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Invalid retro-cues can eliminate the retro-cue benefit: Evidence for a hybridized account

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Abstract

The contents of visual working memory (VWM) are capacity limited and require frequent updating. The retrospective cueing (retro-cueing) paradigm clarifies how directing internal attention among VWM items boosts VWM performance. In this paradigm a cue appears prior to retrieval, but *after* encoding and maintenance. The retro-cue effect (RCE) refers to superior VWM after valid versus neutral retro-cues. Here we investigated the effect of the invalid retro-cues inclusion on VWM performance. We conducted two pairs of experiments changing both probe type (recognition/recall) and in the presence/absence of invalid retro-cue trials. Furthermore, to fully characterize these effects over time we also used extended post-retro-cue delay durations. In the first set of experiments probing VWM using recognition indicated that the RCE remained consistent in magnitude with or without invalid retro-cue trials. In the second set of experiments VWM was probed with recall. Here, the RCE was eliminated when invalid retro-cues were included. This finer-grained measure of VWM fidelity showed that all items were subject to decay over time. We conclude that the invalid retro-cues impaired the protection of validly cued items, but they remain accessible, suggesting greater concordance with a prioritization account.

Keywords

visual working memory; short-term memory; retro-cue; retrospective cueing; attention

It is not always clear ahead of time what things will become important later on. Unlike a mystery program, our internal camera may not linger on seemingly unimportant details: the letter opener, or the strangely placed frame that only become important later on. The strict capacity limits of visual working memory (VWM) and its regular updating create a tension between encoding salient new items and maintaining relevant items. Any advantage, such as a cue, to improve VWM is beneficial. Attentional cues improve detection, discrimination, and recollection of cued items whether they are presented prior to stimuli (reviews include: Carrasco, 2011; Kastner & Ungerleider, 2000; Posner & Petersen, 1990) simultaneously with stimuli (Jiang, Olson, & Chun, 2000) or even well after (~1000 ms) stimulus offset (Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003). This third case of retrospective cueing interests us because VWM performance significantly improves without any additional sensory information. The difference in performance between neutral and

valid trials is termed the retro-cue effect (RCE). Importantly, the retro-cue paradigm offers a window into attentional processing on items held in VWM.

There has been a debate regarding the mechanism of the RCE. Compelling recent work indicates that the validly retro-cued item is likely protected from subsequent decay, but at the cost of uncued items, which decay more quickly over time (Pertzov, Bays, Joseph, & Husain, 2013). These authors improved the standard retro-cue paradigm by employing a recall probe, thereby enhancing their ability to assess VWM in a finer-grained manner (see also: Bays, Gorgoraptis, Wee, Marshall, & Husain, 2011; Hollingworth & Hwang, 2013; Williams, Hong, Kang, Carlisle, & Woodman, 2013). This is consistent with retro-cue studies using recognition VWM probes to show significantly lower accuracy on invalid retro-cue trials when compared to performance with neutral or valid retro-cues (e.g. Astle, Nobre, & Scerif, 2010; Griffin & Nobre, 2003; Matsukura, Luck, & Vecera, 2007). Experiments probing the fate of uncued items require neutral, valid and invalid cues. However, only a subset of retro-cue papers reported data regarding invalid trials (Astle et al., 2010; Griffin & Nobre, 2003; Landman et al., 2003; Pertzov et al., 2013) although others include a proportion of invalid trials that are not discussed in the findings (Nobre et al., 2004). We observed a robust RCE even when the majority of retro-cues were *invalid* and even after instructing participants to ignore the retro-cues (Berryhill, Richmond, Shay, & Olson, 2012). A second study found that there was no penalty to VWM precision when invalid retro-cues were incorporated and responses were probed using a recall measure (Hollingworth & Hwang, 2013). Hollingworth and Hwang (2013) used recall probes and found equivalently precise representations of the items in VWM across valid (80% of trials) and invalid retro-cue trials (20%). However, this pattern showing no negative consequence of invalid retro-cue trials is not universal. For example, other researchers failed to identify an RCE when the retro-cue marked an item to forget and when there were rare invalid retro-cues (10% of trials), although the RCE was present when these directed forgetting retro-cues were always valid (Williams & Woodman, 2012). Williams et al.'s analyses found that this behavior was present beginning with the first block of trials. They concluded that participants ignored the directed forgetting retro-cues entirely when they had the small possibility of being invalid. In short, there is a lack of consistency with regard to the effect of invalid retro-cues on the RCE that is difficult to penetrate because of the paradigmatic differences across this handful of findings. We aimed to address this inconsistency by providing a bridge between different stimulus types and paradigms. Furthermore, although previous studies that included invalid retro-cues report whether they observe a significant RCE or not; they were not designed to compare the magnitude of the RCE when invalid retro-cues were present or absent. In other words, although invalid cues had been used before, what has not been systematically probed is to test whether the inclusion of invalid retro-cue trials changes the RCE magnitude. Here, we address that very question. If the presence of invalid cues does modulate the RCE, it may explain some of the variability in the retro-cue literature and it will inform several theoretical accounts of the RCE, namely prioritization and protection (Matsukura et al., 2007). The prioritization account suggests that the cued item is compared to the probe item first, whereas uncued items remain accessible for subsequent comparisons. Importantly, all memoranda are subject to similar decay profiles. The protection account argues that the cued items are protected from decay

through the focusing of internal attention, whereas the uncued items are subject to more rapid decay. A significant reduction in the RCE when invalid retro-cues are included would support the protection account, whereas consistent decay in performance across conditions without an interaction would support the prioritization account. Therefore by including the invalidly cued trials, and comparing the RCE between with and without invalid retro-cue experiments we aimed to have a better understanding on the mechanisms of the RCE.

This paper asks whether the RCE is modulated by inclusion of invalid trials. We also track VWM decay over an extended time period to better characterize the fate of cued and uncued items. Finally, we aim to supply a missing bridge between the retro-cue literature using recognition and the newer findings employing recall. We completed two pairs of experiments varying probe type (Experiment 1a/b: recognition; Experiment 2a/b: recall), and cue type (Experiments 1a, 2a: neutral, valid; Experiments 1b, 2b: neutral, valid, invalid). We predicted that Experiment 1a/b would confirm the presence of the RCE over time with or without invalid trials. Experiment 2a/b, were included to provide a more sensitive, recall-based measure of the RCE. Inter-experiment comparisons were included to test whether invalid retro-cue trials changed the magnitude of the RCE and whether they replicated previous decay patterns for uncued items.

Experiment 1a/b

These experiments tested the effect of invalid retro-cues on RCE magnitude and the decay of cued and uncued items over the full VWM range (100 ms – 24000 ms). Previous work demonstrates that the RCE shows some reduction with increased 2nd delay durations of 2–15 s when neutral and valid retro-cue conditions are included (Nobre, Griffin, & Rao, 2008). Both experiments tested VWM using recognition. Experiment 1a consisted of valid and neutral retro-cue trials; Experiment 1b included invalid retro-cue trials. This between-subjects design was necessary due to the different trial types across experiments.

Method

Participants—Experiment 1a/b tested groups of 20 volunteers from the University psychology pool (Experiment 1a: ages 18–45, $M = 22.25$, 15 female; Experiment 1b: ages 18–43, $M = 21.2$, 17 female) for extra course credits. The Internal Review Board of the University of Nevada approved all protocols.

Stimuli—Stimuli and cues were presented on a uniform black background. The VWM display consisted of 4 unique equiluminant color disks (5° diameter) selected from a set of 10 disks. Disks were displayed equidistantly (6.5°) from fixation in a square pattern. Neutral retro-cues ('X', 4° × 4°) and valid arrow retro-cue (4.5° × 4°) were white.

Experimental Design and Trial Sequence—Participants sat 57 cm from a 17" LCD monitor (Dell 1707 FPc, Samsung SyncMaster 172N). The experiment was programmed in ePrime (PST, PA, USA). Participants were instructed to remember color-location conjunctions. Participants were informed that the 'X' cues were not informative but that the arrow cues were informative. In Experiment 1b, participants were informed that the arrow retro-cues were informative but sometimes misleading. To characterize RCE magnitude over

time, we used 2nd delay durations of 100, 800, 2400, and 24000 ms to investigate the effect of longer 2nd delay durations as well as effect of inclusion of the invalid retro-cues. These delays were selected to bookend and extend our previous work showing that the RCE magnitude is consistent at 2nd delay durations ranging from 300 ms and 700 ms (Tanoue & Berryhill, 2012).

Trials began with the presentation of a white fixation cross (1500 ms), followed by the VWM array (300 ms). After an unmasked 1st delay interval (1000 ms) the retro-cue (100 ms) appeared. The retro-cue was followed by a 2nd delay (100, 800, 2400, or 24000 ms); see Figure 1 (top panel). These durations were randomized and equally probable. Finally, a probe screen appeared containing a single probe item and three empty annuli. The task was to decide whether the probe item matched the original stimulus. Participants made an unspeeded response by pressing the 'Y' key for a match (50%) and the 'N' key for a non-match. In Experiment 1a, trials were randomized and equally split between valid (50%) and neutral (50%) trials; in Experiment 1b trial types were randomized across valid (40%), neutral (40%) and invalid (20%) trials. Participants completed 200 trials in four blocks separated by rest breaks. In all experiments participants performed an auditory suppression task by repeating different one-syllable words during each block of trials to minimize verbal encoding. Participants were audible through the testing room door and monitored for compliance. In all analyses, Greenhouse-Geisser corrections were applied where sphericity was violated and Bonferroni correction was applied to pairwise comparisons.

Results and Discussion

Experiment 1a—VWM accuracy was subjected to a 2×4 repeated measures ANOVA with the within-subjects factors of retro-cue condition (valid, neutral) and 2nd delay duration (100, 800, 2400 or 24000 ms). Confirming the RCE, performance was significantly better on valid retro-cue trials ($F_{1, 19} = 27.98$, $p < .001$; valid Mean (standard deviation) = .84 (.02); neutral: $M = .73$ (.08); $\eta_p^2 = .59$). There was a significant main effect of 2nd delay duration ($F_{3, 57} = 5.43$, $p = .02$; $\eta_p^2 = .22$) driven by significantly reduced accuracy at the 24000 ms 2nd delay duration as compared to 800 ms ($p = .007$). No other pairwise comparisons were significant (all p 's $> .09$). Importantly, there was a significant interaction between retro-cue condition and 2nd delay duration ($F_{3, 57} = 6.11$, $p = .001$; $\eta_p^2 = .24$). This interaction was driven by two components. First, accuracy on neutral retro-cue trials fell with longer 2nd delay durations, as confirmed by a second ANOVA excluding valid retro-cue trials ($F_{3, 57} = 9.69$, $p = .001$) with significantly lower accuracy after 24000 ms delays than at the other durations (all p 's $< .007$). In contrast, performance on the valid retro-cue trials remained constant across delays ($F < 1$, $p = \text{ns}$); see Figure 2 (left panel).

Experiment 1b—Accuracy data were subjected to a 3×4 repeated measures ANOVA including retro-cue (valid, invalid, neutral) and 2nd delay duration (100, 800, 2400, 24000 ms). There was a significant main effect of retro-cue (neutral: $M = .69$ (.05), valid: $M = .75$ (.05), invalid: $M = .65$ (.07); $F_{2, 38} = 8.51$, $p = .001$; $\eta_p^2 = .30$) such that the valid retro-cue elicited more accurate VWM performance than neutral ($p = .05$) or invalid retro-cues ($p = .004$). Neutral and invalid retro-cues were not significantly different ($p = .41$). As in Experiment 1a, there was a significant main effect of 2nd delay duration ($F_{3, 57} = 11.05$, $p < .$

001; $\eta_p^2 = .36$), indicating that extending the delay hurt accuracy. Accuracy was significantly lower in the 24000 ms condition compared to all other durations (all p 's $< .02$); no other 2nd delay durations differed significantly from each other (all p 's $> .55$). Unlike Experiment 1a, there was no significant interaction between retro-cue and 2nd delay ($F_{6, 114} = 1.02$, $p = .416$; $\eta_p^2 = .05$); see Figure 2 (right).

Experiment 1a/b Comparison

To directly compare the magnitude of the RCE between experiments, we calculated the RCE for each participant and conducted a repeated-measures ANOVA with the within-subjects factors of 2nd delay duration (100, 800, 2400 and 24000 ms) and the between-subjects factor of Experiment (1a and 1b). As expected, there was a main effect of 2nd delay duration ($F_{3, 114} = 3.29$, $p = .023$; $\eta_p^2 = .74$). The main effect of Experiment was not significant ($F_{1, 38} = 1.16$, $p = .288$; $\eta_p^2 = .18$) and neither was the interaction between 2nd delay duration and Experiment ($F_{3, 114} = 2.11$, $p = .102$; $\eta_p^2 = .53$).

Experiment 1a/b tested VWM using recognition to determine whether the inclusion of invalid retro-cues interfered with RCE magnitude. The data showed that the presence of the invalid cues did not weaken the RCE. These results provide initial evidence indicating that the presence of invalid trials does not interfere with RCE magnitude.

Experiment 2a/b

The second pair of experiments employed recall to probe VWM. We compared RCE magnitude across experiments with and without invalid retro-cue trials. We made two changes to the previous methods. First, a preliminary experiment¹ confirmed that replacing color patches with oriented bar stimuli lead to the same conclusions as derived from Experiment 1a/b: including invalid retro-cue trials did not minimize the magnitude of the RCE. In Experiment 2a/b we used oriented bar stimuli and extended the encoding time (e.g. Zhang & Luck, 2009). Second, we changed the 2nd delay durations. In Experiments 1a/b there was no significant difference between the 100, 800 and 2400 ms 2nd delay durations, so we selected 800 ms to maintain a consistent 2nd delay duration across experiments. A recent paper showed that at 2nd delay durations of 3000 ms, invalidly cued items decay twice as much as validly cued items (Pertsov et al., 2013). We included the 3000 ms 2nd delay duration to make contact with their findings. Finally, we included a longer 2nd delay durations (10000 ms) to examine the consequences of delay and to extend the previous observations of Pertsov and colleagues. We excluded the 24000 ms 2nd delay duration used

¹Two groups of 14 participants completed a pair of experiments using oriented line stimuli (1000 ms presentations, 6 orientations: 0°, 30°, 60°, 90°, 120°, 150°) at several 2nd delay durations (200, 400, 600, 800 ms). In each experiment there were 200 trials in a 6-AFC design such that all possible line orientations were available. Statistical analyses revealed a significant RCE including invalid trials ($F_{1, 19, 15.48} = 16.21$, $p = .001$; neutral $M = .56$ (.03), valid $M = .66$ (.02), invalid $M = .45$ (.05)) or excluding them ($F_{1, 13} = 31.62$, $p = < .001$; neutral: $M = .60$ (.04), valid $M = .75$ (.03)). However, over these shorter 2nd delay durations there was no main effect of 2nd delay duration (both p 's $> .12$), and no interaction of cue and delay (both p 's $> .44$), replicating our previous findings (Tanoue & Berryhill, 2012). We also compared the magnitude of the RCE between experiments. We conducted a repeated-measures ANOVA with the within-subjects factors of 2nd delay duration (200, 400, 600 and 800 ms) and the between-subjects factor of Experiment (with invalid trials, without invalid trials). The main effect of 2nd delay duration was not significant ($F_{3, 78} = 1.26$, $p = .293$; $\eta_p^2 = .46$) and neither was the main effect of Experiment ($F_{1, 26} = 2.04$, $p = .164$, $\eta_p^2 = .73$). The interaction effect was also not significant ($F_{3, 78} = 3.05$, $p = .271$, $\eta_p^2 = .69$). In short, using bar stimuli instead of color patches lead to the same conclusion: including invalid retro-cue trials did not modulate RCE magnitude.

in Experiment 1a/b because participants struggled with this long delay when asked for recognition responses and we were concerned that we would not obtain valid recall measures.

Method

Participants—In Experiment 2a and 2b two groups of 20 undergraduate volunteers participated (Experiment 2a: ages 18–40, $M = 23.6$, 13 female; Experiment 2b: ages 18–33, $M = 20.8$, 10 female) in exchange for extra course credits or \$10.

Equipment and Stimuli—Participants sat 57 cm from a 15" MacBook monitor (MacBook Pro). The experiment was programmed in Matlab, using the Psychophysics Toolbox (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). White bars ($7.5^\circ \times 1.5^\circ$) were displayed equidistantly (6.5°) from fixation in a square pattern; cues were neutral ('X', $4^\circ \times 4^\circ$) or valid/invalid arrow retro-cues ($4.5^\circ \times 4^\circ$). In a VWM array the four orientations differed by at least 10° .

Experimental Design and Trial Sequence—The trial sequence was similar to that described above except for expanding stimulus duration to 1000 ms and the 2nd delay durations (800, 3000, 10000 ms); see Figure 1 (bottom panel). At retrieval, participants rotated the single probe item using left and right arrow keys, with each key press incrementing rotation 1° . Pressing the space bar confirmed the response. Participants completed 210 (Experiment 2a) or 195 trials (Experiment 2b). In Experiment 2a, neutral and valid trials were equally likely; in Experiment 2b valid (40%) and neutral (40%) trials were twice as likely as invalid (20%) trials. The distance between the presentation orientation and the reported orientation was calculated as degree error.

Results and Discussion

Experiment 2a—Degree error was subjected to a 2 retro-cue (valid, neutral) $\times$ 3 2nd delay duration (800, 3000, 10000 ms) repeated measures ANOVA. The expected RCE was significant ($F_{1, 19} = 9.57$, $p = .006$; $\eta_p^2 = .33$). Error was significantly larger for neutral ($M = 20.52$ (1.66)) than valid trials ($M = 17.28$ (1.56)). The main effect of 2nd delay duration was also significant ($F_{2, 38} = 8.61$, $p = .001$; $\eta_p^2 = .31$). Greater error was observed in the 10000 ms ($M = 20.70$ (1.50)) than the 800 ms ($M = 17.51$ (1.58), $p = .005$) or 3000 ms ($M = 18.48$ (1.67), $p = .008$) conditions. There was no significant difference between 800 ms and 3000 ms ($p = .763$) conditions. The interaction between retro-cue type and 2nd delay duration was not significant ($F_{2, 38} < 1$, $p = \text{n.s.}$; $\eta_p^2 = .02$); see Figure 3 (left panel).

Experiment 2b—The analysis included the invalid retro-cue condition. There was a significant main effect of cue ($F_{1, 24, 23.67} = 5.99$, $p = .017$; $\eta_p^2 = .24$), but no significant RCE as there was no difference between valid and neutral conditions ($p = .305$). The effect was driven by borderline differences between the invalid ($M = 28.70$ (2.52)) and valid ($M = 21.20$ (2.24), $p = .056$) and invalid and neutral ($M = 23.70$ (2.03), $p = .065$) conditions. The main effect of 2nd delay duration was significant ($F_{2, 38} = 19.50$, $p < .001$; $\eta_p^2 = .50$) with increased error evident between 3000 ms ($M = 23.83$ (2.25)) and 10000 ms ($M = 28.02$ (1.78), $p = .005$) delays and between 800 ms ($M = 21.75$ (1.86)) and 10000 ms delays ($p < .$

001). The interaction of retro-cue and 2nd delay duration was not reliable ($F_{4, 76} = 1.18$, $p = .323$; $\eta_p^2 = .05$); see Figure 3 (right panel).

Experiment 2a alone identified a significant RCE in a recall VWM paradigm. Thus, the presence of invalid retro-cues significantly reduced the RCE. Not surprisingly, recall fidelity dropped over longer delays and there was no evidence that items were preserved from decay. The implications of these findings are discussed below.

General Discussion

Here, we tested the possibility that including invalid retro-cue trials modulated the magnitude of the RCE and found that it did, under certain conditions. Notably, although we found a robust RCE using recognition probes with or without the invalid trials, this pattern was not evident when probing VWM with recall. The recall data from Experiment 2a/b showed the RCE did not persist when invalid trials were included. Thus, we failed to replicate the findings that the retro-cue serves to protect the cued item from VWM decay (Pertzov et al., 2013; Hollingworth & Hwang, 2013). These data challenge our goal of bridging findings from recognition and recall paradigms because the coarser recognition measure demonstrated a statistically reliable RCE, whereas the finer-grained recall measure revealed an RCE only when the retro-cues were always valid. We were able to evaluate the decay of cued and uncued items over an extended time frame using long 2nd delay durations.

Theoretical Implications

The question remains as to what mechanism subserves the retro-cue effect in VWM. Two primary accounts of the RCE have received the most attention: protection and prioritization (Matsukura et al., 2007). As noted, protection states that the retro-cue focuses internal attention on the cued item preventing interference from competing representations in VWM. Prioritization proposes that the retro-cued item is the first VWM representation compared to the probe item at retrieval (Matsukura et al., 2007). A similar proposal suggests that the retro-cue optimizes the search through items in VWM (reviewed in: Lepsien & Nobre, 2006). The strongest support for a protection account was apparent in Experiment 1a/b in which accuracy in neutral trials showed steady, significant decline and valid trials showed no loss of VWM accuracy over time even with the inclusion of the invalid retro-cues. This suggested that the valid retro-cues prevented the cued item from experiencing decay. However, the remaining data sets did not support this interpretation, as decay functions across all trial types were similar, contrary to previous results (Pertzov et al., 2013). The prioritization account predicts that performance on all trials would drop steadily with increased delays, a pattern we observed in Experiment 2a/b. One possibility is to interpret these data using a hybridized unifying account (Pertzov et al., 2013). Accordingly, when the retro-cues were valid or neutral, protection could dominate, as there was no cost to focusing all resources on the cued item and protecting it from decay. However, in the presence of invalid retro-cues on a demanding probe like recall, protection would be detrimental and a prioritization approach was adopted. Importantly, going forward it will be important for further research to include invalid retro-cue trials because only then will a full accounting of the RCE be possible.

Concerns and Limitations

We discussed several concerns and limitations for this study below. These concerns are limited to our stimuli and manipulation of the 2nd delay durations. We used color disks for Experiment 1a/b, and oriented bars for Experiment 2a/b. This difference raises the concern that different stimuli might result in differences that are not resulted from our manipulations. We do not think that this is a serious concern because a pilot study using oriented bar stimuli revealed a significant RCE with and without invalid retro-cues across 2nd delay durations up to 800 ms (See Footnote 1). Also, others have found significant RCE using a similar recall paradigm and testing bar, color and shape stimuli (Pertzov et al., 2013). Thus, we believe that the present experiments serve as a bridge between recall and recognition paradigms even though the stimuli differ.

Another concern is that different 2nd delay durations were used between experiments. We selected a single 2nd delay duration from Experiment 1a/b (800 ms) to include in Experiment 2a/b. We felt comfortable doing so because our previous work showed no significant differences in the RCE for 2nd delay durations from 300–700 ms (Tanoue & Berryhill, 2012) and in Experiment 1a/b there were no significant differences between the shorter 2nd delay durations (100, 800, 2400 ms). In contrast, we elected to shorten the longest 2nd delay duration from Experiment 1a/b (24000 ms) because trials were very long, participants found them difficult and the data confirmed that their recognition performance was significantly less accurate. Experiment 2a/b required a more challenging recall response. As such, we elected to use a 10000 ms 2nd delay duration as our longest delay instead. The general robustness of the RCE provides some flexibility in timing, but we certainly acknowledge that a full parallel structure between Experiments 1 and 2 would be preferable.

On a related note, the retro-cue literature typically uses short 2nd delay durations. By probing the RCE across longer 2nd delay durations we expose ourselves to concerns regarding the contributions of long-term memory. Neuropsychological data indicate that there is a maximum of ~40–45 seconds for short-term memory to operate (Damasio, Graff-Radford, Eslinger, Damasio, & Kassell, 1985; Tranel & Eslinger, 2000; Sidman, Stoddard, & Mohr, 1968). However, it is difficult to ever disentangle long-term memory from interacting with shorter forms of memory (e.g. Baddeley, 2012) and at the longer 2nd delay durations we used we may have measured from ‘long-term working memory’. This term refers to the involvement of long-term memory activated by cues in WM (Ericsson & Kintsch, 1995). For our purposes, we were interested in observing decay functions over the temporal window of WM. We would argue that WM was certainly engaged, but very possibly, at the longer 2nd delay durations long-term memory was playing some role as well.

In spite of the aforementioned concerns and criticisms, we conclude that the present data extended recent findings testing VWM using recall retro-cue paradigms. They also provide additional support for a hybridized theoretical account of the RCE that is in greater accord with the prioritization account.

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Experiment 1a/b

Experiment 2a/b

Figure 1. Trial Sequence

After a fixation cross, the four-item stimulus array appeared and was followed by an initial delay period. Next, either a neutral or arrow retro-cue flashed and was followed by a 2nd delay period. After the 2nd delay period, a probe item appeared and participants judged whether it matched what had been shown in the stimulus array (Experiment 1a/b, top panel) or a bar appeared again on one of the 4 locations with random angle and participants are asked to make a response by using left or right arrow keys on the keyboard (Experiment 2a/b, bottom panel).

Figure 2. Experiment 1a/b VWM accuracy results

In all figures, the white boxes show neutral retro-cue performance, black boxes show the valid arrow retro-cue performance, and grey boxes show the invalid retro-cue performance. Error bars reflect the standard error of the mean.

Figure 3. Experiment 2a/b VWM error degree results

In all figures, the white boxes show neutral retro-cue performance, black boxes show the valid arrow retro-cue performance, and grey boxes show the invalid retro-cue performance. Error bars reflect the standard error of the mean.