condition and the 70° separation without interference (middle-distance invalid cue without interference) condition, $t(31) = 1.299$, $p = 0.203$, Cohen's $d = 0.230$, $BF_{10} = 0.406$, nor between the 35° separation (near-distance invalid cue) condition and the 105° separation (far-distance invalid cue) condition, $t(31) = 1.214$, $p = 0.234$,

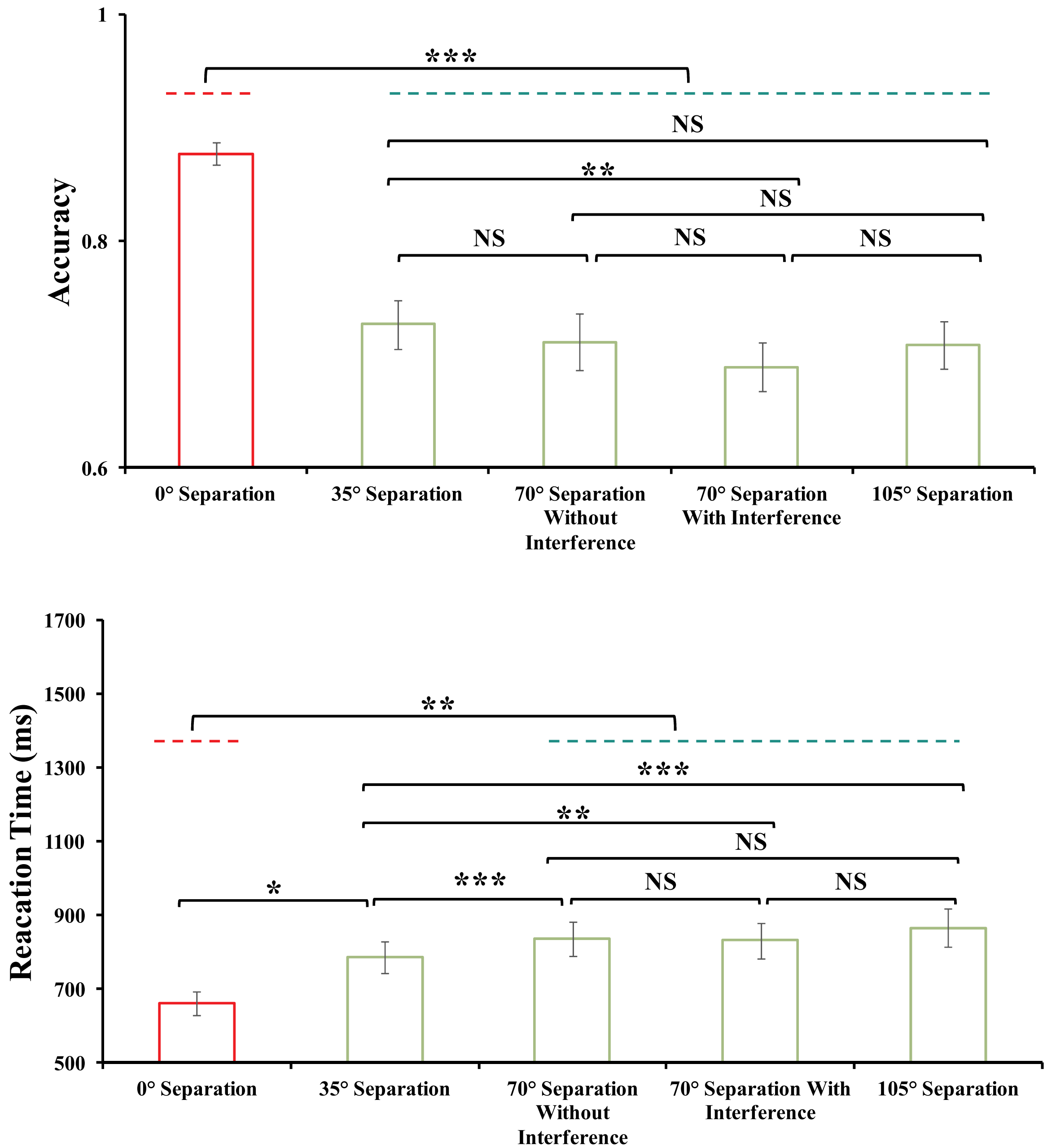

Figure 4. Accuracy and reaction time in each experimental condition in Experiment 2. The upper panel displays the accuracy results across the 0° separation (valid cue) condition (red), 35° separation (near-distance invalid cue) condition (green), 70° separation without interference (middle-distance invalid cue without interference) condition (green), 70° separation with interference (middle-distance invalid cue with interference) condition (green), and 105° separation (far-distance invalid cue) condition (green). The lower panel shows the reaction times for the same conditions. Note that the dashed lines at the top of the figure indicate comparisons between the condition corresponding to the red dashed line (valid cue) and the multiple conditions corresponding to the green dashed lines (invalid cue). Error bars represent the standard errors of the mean. NS: non significance, *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Cohen's $d = 0.215$, $BF_{10} = 0.369$. Additionally, no significant differences were found between the 70° separation with interference (middle-distance invalid cue with interference) condition and the 70° separation without interference (middle-distance invalid cue without interference) condition, $t(31) = 1.449$, $p = 0.157$, Cohen's $d = 0.256$, $BF_{10} = 0.487$, between the 70° separation without interference (middle-distance invalid cue without interference) condition and the 105° separation (far-distance invalid cue) condition, $t(31) = 0.164$, $p = 0.871$, Cohen's $d = 0.029$, $BF_{10} = 0.191$, or between the 70° separation with interference (middle-distance invalid cue with interference) condition and the 105° separation without interference (far-distance invalid cue) condition, $t(31) = 1.301$, $p = 0.203$, Cohen's $d = 0.230$, $BF_{10} = 0.407$. These findings suggest that, among the invalid cue conditions, memory performance was only significantly impaired in the 70° separation with interference condition compared to 35° separation condition. No significant differences in memory performance were observed among the other invalid cue conditions.

For reaction time, a significant main effect of condition was observed, $F(4,124) = 9.220$, $p < 0.001$, $\eta^2 = 0.229$. Post hoc comparisons revealed that reaction time was significantly shorter in the 0° separation (valid cue) condition ($M = 660$ ms, $SD = 182$) compared to the 35° separation (near-distance invalid cue) condition ($M = 785$ ms, $SD = 245$), $t(31) = 2.430$, $p = 0.021$, Cohen's $d = 0.430$, $BF_{10} = 2.359$; the 70° separation without interference (middle-distance invalid cue without interference) condition ($M = 836$ ms, $SD = 264$), $t(31) = 3.174$, $p = 0.003$, Cohen's $d = 0.561$, BF10 = 11.161, the 70° separation with interference (middle-distance invalid cue with interference) condition ($M = 831$ ms, $SD = 266$), $t(31) = 3.048$, $p = 0.005$, Cohen's $d = 0.539$, $BF_{10} = 8.445$, and the 105° separation (far-distance invalid cue) condition ($M = 865$ ms, $SD = 292$), $t(31) = 3.341$, $p = 0.002$, Cohen's $d = 0.602$, $BF_{10} = 16.359$. These results suggest that participants responded significantly faster in the valid cue condition than in any of the invalid cue conditions. Additionally, reaction time was significantly shorter in the 35° separation (near-distance invalid cue) condition than in the 70° separation without interference (middle-distance invalid cue without interference) condition, $t(31) = 5.196$, $p < 0.001$, Cohen's $d = 0.919$, $BF_{10} > 1000$; the 70° separation with interference (middle-distance invalid cue with interference) condition, $t(31) = 3.215$, $p = 0.003$, Cohen's $d = 0.568$, $BF_{10} = 12.248$, and the 105° separation with interference (far-distance invalid cue) condition, $t(31) = 4.594$, $p < 0.001$, Cohen's $d = 0.812$, $BF_{10} = 360.333$. This indicates that reaction speed in the 35° separation condition was significantly faster than in the 70° separation or 105° separation conditions. However, no significant differences were found between the 70° separation without interference (middle-distance invalid cue without interference) condition and the 70° separation with interference (middle-distance invalid cue with interference) condition, $t(31) = 0.349$, $p = 0.729$, Cohen's $d = 0.062$, $BF_{10} = 0.200$, between the 70° separation without interference (middle-distance invalid cue without interference) condition and the 105° separation (far-distance invalid cue) condition, $t(31) = 1.611$, $p = 0.117$, Cohen's $d = 0.285$, $BF_{10} = 0.604$, or between the 70° separation with interference (middle-distance invalid cue with interference) condition and the 105° separation (far-distance invalid cue) condition, $t(31) = 1.684$, $p = 0.102$, Cohen's $d = 0.298$, $BF_{10} = 0.670$. These findings suggest that reaction speed did not differ significantly between the 70° separation and 105° separation conditions.

Discussion

In Experiment 2, we found that accuracy was significantly better under valid cue conditions compared to invalid cue conditions. This indicates that participants indeed used the retro-cues to enhance their performance in Experiment 2.

Notably, in this experiment, the number of trials in the 35° separation condition was more than in the 70° separation without interference, 70° separation with interference, and 105° separation conditions. Previous research has shown that VWM resources are not rigidly distributed but can be dynamically reallocated based on task demands (Emrich et al., 2017). Items with high priority cues are allocated more VWM resources, leading to significantly better VWM performance compared to lower-priority items. Therefore, although in Experiment 2 participants were not explicitly informed of the differences in trial numbers across the invalid cue conditions, they may have intuitively allocated resources not only to the cued item but also to the near-distance uncued item (i.e., the item at 35° separation) after seeing the retro-cue. This design likely reduced participants' motivation to suppress the uncued item at 35° separation before the probed item appeared, thereby maintaining its representation in VWM. As a result, in the 70° separation with interference condition, participants might have been more motivated to preserve the intervening distractor (i.e., the uncued item at 35° separation) in VWM. However, differences in trial numbers across conditions may also have introduced probe probability effects that influenced performance in the 35° separation condition. Consequently, direct comparisons between the 35°

separation condition and other invalid conditions with fewer trials (e.g., 70° separation and 105° separation conditions) cannot be reliably used as evidence for the impact of distance on retro-cue effects. More importantly, in Experiment 2, the number of trials was consistent across the three key conditions: 70° separation without interference, 70° separation with interference, and 105° separation. Comparisons among these three conditions are thus unaffected by probe probability and provide a robust basis for subsequent discussions.

Our primary focus in Experiment 2 was on two key questions: first, whether the presence of intervening distractors contributes to performance impairments under invalid cue conditions; and second, how increasing the spatial separation (i.e., increasing to 105° separation) between the cued item and the probed item affects memory performance under invalid cue conditions. Regarding whether the presence of additional uncued items between the cued item and the probed uncued item affects cuing costs, we found that, in the 70° separation conditions, there was no significant difference in memory performance between the 70° separation without interference and the 70° separation with interference conditions. Thus, we did not find evidence to support the notion that the observed decrease in VWM performance with increasing distance between the cued item and the probed uncued item was due to the presence of additional uncued items between them. These results rule out the possibility in the studies by Souza et al. (2018) and Fang et al. (2019) that the relationship between cuing costs and the distance between the cued and probed uncued items is influenced by the presence of extra uncued items between the the cued and probed uncued items.

To address whether increasing the spatial separation to 105° affects memory performance, we found no significant differences in accuracy between the 70° separation and 105° separation conditions. This lack of effect contrasts with the findings of Fang et al. (2019), who reported that larger separations (e.g., 120°) led to more pronounced impairments in the memory performance of probed items. Conversely, our results are consistent with Souza et al. (2018), who found that when all probed uncued items were relatively distant from the cued item (e.g., 45° to 180° separations), the spatial distance between the cued and probed uncued items had no measurable impact on cuing costs in retro-cue trials.

It is also noteworthy that, in Experiment 2, we found no significant differences in reaction times between the 70° separation and 105° separation conditions. Although the distance from the stimuli to the center was constant across all separation conditions, the actual distance between the probed item and the cued item varied. For example, in the 35° separation condition, the actual distance between the probed and cued items was 3.6 dva, whereas in the 70° separation condition, this distance was 6.9 dva, and in the 105° separation condition, it was 9.5 dva. Importantly, the difference in actual distances between the 105° and 70° separation conditions is smaller than the difference between the 70° and 35° separation conditions. This may explain why a significant difference in reaction times was observed between the 35° and 70° separation conditions in Experiment 1 but not between the 70° and 105° separation conditions in Experiment 2. Given that the comparison between the 105° and 70° separation conditions in Experiment 2 does not provide strong evidence regarding the role of spatial distance on memory performance for invalid cued items, we will focus on the results of Experiment 1 in the General Discussion when addressing the role of spatial distance in retro-cue effects.

General discussion

Our study demonstrates that even under conditions of unilateral memory and relatively low cognitive load, the memory performance of unattended VWM representations is influenced by their spatial distance from attended VWM representations. Specifically, unattended VWM representations located in close proximity to attended representations incur lower cuing costs. These findings are consistent with those of Souza et al. (2018) and provide new evidence for the existence of an attentional spatial proximity effect when internal attention prioritizes items maintained in VWM. Our results suggest that the selection of representations in VWM may not be rigidly confined to the spatial location of a single item.

Moreover, we propose that the reduction in cuing costs for adjacent unattended representations is simply a consequence of the attentional spatial proximity effect. This does not imply that individuals are utilizing the retro-cue to simultaneously focus attention on multiple nearby items. Previous research has shown that retro-cue benefits in VWM are generally limited to a single location at a time (DiPuma et al., 2023; Makovski & Jiang, 2007). While attending to multiple items simultaneously might increase the accessibility of both, it also raises the likelihood of confusing the target with its nearby neighbor during testing, thereby diminishing the overall cuing benefit.

Our study provides evidence supporting an attentional spatial proximity effect in VWM, even under conditions of low memory load. However, it is noteworthy that the pattern of the attentional spatial proximity effect observed in our study may differ from that identified by Souza et al. (2018) under high memory load conditions. In their study, participants were required to remember a larger number of items (eight), far exceeding the average memory capacity limit. As a result, participants could only fully consolidate a limited number of items into robust VWM representations, while the remaining items were relegated to a state known as fragile visual short-term memory (FM). This state seems to exist between iconic memory and robust VWM (Pinto et al., 2013; Sligte et al., 2008; Vandenbroucke et al., 2011; Vandenbroucke et al., 2015). FM has a large capacity (at least two items more than VWM capacity) and a long-lasting lifetime, potentially persisting as long as VWM without interference from new stimuli (e.g., the appearance of a probe array). Upon the appearance of a probe array, the representations in FM are degraded, and only the items that have been consolidated into robust VWM representations can be compared to the probe array. In this scenario, individuals can use a retro-cue to transfer representations from FM into robust VWM, thereby gaining the retro-cue benefit. The findings from the study by Souza et al. (2018) may partly stem from the possibility that during the transfer of representations from FM to robust VWM, nearby FM representations were also transferred, leading to the observed reduction in cuing costs for probed uncued items located very close to the cued item. In contrast, our study used a lower memory load, enabling participants to consolidate all memory items into robust VWM representations during the encoding phase. Consequently, the retro-cue in our study served to further enhance a particular robust VWM representation, without necessitating the transition of representations from FM to robust VWM. Despite this, we still found evidence supporting the attentional spatial proximity effect, indicating that even when internal attention is used to enhance a robust VWM representation, this enhancement can extend to uncued items in close proximity to the cued item. These results collectively suggest that although the mechanisms underlying the retro-cue benefit may vary under different memory loads, the improvement of internal attention on a specific memory representation not only enhances that representation but also confers some benefit on nearby representations.

While our results align with those of Souza et al. (2018), this does not imply a rejection of the findings from Fang et al. (2019). In the study by Fang et al. (2019), they found that the memory performance of probed uncued items exhibited a non-monotonic relationship with the distance between the cued and uncued items. Specifically, they observed a significant cuing cost for uncued items located 60° separation to the cued item, with the strongest cuing cost occurring at 120° separation to the cued item, and a reduced cuing cost for 180° separation to the cued item, even lower than that for 120° separation probed items. We believe that the differences between our findings and those of Fang et al. (2019) may be due to their possibilities. First, in their study, the 180° separation item was always located on the opposite side of the cued item. The better memory performance observed for 180° separation uncued items compared to 120° separation uncued items may be attributed to the bilateral field advantage in VWM (Delvenne, 2005; Umemoto et al., 2010; Zhang et al., 2018). Under conditions of bilateral memory arrays, the allocation of resources to each hemifield may be relatively independent, potentially preventing attentional suppression on one side from spreading to the opposite hemifield. This could explain why the 180° separation uncued items in Fang et al. (2019) were less affected by attentional suppression, resulting in better memory performance than the 120° separation uncued items. In our study, however, participants only memorized stimuli presented in one hemifield, so no such bilateral effect would be observed. Second, pervious research suggests that the spatial distribution of human attention typically focuses on a central area of approximately 2° to 5° of visual angle (dva). This range reflects the high-resolution processing capabilities of the foveal region and represents the optimal allocation of attentional resources (Eriksen & St James, 1986). Beyond this range, attention can extend up to 10° of visual angle, though with reduced efficiency (LaBerge, 1983). In Fang et al. (2019), the eccentricity was set at 2.8 dva, meaning that even at 120° separation (probed item at 4.9 dva away) and 180° separation (probed item at 5.6 dva away), the probed items remained within or near the central focus. In contrast, both our study and that of Souza et al. (2018) used larger eccentricities: In our study, the probed item distances were 6.9 dva (70° separation) and 9.8 dva (105° separation). In Souza et al. (2018), the distances were 7.1 dva (90° separation), 9.2 dva (145° separation), and 10 dva (180° separation). These distances fall outside the central focus range, suggesting that the patterns observed in Fang et al. (2019) may primarily apply to uncued items probed within the central focus range. This difference in the distance range may also explain why our findings align more closely with those of Souza et al. (2018). Third, in our study and that of Souza et al. (2018), the retro-cue used was an endogenous cue, presented at the center of the screen and pointing to a target location. In contrast, Fang et al. (2019) used an exogenous cue, presented directly at the target location. The difference in cue types might influence the manner in which internal attention is shifted. Upon seeing an endogenous cue, participants might be more inclined to allocate attention to a broader region surrounding the cued location, thereby benefiting nearby uncued items. Conversely, upon seeing an exogenous cue, participants might focus attention more narrowly on the specific location, while suppressing attention to surrounding areas, leading to greater detriments for nearby uncued items. This could explain why Fang et al. (2019) found a significant cuing cost for uncued items close to the cued item.

It is important to note that our study does not aim to determine whether the conclusions of Souza et al. (2018) or Fang et al. (2019) are correct. Instead, our goal is to build upon the areas of consensus in their research and further explore the impact of spatial distance on the retro-cue effect, thereby contributing to a deeper understanding of the mechanisms underlying the use of internal attention. Future research could explore whether the discrepancies between the findings of Souza et al. (2018) and Fang et al. (2019) arise from whether the probed item falls within the central focus range or from differences in the types of retro-cues used in their studies.

In addition, in the studies by Souza et al. (2018) and Fang et al. (2019), as the distance between the cued item and the uncued item increased, the number of other uncued items within the intervening space also increased. They did not account for whether these additional uncued items might have contributed to the observed changes in cuing cost for the uncued item. Our Experiment 2 addressed this potential confound and provided results that rule out this possibility.

It is also noteworthy that in our study, we used a retro-cue with relatively high validity (73%). Previous research has shown that the processing of uncued representations is influenced by cue validity. In tasks with high cue validity (e.g., 80%), participants tend to retain only the cued representation while suppressing other uncued representations. However, in tasks with low cue validity (e.g., 20-50%), participants are more likely to continue preserving both cued and uncued representations (Fu et al., 2022; Günseli et al., 2015; Günseli et al., 2019). Thus, it is possible that the attentional spatial proximity effect observed in our study when using a retro-cue might be modulated by cue validity. Future research could systematically manipulate cue validity to explore this issue further.

Conclusion

This study found that under conditions of unilateral memory and low memory load, the retro-cue benefit in VWM can extend to uncued items that are in close proximity to the cued item. However, as the distance between the cued and uncued items increases, this benefit diminishes and eventually disappears. Notably, this phenomenon is influenced solely by the spatial distance between the cued and uncued items and is not affected by the presence of other uncued items between them. Therefore, our findings support the notion that when internal attention is directed toward a specific VWM representation, attention is preferentially allocated to the location of the target representation, with a gradual decline in attentional resources extending to nearby locations of unattended representations. This mechanism allows non-target representations that are spatially close to the target representation to benefit via the retro-cue.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The datasets generated/analyzed for this study can be found in the Open Science Framework at https://osf.io/zfbmd/.

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