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The Passive State: A Protective Mechanism for Information in Working Memory Tasks

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Abstract

Memory representations can be stored in a passive state in a visual working memory (VWM) task. However, it remains unclear whether the representations stored in the passive state are prone to interference and decay. To explore this issue, we asked participants to successively remember two sets of memory items (M1 and M2) in three test manners: a *combined test* (both M1 and M2 are probed simultaneously), a *backward test* (probe M2 first and M1 second), or a *forward test* (probe M1 first and M2 second). We found that the contralateral delay activity (CDA) amplitude after the onset of M2 only tracked M2 independently of M1 in the two *separate tests* (Experiments 1–3), and the accuracy of M1 was well above chance. These results implied that the M1 representations had been transferred from the online state into the passive state after the onset of M2. Furthermore, the accuracy of M1 (two representations were transferred from the online state into the passive state and retrieved later) in the *backward test* was worse than M2 (two representations in the online state throughout) in the *backward test* (Experiments 1–2), but was comparable to M1 (two representations were transferred from the online state into the passive state and retrieved first) in the *forward test* (Experiment 2). These results demonstrated that the memory representations were impaired during state switching. Importantly, once the representations had been stored in the passive state, they were robust with little memory loss during latent retention.

Keywords**:** visual working memory; online state; passive state; contralateral delay activity; serial presentation

Introduction

Short-term maintenance of information is a critical component of cognitive processing. Human beings can temporarily maintain and manipulate information for advanced cognitive processing via the visual working memory (VWM) system (Baddeley, 2012; Luck & Vogel, 2013). Previous research has established that VWM interacts with many essential cognitive processes, including attention and long-term memory (LTM) (Cowan, 1995). Understanding the mechanisms that support short-term maintenance is an essential aim of cognitive psychology.

Traditionally, researchers have asserted that information can be maintained in VWM for a short time via persistent neural activity (Curtis & D'Esposito, 2003; Goldman-Rakic, 1995; Sreenivasan et al., 2014). That is, individuals can temporarily hold VWM representations in an active or online state (herein, we refer to this state as the *online state*). Recently, however, cognitive and neural evidence has suggested that the representations of short-term maintenance could also be stored in a passive state without any accompanying persistent neural activity (LaRocque et al., 2013; Lewis-Peacock et al., 2012; Rose et al., 2016). For the passive state, short-term maintenance of information might be accomplished via weight-based changes in synaptic connectivity; thus, standard recording methods would not allow for direct observation of maintenance in the passive state (Stokes, 2015; Wolff et al., 2017). Some researchers have also proposed that the LTM system assists in the storage of representations in the passive state (Foster et al., in press; Rose, 2020).

Although research shows that representations can be stored in the passive state, it remains unclear whether VWM representations stored in the passive state are prone to interference and decay . For example, Cowan (1995, 2005) proposed that representations stored in the passive state (also called the activated part of LTM) are likely to be forgotten due to decay over time and interference (e.g., perceptual interference, interference from other cognitive processes, and competition among memory representations). However, some researchers have proposed that memory representations in the passive state could be protected from decay and shielded from interaction with the current task to minimize interference from the currently prioritized cognition or activity-based representations (de Vries et al., 2020; Muhle-Karbe et al., 2021; Stokes, 2015; Stokes et al., 2020). Thus, the passive state could be regarded as being protective, preventing information loss of the VWM representations.

To investigate the storage mechanism of the passive state, researchers have tried to manipulate the storage states of VWM representations. For instance, researchers have adopted a double retro-cue paradigm to guide participants to store the memory representations in either the online state or the passive state (LaRocque et al., 2013; Lewis-Peacock et al., 2012; Rose et al., 2016). In these double retro-cue studies, two retro-cues appear sequentially and point to the to-be-tested items after the memory array disappears. When the first retro-cue appears, participants store the cued representation in the online state and the uncued representations in the passive state. After the first cued item has been detected, the second retro-cue appears to indicate the representation which was initially stored in the online state (repeat retro-cue) or the passive state (switch retro-cue). These studies showed that VWM performance under the switch retro-cue condition was worse than under the repeat retro-cue condition. The inferior performance under the switch retro-cue condition implies that representations stored in the passive state are impaired compared to those stored in the online state. Actually, the inferior performance under the switch retro-cue condition might be due to the comparison between the representations stored in the passive state and the online state. Because the representations in the passive state suffered state-switching from the online state into the passive state for transient maintenance and from the passive state to the online state again for the probe, the cost of VWM performance under the switch retro-cue condition compared to the repeat retro-cue condition may be derived from the transferring process between different states instead of impairment in the passive state. However, previous studies did not directly manipulate the interference or delay conditions to compare the representations in the passive state (LaRocque et al., 2013; Lewis-Peacock et al., 2012; Rose et al., 2016). One possible way to investigate the effect of the passive state on VWM representations is to directly compare the memory performance of the items in the passive state over different retention periods and to manipulate the factors of interference (e.g., perceptual interference and judging decision interference). Research on the single retro-cue paradigm has manipulated the stimulus-onset asynchrony between the retro-cue and the probe array (Astle et al., 2012; Gressmann & Janczyk, 2016; Pertzov et al., 2013; van Moorselaar et al., 2015); however, the retro-cue validity in these studies using the single retro-cue paradigm was fairly high (usually > 65%). There was a much lower probability of retrieving the uncued items, and the participants tended to forget the uncued representations rather than maintain them in the passive state. Therefore, these studies did not provide direct insight into whether the information in the passive state is prone to interference and decay. The current study addresses this issue.

In the current study, participants were required to perform a new modified sequential encoding version of the change detection paradigm during an Electrophysiology (EEG) recording, in which two memory arrays were presented in sequence (M1 and M2). The key manipulation of the experiment was using a setup of probe arrays. Participants were encouraged to store the memory arrays in different ways: (1) a *combined test*—change detection was required for test stimuli when both arrays were combined; (2) a *forward test*—change detection was required first for the test stimuli for M1, then for the test stimuli for M2; and (3) a *backward test*—change detection was required first for the test stimuli for M2, then for the test stimuli for M1. M1 and M2 were tested separately in the *forward test* and the *backward test*; thus, the two tests fell into the same general category: the *separate test*.

We expected that for the task requiring sequential retrieval of the two arrays (the *separate test*), participants would first retain M1 in the online state, then put it into the passive state when M2 appeared. To identify whether the memory state indeed changed, we recorded the contralateral delay activity (CDA), a widely used marker in event-related potential. CDA tracks the number of visual representations stored in the online state during the maintenance phase. Its amplitude increases with the number of memory representations, approaching an asymptote once approximately 3–4 representations are stored, reflecting the limit of VWM capacity (Luria et al., 2016; Vogel & Machizawa, 2004; Vogel et al., 2005).

The aim of Experiment 1 was to examine whether the M1 representations in the *backward test* were stored in the passive state. By using a blocked design, participants were required to perform a VWM task in the *backward test* and the *combined test*. In Experiment 2, participants performed a VWM task in the *backward test* and the *forward test*. The same memory load (two items) in M1 and M2 enabled us to directly compare the memory performance of representations stored in the different states. By comparing the memory performance of the items in M1 between the *forward test* and the *backward test*, we could assess whether the representations stored in the passive state were prone to interference and decay. In Experiment 3, we varied the load of the two memory arrays to investigate whether the CDA component following the onset of M2 only tracked the M2 representations independently of M1 in the *forward test*.

Experiment 1

We examined whether the separate retrieval of the two memory arrays due to our experimental design would encourage participants to store items of M1 in the passive state. To this end, we asked participants to perform the *backward test*, and we compared their performances to that of the *combined test*. The encoding process sought to bind the items to their temporal and spatial contexts (time or serial position), allowing item retrieval by reactivating the context (i.e., Oberauer & Lin, 2017). In the *backward test*, M1 and M2 were retrieved separately. If the memory representations of both M1 and M2 were maintained in the online state, the temporal context (time and position) of the two arrays would be mixed together in the online state. When participants retrieved the M2 representations, they would have to distinguish the temporal context from M1 first. Thus, it might become more difficult if they combined the temporal context of M1 and M2 in the online state and then separated them. Moreover, M1 interference would increase due to M2 perceptual input if both memory arrays were stored in the online state (Bettencourt & Xu, 2016; Olivers et al., 2011; Postle, 2006). Therefore, we expected the participants to maintain M1 in the online state before transferring the representations into the passive state when M2 appeared. We encouraged participants to apply this storage strategy in our experiment, specifically asking them to remember the two memory arrays with two separate mental images rather than an integrated visual array of the two memory arrays.

In the *backward test*, if the VWM representations of M1 were transferred into the passive state, we expected that the memory accuracy for M1 would still show a level of performance well above the chance (50%) level. In the meantime, the CDA amplitude after the onset of M2 would not include any residual activity for M1. Consequently, given that both M1 and M2 contained two stimulus items, the CDA should be limited to the same asymptote as that for M1 after the onset of M2.

We must also factor in the possibility that CDA amplitude might decay as time elapses. If we find a low level of CDA after the onset of M2 in the *backward test*, this condition might also result from time elapsing, not from M1 dropping out of the online state. In addition, if the participants' VWM capacity was limited in two items, in the *backward test*, we would not observe a higher CDA amplitude of M2 than M1. We thus used the *combined test* as our baseline, requiring participants to combine M1 and M2 for storage in the online state (four items) for the final comparison. In the *combined test*, we expected to observe a higher level of CDA amplitude after the onset of M2, indicating the representations of both M1 and M2 had been stored in the online state.

Method

Sample Size

We calculated the sample size by using G-power (version: 3.1.9.4). In our previous study (Hao et al., 2018), the effect size (based on Cohen's *d*) was 0.64. We could assume that our effect size would be 0.64 based on Cohen's *d* in the current study, with a power of 0.8 and an α level of 0.05. Therefore, our study included a sample size of 22 participants.

Participants

Twenty-seven participants were initially recruited from a population of undergraduate and graduate students. Participants received remuneration of CNY 50 for their participation. All had normal or corrected-to-normal vision. No participants had completed memory experiments before the current study to avoid a particular mindset of memory. Five participants were excluded from data analysis due to excessive EEG artifacts. The remaining 22 participants (13 females, 9 males; age range: 18−28 years, *M* = 22.455, *SD* = 2.558) were used for the final data analysis. The study was approved by the Human Research Institutional Review Board at Liaoning Normal University (approval number: LNNUNZX20180710). All participants provided informed written consent prior to participating in the study.

Stimuli

Memory items (0.65° × 0.65°) were randomly selected from seven easily distinguishable colored squares. The RGB values of these colors were red (255, 0, 0); orange (255, 125, 0); yellow (255, 255, 0); green (0, 255, 0); blue (0, 0, 255); indigo (0, 255, 255); and violet (255, 0, 255). All memory items were randomly presented within two imaginary 4° × 7.3° rectangular regions symmetrically positioned 3° to the left and right of a blank central fixation cross (0.2° × 0.2°) on a gray screen. The positions of the memory items between M1 and M2 did not overlap, and the center distance of any two memory items was greater than 2°.

Procedure

Figure 1 shows a schematic illustration of a sample trial. Participants were seated in front of the screen at a distance of 70 cm. Each trial began with a display of the central fixation cross for 1 500 ms. Then, an arrow cue (200 ms) asked the participants to memorize the stimuli on the left or right field of the fixation cross. After a random interval (100−300 ms), the first memory array (M1) was presented for 200 ms, followed by a retention interval of 800 ms. Then, the second memory array (M2) was presented for 200 ms, also followed by a retention interval of 800 ms. The probe array was then be presented after the second retention interval. There were two kinds of detection conditions.

In the *backward test*, participants first detected M2 (probe 2) and then detected M1 (probe 1). When probe 2 appeared, if the memory items in the cued visual field of M2 were identical to probe 2, the participants should choose the “same” response (pressing the *F* key); otherwise, they should select the “different” response (pressing the *J* key). Following a delay of 800 ms, probe 1 appeared. Similarly, if the memory items in the cued visual field of M1 were identical to probe 1, participants were to choose the “same” response (pressing the *F* key); otherwise, they should select the “different” response (pressing the *J* key). In the *combined test*, the participants had to mentally combine both the M1 and M2 items and compare them with the test display in the cued visual field (combined probe), selecting the “same” or “different” response. The proportion of “same” and “different” responses was 50% in each condition. In addition, the “different” item in the probe array was a “new” item that was never presented in the memory field of the two memory arrays. The probe arrays (probe 1, probe 2, or the combined probe) disappeared following the response.

Participants received a practice block of 16 trials to understand the experimental procedure before starting either the *backward test* (four blocks, each consisting of 64 trials) or the *combined test* (four blocks, each consisting of 64 trials) to finish the formal experiment. Half of the participants experienced sequence 1. They practiced the *backward test* and then completed the formal *backward test*; they then practiced the *combined test* before taking the formal *combined test*. The other half of the participants finished the experiment by experiencing sequence 2. They practiced the *combined test* and then completed the formal *combined test*. They then practiced the *backward test* before taking the formal *backward test*. Their accuracy had to be at least 75% in the practice block before participating in the formal experiment (the trial was correct only when both of the probes were correct in the *backward test*). Therefore, participants knew what kind of probe condition they were to perform before the formal experiment. Participants were encouraged to adopt different memory techniques according to the two test manners. In the *backward test*, participants were encouraged to remember the two memory arrays using two separate representations rather than an integrated visual array combining the two memory arrays; however, this technique was not emphasized in the *combined test*. In addition, we strongly emphasized accuracy over response speed in the instructions. On average, it took 80 minutes to finish the entire experiment.

INSERT FIGURE 1 ABOUT HERE

Electrophysiology (EEG) Recording and Analyses

The EEG signals were recorded using a 64-channel amplifier (ANT Neuro EEGO) mounted in a cap using a 10/20 montage, including Fp1, Fp2, Fpz, AF3, AF4, GND, AF7, AF8, F1, F2, F3, F4, F5, F6, F7, F8, Fz, FT7, FT8, FC1, FC2, FC3, FC4, FC5, FC6, FCz, T7, T8, C1, C2, C3, C4, C5, C6, Cz, TP7, TP8, CP1, CP2, CP3, CP4, CP5, CP6, CPz, P1, P2, P3, P4, P5, P6, P7, P8, Pz, PO3, PO4, PO7, PO8, POz, O1, O2, and two mastoid electrodes. In these electrodes, CPz served as the online reference, and GND served as the ground electrode. The O2 was not recorded because it was broken. The horizontal EOG was recorded from electrodes placed 1 cm to the left and right of the external canthi; the vertical EOG was recorded from the electrodes above and below the left eye. All electrode impedances were kept below 10 KΩ. The data were collected at a sampling rate of 500 Hz.

EEGLAB Toolbox (Delorme & Makeig, 2004) and MATLAB (Makeig et al., 2004) were used to process the offline signal. The offline EEG signals used low-pass filtering at 40 Hz. All channels were referenced to the average of the two mastoid electrodes (left and right mastoids). The continuous signal was segmented from 200 ms before to 2 000 ms after the onset of the first memory array. We used the 200 ms prior to the first memory array onset to perform baseline correction. Bad channels were replaced by interpolation and eliminated by artifact detection and rejection (Kuo et al., 2014; Sander et al., 2011). The EOG artifacts were first corrected by an independent component analysis algorithm (Jung et al., 2001; Makeig et al., 2004). Finally, we also excluded trials containing artifacts with amplitudes exceeding ± 100 μV for the analyzed electrodes (PO7/PO8).

The contralateral delay activity (CDA) was evident in electrode PO7/PO8 (Luria et al., 2010; Luria et al., 2016; Luria & Vogel, 2014; Vogel & Machizawa, 2004). The CDA was calculated by subtracting the ipsilateral side from the contralateral side with the memory items (Williams & Woodman, 2012). The CDA mean amplitude was calculated using a window of 300−900 ms after the onset of the learning stimulus. For visualization purposes, we adopted a low-pass filter (“eegfilt.m”) (Delorme & Makeig, 2004) of 17 Hz to smooth the CDA waveforms; this practice aligned with previous studies (Adam et al., 2018; Gao et al., 2009; Gao et al., 2011;

Ye et al., 2014) and did not cause a loss of relevant information. It should be noted that the results were calculated using data from a 40-Hz low-pass filter.

Data Analysis

Bayes factor analysis could provide some evidence for supporting the null results (Rouder et al., 2009). The results of the Bayes factor analyses were also reported. The Bayes factor (BF_{01}) can provide an odds ratio for the null/alternative hypotheses ($BF_{01} > 1$ favors the null hypothesis and $BF_{01} < 1$ favors the alternative hypothesis). For example, a BF_{01} of 2 indicates that the null hypothesis is two times more likely than the alternative hypothesis. For the reaction time, we followed three steps to eliminate bad trials before analyzing the result. Firstly, we removed the trials with incorrect responses from further analysis. We then rejected trials in which the reaction time was faster than 400 ms and slower than 4000 ms. Finally, we removed trials that diverged by more than 2.5 SD under any condition.

Results

Behavioral Results

Figure 2A shows the memory accuracy. We employed a one-sample *t*-test and determined that the accuracy of the memory arrays under each condition was greater than chance (50%) (all with a $p < .001$). We then conducted a 2 (test manner: *backward test, combined test*)×2 (memory array: M1, M2) repeated measures ANOVA to analyze memory accuracy (Figure 2A). The main effect of test manner was significant ($F(1,21) = 36.456$, $p < .001$, $\eta_p^2 = 0.635$), as was the main effect of memory array ($F(1, 21) = 18.889$, $p < .001$, $\eta_p^2 = 0.474$). Additionally, there was a significant interaction between test manner and memory array ($F(1,21) = 13.071$, $p = .002$, $\eta_p^2 = 0.384$).

Simple effect analysis and the Bayesian paired samples *t*-test revealed that the accuracy of M2 was higher than M1 in the *backward test* ($F(1,21) = 26.27$, $p < .001$, $\eta_p^2 = 0.556$, Cohen's $d = 1.093$, $BF_{01} = 0.002$). However, the difference in accuracy between M1 and M2 was not significant in the *combined test* ($F(1,21) = 1.17$, $p = .292$, $\eta_p^2 = 0.053$, Cohen's $d = 0.230$, $BF_{01} = 2.673$). For M1, the difference in accuracy between the *backward test* and the *combined test* was not significant ($F(1,21) = 2.49$, $p = .129$, $\eta_p^2 = 0.106$, Cohen's $d = 0.337$, $BF_{01} = 1.531$). For M2, however, the participants' accuracy in the *backward test* was significantly higher than in the *combined test* ($F(1,21) = 40.94$, $p < .001$, $\eta_p^2 = 0.661$, Cohen's $d = 1.315$, $BF_{01} = 1.255\times10^{-4}$).

Figure 2B shows the reaction time results. To analyze the reaction time results, we conducted a 2 (test manner: *backward test, combined test*)×2 (memory array: M1, M2) repeated measures ANOVA. The main effect of test manner was significant ($F(1,21) = 32.420$, $p < .001$, $\eta_p^2 = 0.607$), as was the main effect of memory array ($F(1,21) = 68.962$, $p < .001$, $\eta_p^2 = 0.767$). There was also a significant interaction between test manner and memory array ($F(1,21) = 25.792$, $p < .001$, $\eta_p^2 = 0.551$).

Simple effect analysis and the Bayesian paired samples *t*-test revealed that the reaction time of M2 was significantly lower than M1 in the *backward test* ($F(1,21) = 51.84$, $p < .001$, $\eta_p^2 = 0.712$, Cohen's $d = 1.534$, $BF_{01} = 2.550\times10^{-5}$). The reaction time of M2 significantly lower than M1 in the *combined test* ($F(1,21) = 8.87$, $p = .007$, $\eta_p^2 = 0.297$, Cohen's $d = 0.638$, $BF_{01} = 0.152$). For M1, the reaction time in the *backward test* was significantly lower than in the *combined test* ($F(1,21) = 16.86$, $p = .001$, $\eta_p^2 = 0.445$, Cohen's $d = 0.875$, $BF_{01} = 0.015$). For M2, the reaction time in the *backward test* was also lower than in the *combined test* ($F(1,21) = 47.69$, $p < .001$, $\eta_p^2 = 0.694$, Cohen's $d = 1.472$, $BF_{01} = 4.538\times10^{-5}$).

INSERT FIGURE 2 ABOUT HERE

Electrophysiological Results

We first focused on the CDA in the two phases soon after the disappearance of the two stimulus arrays: the time windows of delay 1: 300−900 ms and delay 2: 1300−1900 ms (see Figure 2D for the waveforms). We conducted a 2 (test manner: *backward test, combined test*)×2 (delay: delay1, delay2) repeated measures ANOVA to analyze the average CDA amplitude (Figure 2C). The main effect of test manner was significant (F = 15.062, p = .001, η_p^2 = 0.418), as was the main effect of delay ($F(1, 21)$ = 13.378, p = .001, η_p^2 = 0.389). Further, there was a significant interaction between test manner and delay ($F(1,21)$ = 10.329, p = .004, η_p^2 = 0.330).

Simple effect analysis and the Bayesian paired samples *t*-test revealed that the difference in CDA amplitude between delay 2 and delay 1 was not significant in the *backward test* ($F(1,21)$ = 0.49, p = .494, η_p^2 = 0.023, Cohen's d = 0.148, BF_{01} = 3.604). However, the CDA amplitude of delay 2 was greater than delay 1 in the *combined test* ($F(1,21)$ = 27.06, p < .001, η_p^2 = 0.563, Cohen's d = 1.109, BF_{01} = 0.002). In addition, for delay 1, the CDA amplitude in the *combined test* was greater than in the *backward test* ($F(1,21)$ = 7.46, p = .013, η_p^2 = 0.262, Cohen's d = 0.582, BF_{01} = 0.242). For delay 2, the CDA amplitude in the *combined test* was also greater than the *backward test* ($F(1,21)$ = 15.01, p = .001, η_p^2 = 0.417, Cohen's d = 0.826, BF_{01} = 0.025).

We then focused on delay 1 during the earlier versus later phase following stimulus presentation: early-CDA (300−600 ms) and late-CDA (600−900 ms) segments. We found that there was no significant difference in early-CDA between the *combined test* and the *backward* *test* ($t(21) = 1.580$, $p = .129$, Cohen's $d = 0.337$, $BF_{01} = 1.528$). However, the *combined test* had a significantly higher late-CDA than the *backward test* ($t(21) = 2.908$, $p = .008$, Cohen's $d = 0.619$, $BF_{01} = 0.174$).

We also analyzed the effect of the ordering of the conditions (half of the participants did the *backward test* first and then the *combined test*; the other half did the *combined test* first and then the *backward test*). We used mixed ANOVA to measure the accuracy, reaction time, and CDA. We used group (*backward-combined*, *combined-backward*) as the between-subject factor. For the accuracy and the reaction time, we utilized test manner (*backward test, combined test*) and memory array (M1, M2) as the within-subject factors. For the CDA, we used test manner (*backward test, combined test*) and delay (delay 1: 300−900 ms; delay 2: 1300−1900 ms) as the within-subject factors. In terms of accuracy, there were no significant main effects of group ($F(1,20) = 0.533$, $p = .474$, $\eta_p^2 = 0.026$) and no significant interaction between group, memory array and test manner ($F(1,20) = 0.304$, $p = .588$, $\eta_p^2 = 0.015$). For the reaction time, there were no significant main effects of group ($F(1,20) = 0.007$, $p = .933$, $\eta_p^2 = 0.000$) and no significant interaction between group, memory array, and test manner ($F(1,20) = 1.410$, $p = .249$, $\eta_p^2 = 0.066$). For the CDA, there were no significant main effects of group ($F(1,20) = 0.030$, $p = .865$, $\eta_p^2 = 0.001$) and no significant interaction between group, delay, and test manner ($F(1,20) = 1.078$, $p = .312$, $\eta_p^2 = 0.051$).

Discussion

The results of Experiment 1 show that, in the *backward test*, M1 accuracy was much higher than the level of chance alone. Meanwhile, the CDA amplitude was comparable following M2 and M1 in the *backward test*, while the CDA amplitude following M2 was significantly greater than that following M1 in the *combined test*. These results suggest that, in the *combined test*, both M1 and M2 were stored together in the online state (four items). Notably, although the participants have enough storage space to store both the M1 and M2 representations in the online state (as shown by the results in the *combined test*), they still transferred the M1 representations to the passive state in the *backward test*. In addition, there was a significant difference in CDA amplitude between the *backward test* and the *combined test* during the late period (600−900 ms) of M1 and the entire period of M2. This finding might suggest that the information retention declined in the online state to some extent. Of course, it was also possible that in some proportion of trials (not all trials), participants transferred all of the M1 representations into the passive state before the onset of M2.

The *combined test* may involve a more complex process and added allocation of spatial attention compared to the *backward test*. Thus, the CDA may reflect current attentional processing demands. However, the current locus of spatial attention is actually quantified by the alpha power (Hakim, et al. 2019; Wang et al., 2019). A recent study supports the idea that the CDA tracks the active maintenance of items (Feldmann-Wustefeld et al., 2018). Indeed, the CDA could track the involvement of ongoing VWM processing (Luria et al., 2016), but this active manipulation only occurred in the online state. Therefore, we considered CDA as a useful biomarker for tracking the number of items stored in the online state.

The accuracy of M2 was lower in the *combined test* than in the *backward test*. There was no difference in accuracy between M1 and M2 in the *combined test*. These results were consistent with the general notion that accuracy decreases as the stimulus set size increases in the online state (Ikkai et al., 2010). In addition, the reaction time was longer in the *combined test* than the *backward test* for M2. It is possible that M1 and M2 interfered with each other in the online state under the *combined test* (Postle, 2006; Bettencourt & Xu, 2016), resulting in lower accuracy and a longer reaction time in both memory arrays. In the *backward test*, M1 was stored in the passive state, so the M1 representations could not interfere with the M2 representations that were stored in the online state. Thus, there was higher accuracy and a shorter reaction time for M2 in the *backward test* than the *combined test*. In addition, in the *backward test*, the accuracy of M1 was significantly lower than that of M2. These results could suggest an impairment for the M1 representations in the *backward test*.

Another interesting result was that, for M1, there was no significant difference in accuracy between the *backward test* and the *combined test*. Compared to the accuracy for M2 in the *backward test*, the storage of M1 was impaired in both the *backward test* and the *combined test*. There were at least three different factors for the similar accuracy of M1 in the *backward test* and the *combined test*. One factor was the storage state: M1 was first stored in the online state and then transferred to the passive state in the *backward test*; however, M1 was stored in the online state at all times in the *combined test*, suffering interference between the two memory arrays in the online state (Bettencourt & Xu, 2016; Postle, 2006). The second factor was the retention time: M1 was retained longer in the *backward test* than in the *combined test*. The third factor was the number of items tested at a given time. In the *combined test* (but not in the *backward test*), participants had to integrate the spatial and color information of two arrays. Collectively, these factors could have contributed to the final performance, which happened to show comparable accuracy across the two conditions.

Experiment 2

We confirmed that the participants stored the M1 representations in the passive state in the *backward test* in Experiment 1. An impairment for the M1 representations was found in the *backward test*. In Experiment 2, we investigated the mechanisms underlying the impairment. In the *backward test*, the M1 VWM representations were transferred from the online state to the passive state. The information was then retrieved from the passive state back to the online state. The M2 representation was not subject to this transferring process because M2 detection was performed right after retention. Therefore, the first possible reason for the decline in memory representation is the transferring process for representation between states. In addition to the process of switching between memory states, the impairment might also occur after the representation has been transferred to the passive state. In the *backward test*, the probe for M1 was performed later than it was for M2; thus, the difference in accuracy between M1 and M2 might result from the information in the passive state simply decaying over time. Alternatively, the probe for M2 (appearance of the M2 probe as well as the decision process for the M2 change detection) might also cause extra interference for the representations stored in the passive state. Therefore, it was unclear whether the loss of the M1 representations occurred during the switching of states or the maintenance in the passive state (due to decay over time or interference from the M2 probe).

In Experiment 2, we manipulated the retrieval order in the *forward test* and the *backward test*. In the *forward test,* the change detection was required for M1 and then for M2. Specifically, during the test phase, participants were first required to retrieve the M1 representations from the passive state at the onset of the M1 probe array; they then had to do the same for M2. This process represented a reversal of test order from that of the *backward test*, where they would retrieve the M1 representations *after* completing the M2 probe.

We expected that, in both tests, the M1 representations would be stored first in the online state and then in the passive state when M2 appeared. Thus, there would be no significant difference in the CDA signal in the time segments following the M1 and M2 presentations (both containing two items). Importantly, there would be no significant CDA difference between the two separate tests in each of the two time segments mentioned above. In addition, in both tests following the presentation of M1, the CDA waveforms would increase and reach a high level, indicating the maintenance of the representation in the online state; they then would gradually decrease, showing a transferring process of representations to a passive state. Following the M2 presentation, the CDA waveform would again increase to a high level to record the maintenance of the M2 representation (in the online state).

The reasons for the performance impairment of the M1 representations (relative to M2) in the *backward test* could be examined by measuring accuracy. If the performance cost occurred only due to the switching of states, we would expect to find no difference in M1 accuracy between the *backward test* and the *forward test* as the same switching process occurred in both tests. Conversely, if, following switching, storage in the passive state was easily impaired due to decay or interference from the M2 probe, we would expect higher M1 accuracy in the *forward test* compared to the *backward test*. This expectation rests on the fact that M1 was tested firstly and without interference from the M2 probe in the *forward test* compared to the *backward test*. Therefore, it should exhibit a smaller effect for delay and interference. Of course, there was a long retention time and interference in the *backward test* for M1 storage in the passive state, but Experiment 2 did not differentiate between these two factors.

Method

Participants

In Experiment 2, we recruited 24 new participants to finish the task. There were 22 participants (15 females, 7 males; age range: 18−25 years, $M = 21.046$, $SD = 1.864$) used in the final data analysis; two participants were eliminated because of low accuracy (< 50%) or excessive EEG artifacts.

Procedure

Aside from the test manners, Experiment 2 was identical to Experiment 1. We replaced the *combined test* from Experiment 1 with the *separate test*, described as the *forward test*, in which the participants remembered the colored squares of the first memory array, and the second memory array in sequence. They first detected whether there were any changes from M1's colored squares before doing the same for M2. Accordingly, there were two kinds of *separate tests*: a *forward test* and a *backward test*.

Results

Behavioral Results

We first analyzed accuracy under the different conditions (Figure 3A). We employed a one-sample *t*-test to conclude that the memory arrays' accuracies in the different tests were higher than chance alone (50%) (all $p < .001$). Then, we conducted a 2 (test manner: *backward test, combined test*)×2 (memory array: M1, M2) repeated measures ANOVA to analyze the memory accuracy (Figure 3A). The main effect of test manner was significant (F (1,21) = 25.778,

$p < .001$, $\eta_p^2 = 0.551$), but the main effect of memory array was not significant ($F(1, 21) = 0.566$, $p = .460$, $\eta_p^2 = 0.026$). The interaction between test manner and memory array was significant ($F(1,21) = 20.423$, $p < .001$, $\eta_p^2 = 0.493$).

Simple effect analysis and the Bayesian paired samples *t*-test revealed that the accuracy of M2 was higher than M1 in the *backward test* ($F(1,21) = 22.32$, $p < .001$, $\eta_p^2 = 0.515$, Cohen's $d = 1.007$, $BF_{01} = 0.004$), but the accuracy of M2 was lower than M1 in the *forward test* ($F(1,21) = 8.69$, $p = .008$, $\eta_p^2 = 0.293$, Cohen's $d = 0.628$, $BF_{01} = 0.161$). For M1, the difference in accuracy between the *forward test* and the *backward test* was not significant ($F(1,21) = 0.27$, $p = .611$, $\eta_p^2 = 0.013$, Cohen's $d = 0.110$, $BF_{01} = 3.974$). Meanwhile, for M2, the accuracy in the *backward test* was higher than that in the *forward test* ($F(1,21) = 55.26$, $p < .001$, $\eta_p^2 = 0.725$, Cohen's $d = 1.584$, $BF_{01} = 1.624\times10^{-5}$).

Figure 3B shows the reaction time results. We conducted a 2 (test manner: *backward test, combined test*)×2 (memory array: M1, M2) repeated measures ANOVA to analyze the reaction time. The main effect of test manner was significant ($F(1,21) = 6.418$, $p = .019$, $\eta_p^2 = 0.234$), as was the main effect of memory array ($F(1,21) = 26.488$, $p < .001$, $\eta_p^2 = 0.558$). The interaction between test manner and memory array was not significant ($F(1,21) = 1.846$, $p = .189$, $\eta_p^2 = 0.081$).

INSERT FIGURE 3 ABOUT HERE

Electrophysiological Results

We conducted a 2 (test manner: *backward test, combined test*)×2 (delay: delay1, delay2) repeated measures ANOVA to analyze the CDA amplitude (Figure 3C and Figure 3D). The main effect of test manner was not significant ($F(1, 21) = 0.804$, $p = .380$, $\eta_p^2 = 0.037$), and the main effect of delay was not significant ($F(1, 21) = 0.619$, $p = .440$, $\eta_p^2 = 0.029$). To some extent, the information in M1 was removed from the online state in both the *forward test* and the *backward test*. The interaction between test manner and delay was not significant ($F(1,21) = 0.185$, $p = .672$, $\eta_p^2 = 0.009$).

We also used the Bayesian paired samples *t*-test to compare the CDA amplitude between delay 2 and delay 1 in the *backward test*. The results showed that the null hypothesis was 3.091 times more likely than the alternative hypothesis ($BF_{01} = 3.091$). In addition, the Bayesian paired samples *t*-test was used to compare the CDA amplitude between delay 2 and delay 1 in the *forward test*, with results showing that the null hypothesis was 4.219 times more likely than the alternative hypothesis ($BF_{01} = 4.219$).

We also analyzed the effect on the ordering of conditions (half of the participants did the *backward test* first and then the *forward test*; the other half did the *forward test* first, and then the *backward test*). We used a mixed ANOVA to analyze the accuracy, the reaction time, and the CDA. The group (*backward-forward*, *forward-backward*) served as the between-subject factor. For the accuracy and the reaction time, test manner (*backward test, forward test*) and memory array (M1, M2) functioned as the within-subject factors. For the CDA, test manner (*backward test, forward test*) and delay (delay 1: 300−900 ms; delay 2: 1300−1900 ms) were used as the within-subject factors. For the accuracy, there was no significant main effect of group ($F(1,20) =$

0.248, p = .624, η_p^2 = 0.012) and no significant interaction between group, memory array, and test manner (F(1,20) = 0.086, p = .773, η_p^2 = 0.004). For the reaction time, there was no significant main effect of group (F(1,20) = 2.922, p = .103, η_p^2 = 0.127) and no significant interaction between group, memory array, and test manner (F(1,20) = 0.846, p = .369, η_p^2 = 0.041). For CDA, there was no significant main effect of group (F(1,20) = 2.497, p = .130, η_p^2 = 0.111) and no significant interaction between group, delay, and test manner (F(1,20) = 3.359, p = .082, η_p^2 = 0.144).

Discussion

Regardless of the retrieval order, following the presentation of the M1 stimulus, the CDA amplitude reached a peak before gradually decreasing. Following the M2 stimulus, the CDA then reached a peak with a magnitude comparable to the peak following the M1 stimulus and subsequently maintained a high value. Moreover, M1 accuracy under both conditions was much higher than that of chance level (50%). These results indicate that M1 memory representations were transferred to the passive state in both tests.

Superficially, it seems contradictory that a previous study also used the *forward test* but did not find the same CDA pattern (Ikkai et al., 2010). We believe that this discrepancy can be explained by their short (400 ms) interval between M1 and M2 (Ikkai et al., 2010). Previous research has demonstrated that the two array representations are combined when the interstimulus interval is below 500 ms (Ikkai et al., 2010; Jiang & Kumar, 2004; Li et al., 2020) but separated if the interval is 500 ms or longer (Jiang & Kumar, 2004). In the current work, the interval between the two memory arrays was 800 ms—long enough for switching between the two states. None of the participants had completed any memory experiments prior to the current study to avoid the formation of a particular memory mindset. Participants were also encouraged to remember the two memory arrays with two separate mental images rather than an integrated visual array. Thus, it was not surprising to see a different pattern of results in our *forward test* than in Ikkai and colleagues' (2010) study. In addition, some studies from the sequential change detection paradigm found no increase in the CDA amplitude after the onset of M2 if the item locations differed between the probe and memory arrays (Feldmann-Wustefeld et al., 2018) or if the two memory arrays appeared in different fields (Berggren & Eimer, 2016). Therefore, it should not be surprising to see separate storage in the current study using the sequential change detection paradigm. Future studies can systematically investigate this issue by manipulating the factors mentioned above.

Comparable M1 accuracy was found in the two separate tests, but M1 retrieval was earlier in the *forward test* than in the *backward test*; as such, these results suggest that storage in the passive state was not significantly impaired due to memory decay over time or interference from other tasks (e.g., perceptual interference from the M2 probe for M2 or interference from decision processing). In this regard, the passive state offers a protective mechanism that prevents the loss of information about the VWM representations resulting from interference from other tasks. However, in the *backward test*, M1 accuracy (representation transferred from the active to passive state) was indeed lower than that of M2 (representation held in the active state throughout), suggesting that information storage for the VWM representations in M1 was impaired while switching between the different states.

Under both the *forward test* and *backward test*, the reaction time was shorter in M2 than it was in M1, which could result from the time difference in the switching process between states.

In the *forward test*, the M2 representations should first be transferred from the online state to the passive state before M1 retrieval into the online state for probing. The M2 transferring process would cost additional time. Therefore, the behavioral results of probe 1 indicate that it took more time (the switching process between states for both M1 and M2) to retrieve M1 representations. M2 (probe 2) could be directly retrieved from the passive state into the online state for probing (state switching process for only M2). Thus, there was a reaction time difference between the two probes. Similar to Experiment 1, in the *backward test*, M2 was directly retrieved in the online state (no state switching process); however, the M1 VWM representations were impaired during the switch between the different states. Thus, the reaction time was shorter in the probe for M2 than it was for M1 in the *backward test*.

Experiment 3

We had found that there was no significant CDA difference between M1 and M2 in the *forward test* in Experiment 2, which indicated that two items were stored in the online state during delay 2. However, this result does not necessarily confirm whether the representations from M1 were constantly kept in the passive state during delay 2. Firstly, because the M1 representations were probed firstly in the *forward test*, the items in M2 might be directly encoded into the passive state. In this case, the M1 representations would be still retained in the online state during delay 2. Secondly, M1 and M2 representations might be switched in and out of the online state alternately during delay 2, and then there might be an average of two items in the online state. Therefore, during delay 2, it was not clear whether the two items in the online state came from the M1 representations, the M2 representations, or both arrays.

In experiment 3, we varied the load of two memory arrays (one or two) based on the *forward test* to investigate whether the CDA amplitude during delay 2 only tracked the M2 representations independently of M1. If the CDA amplitude during delay 2 tracked the M1 representations, the memory load of M1 would have effect on the CDA amplitude; otherwise, the CDA amplitude during delay 2 would vary with the memory load of M2 only.

Method

Participants

In Experiment 3, we recruited 27 new participants to finish the task. There were 22 participants (15 females, 7 males; age range: 18−28 years, *M* = 20.682, *SD* = 2.398) used in the final data analysis; five participants were eliminated because of excessive EEG artifacts.

Procedure

Experiment 3 only adopted the *forward test*, but varied the number of items in the two memory arrays. Specifically, there were four conditions: condition 1-1, where the participants needed to remember one item in the first memory array and one item in the second memory array; condition 1-2, where the participants need to remember one item in the first memory array and two items in the second memory array; condition 2-1, where the participants need to remember two items in the first memory array and one item in the second memory array; and condition 2-2, where the participants need to remember two items in both memory arrays. In addition, there were 160 trials in each condition, and it took 100 minutes to finish the entire experiment on average.

Results

Behavioral Results

We first assessed accuracy under the different conditions (Figure 4A). We employed a one-sample *t*-test to conclude that the memory arrays' accuracies under the different conditions were higher than chance alone (50%) (all $p < .001$). For the accuracy and the reaction time, we conducted a 2 (M1 load: 1, 2)×2 (M2 load: 1, 2) repeated measures ANOVA on different memory arrays (M1, M2) separately.

Figure 4A shows the accuracy results. For M1, the main effect of M1 load was significant ($F(1, 21) = 62.898$, $p < .001$, $\eta_p^2 = 0.750$). The main effect of M2 load was significant ($F(1, 21) = 18.180$, $p < .001$, $\eta_p^2 = 0.464$), but the interaction between M1 load and M2 load was not significant ($F(1, 21) = 1.192$, $p = .287$, $\eta_p^2 = 0.054$). For M2, the main effect of M1 load was significant ($F(1, 21) = 148.227$, $p < .001$, $\eta_p^2 = 0.876$); the main effect of M2 load was significant ($F(1, 21) = 113.247$, $p < .001$, $\eta_p^2 = 0.844$), and the interaction between M1 load and M2 load was significant ($F(1, 21) = 13.416$, $p = .001$, $\eta_p^2 = 0.390$). Simple effect analysis and the Bayesian paired samples *t*-test revealed that the accuracy was significant lower when the load of M2 was 2 than when the load of M2 was 1 in both the conditions that the load of M1 was 1 ($F(1, 21) = 47.49$, $p < .001$, $\eta_p^2 = 0.693$, Cohen's $d = 1.469$, $BF_{01} = 4.673\times10^{-5}$) and 2 ($F(1, 21) = 124.68$, $p < .001$, $\eta_p^2 = 0.856$, Cohen's $d = 2.383$, $BF_{01} = 2.701\times10^{-8}$).

Figure 4B shows the reaction time results. For M1, the main effect of M1 load was significant ($F(1, 21) = 8.927$, $p = .007$, $\eta_p^2 = 0.298$), the main effect of M2 load was significant ($F(1, 21) = 12.658$, $p = .002$, $\eta_p^2 = 0.376$), but the interaction between M1 load and M2 load was not significant ($F(1, 21) = 2.531$, $p = .127$, $\eta_p^2 = 0.108$). For M2, the main effect of M1 load was significant ($F(1, 21) = 6.315$, $p = .020$, $\eta_p^2 = 0.231$); the main effect of M2 load was significant ($F(1, 21) = 33.905$, $p < .001$, $\eta_p^2 = 0.618$), but the interaction between M1 load and M2 load was not significant ($F(1, 21) = 3.262$, $p = .085$, $\eta_p^2 = 0.134$).

INSERT FIGURE 4 ABOUT HERE

Electrophysiological Results

For the CDA amplitude, we conducted a 2 (M1 load: 1, 2)×2 (M2 load: 1, 2) repeated measures ANOVA on different delays (delay 1: 300–900 ms, delay 2: 1300–1900 ms) separately (Figure 4C-D).

For delay 1, only the main effect of M1 load was significant ($F(1, 21) = 40.224$, $p < .001$, $\eta_p^2 = 0.657$). The main effect of M2 load was not significant ($F(1, 21) = 0.007$, $p = .936$, $\eta_p^2 = 0.000$), and the interaction between M1 load and M2 load was not significant ($F(1, 21) = 0.189$, $p = .668$, $\eta_p^2 = 0.009$).

For delay 2, only the main effect of M2 load was significant ($F(1, 21) = 34.419$, $p < .001$, $\eta_p^2 = 0.621$). The main effect of M1 load was not significant ($F(1, 21) = 0.302$, $p = .588$, $\eta_p^2 = 0.014$), and the interaction between M1 load and M2 load was not significant ($F(1, 21) = 1.519$, $p = .231$, $\eta_p^2 = 0.067$).

Discussion

In Experiment 3, the CDA amplitude during delay 2 only varied with the M2 load, suggesting that the CDA amplitude during delay 2 exclusively tracked the M2 representations in the *forward test*. Varying the M1 load caused, corresponding changes in CDA amplitude only during delay 1. In addition, the accuracy of M1 in all the test manners was much higher than the chance level (50%). These results confirmed that the M1 representations were constantly kept in the passive state during delay 2.

The behavioral results showed that the M2 load had an impact on the memory performance of M1. When more M2 representations needed to be encoded, we observed poorer accuracy and a slower reaction time to the M1 representations although the memory load of M1 was the same. The impaired performance of M1 representations might be due to the concurrent encoding of M2 representations. When M1 representations were being transferred from the online state into the passive state, the M2 appeared and participants allocated some cognitive resources to encode M2 representations, which resulted in a cost to the memory performance of M1. In such a case, more cognitive resources would be allocated to M2 when encoding more M2 representations, thus resulting in a greater cost when switching the M1 representations between states. That, however, raised the question regarding why the M1 representations had not accomplished the state switching before the encoding of M2. One possible explanation is that such a short presentation of memory stimuli (i.e., 200 ms in the current experiments) might make it difficult to demarcate the cognitive processes on the state switching of M1 representations and encoding of M2 representations, thus providing a cost to the memory performance of M1.

General Discussion

The current study explored whether VWM representations stored in the passive state are prone to interference and decay via a modified change detection paradigm. In Experiment 1-2, the

CDA peak after the onset of M1 (two items) was comparable to that after M2 (two items) in the two *separate tests* (the *backward* and *forward tests)*. Together with Experiment 3, it was confirmed that in the *separate tests,* the CDA components after M2 exclusively indexed the M2 representations. These results suggest that, in the *separate test*s, only the M2 representations were retained in the online state after the appearance of M2. This also excluded the possibility that the comparable CDA amplitudes after M1 and M2 in the *separate test* was due to the participants' VWM capacities being limited to two items. Importantly, under both the *forward test* and *backward test* (Experiment 1-3), M1 accuracy was much higher than the chance level, suggesting effective maintenance of the M1 representations. Collectively, these results confirmed that the M1 representations were transferred into the passive state after the appearance of M2 in the *separate test*.

As for the behavioral results, M1 was retrieved earlier in the *forward test* than in the *backward test* in Experiment 2, which, however, failed to produce better accuracy in M1 in the *forward test*. Thus, it could be conjectured that the memory representations stored in the passive state suffer no impairment during latent maintenance. That is, the passive state could provide robust protection for the memory representations. On the other hand, we observed lower accuracy of M1 (two representations were transferred from the online state to passive state) than M2 (two representations were held in the online state throughout) in the *backward test* in Experiment 1-2, which allowed us to postulate that there was a cost to memory performance due to the switching between the online and passive states.

Experiment 3 afforded the opportunity to explore how the switching cost occurs. The results of Experiment 3, which showed that the memory load of M2 had an impact on the memory performance of M1, motivates the conclusion that in the sequential encoding task, the switching cost might be derived from the concurrent encoding of the M2 representations which would compete for resources with the state switching of the M1 representations. Namely, when more M2 representations were concurrently encoded during the state switching of the M1 representations, the performance cost might be greater. In addition, some researchers have proposed that the online state can retain representations with high-fidelity via persistent neural activity in the sensory processing areas (de Vries, Slagter, & Olivers, 2020; Sreenivasan, Curtis, & D'Esposito, 2014); in contrast, the items stored in the passive state do not accompany persistent neural activity (Myers, Stokes, & Nobre, 2017), possibly producing low fidelity of the passive representations. Thus, some details might be lost when memory representations are transferred into the passive state for transient retention.

The switching cost can be also found in previous retro-cue study. In the double retro-cue condition, the participants transferred the uncued items from the online state into the passive state after indication from the first retro-cue, so it was natural to observe that, when the uncued items were cued by the second retro-cue for probing, the memory performance was lower than in the single retro-cue condition (LaRocque et al., 2013; Lewis-Peacock et al., 2012; Matsukura et al., 2007; van Moorselaar et al., 2015), displaying a switching cost for the uncued items. However, some researchers found no difference in accuracy between a double retro-cue condition and a single retro-cue condition (Landman et al., 2003; Rerko & Oberauer, 2013). In these double-cue conditions (Landman et al., 2003; Rerko & Oberauer, 2013), there was no probe between the first and second retro-cues. As a result, the participants might be hesitant to move the uncued items to the passive state after the first retro-cue (see van Moorselaar et al., 2015), thus resulting in no cost in switching states. Of course, it should be noted that participants possibly utilize the first retro-cue to strengthen the cued item, rather than change the state of the uncued items.

In the *forward test* of the current experiment, before retrieving M1, the M2 memory representations were definitely transferred from the online state to the passive state. Thus, it might be unreasonable to attribute the performance difference between M1 and M2 to merely a difference in the current storage states. An alternative explanation for this difference could be the output interference from the retrieval of M1, which was one of the factors contributing to the serial position effect (Lewandowsky et al., 2004; Lewandowsky & Murdock, 1989). In addition, Experiment 3 also found that the M2 accuracy decreased as the load of M1 increased, suggesting that the output interference from M1 was greater when retrieving more M1 representations was necessary. Nevertheless, M1 accuracy (two items) in the *forward test* was comparable to that of the *backward test*, which indicated that M2 retrieval seemed to have no impact on the retention of M1 in the *backward test*. A reasonable explanation is that output interference might occur only when these representations of M1 and M2 were encountered in the same state. In the *backward test*, the M1 representations were kept in the passive state when M2 was constantly retained in the online state from encoding to retrieval, such that there was little output interference from M2. Thus, there was no difference in accuracy for M1 in the two *separate test*s.

In the *backward test* (Experiment 1), we observed higher accuracy for M2 (two items) that was recently presented and first retrieved relative to M1 (two items), which was similar to results found in backward serial recall tasks (Farrand & Jones, 1996; Guérard et al., 2012;

Hinrichs, 1968; Hulme et al., 1997; Li & Lewandowsky, 1995; St Clair-Thompson & Allen, 2013). In the *forward test* (Experiment 2-3), if the loads of M1 and M2 were equal, the accuracy was higher for M1 that was first retrieved than in M2, which was consistent with the results of forward serial recall tasks (Farrand & Jones, 1996; Hulme et al., 1997; Li & Lewandowsky, 1995). For the sequential encoding memory task, it has been shown that participants generally store the first memory item in the activated long-term memory (or secondary memory) system but store the last memory item in focal attention ("short-term storage" or primary memory) (Atkinson & Shiffrin, 1968; Nee & Jonides, 2013a, 2013b). Combined with the current CDA results that found participants retained M1 representations in the passive state after the onset of M2, we can speculate that the LTM system assists in the storage of representations in the passive state (Foster et al., in press; Rose, 2020).

In summary, by using a sequential change detection paradigm, we have verified that memory representations could be protected in the passive state, but the state switching of WM representations could result in the impairment of memory performance.

Author Contributions

Q. Liu and J. Zhang conceived and designed the experiments. J. Zhang performed the experiments. J. Zhang, T. Liang and Y. Li analyzed the data. Q. Liu and J. Zhang interpreted the data. J. Zhang, C. Ye, H. Sun and J. Zhou drafted the manuscript. C. Ye and Q. Liu provided critical revisions. All authors revised and approved the manuscript.

Declaration of Conflicting Interests

The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

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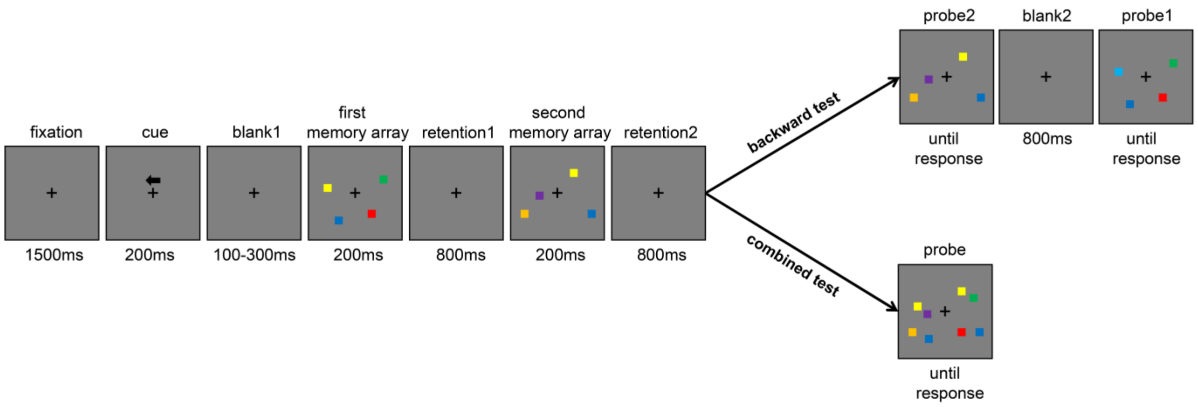
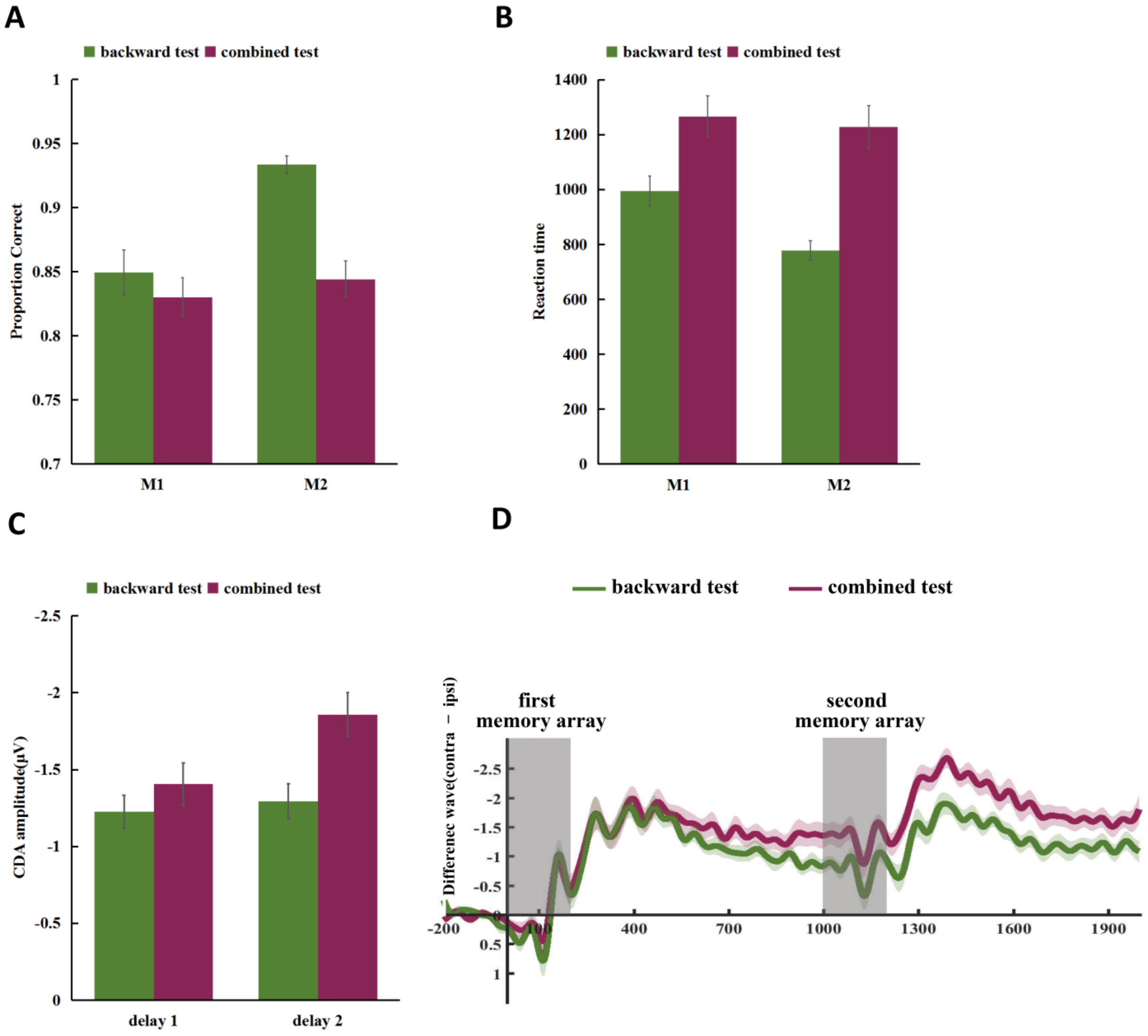
Figure captions

Figure 1



Experiment 1 Procedure

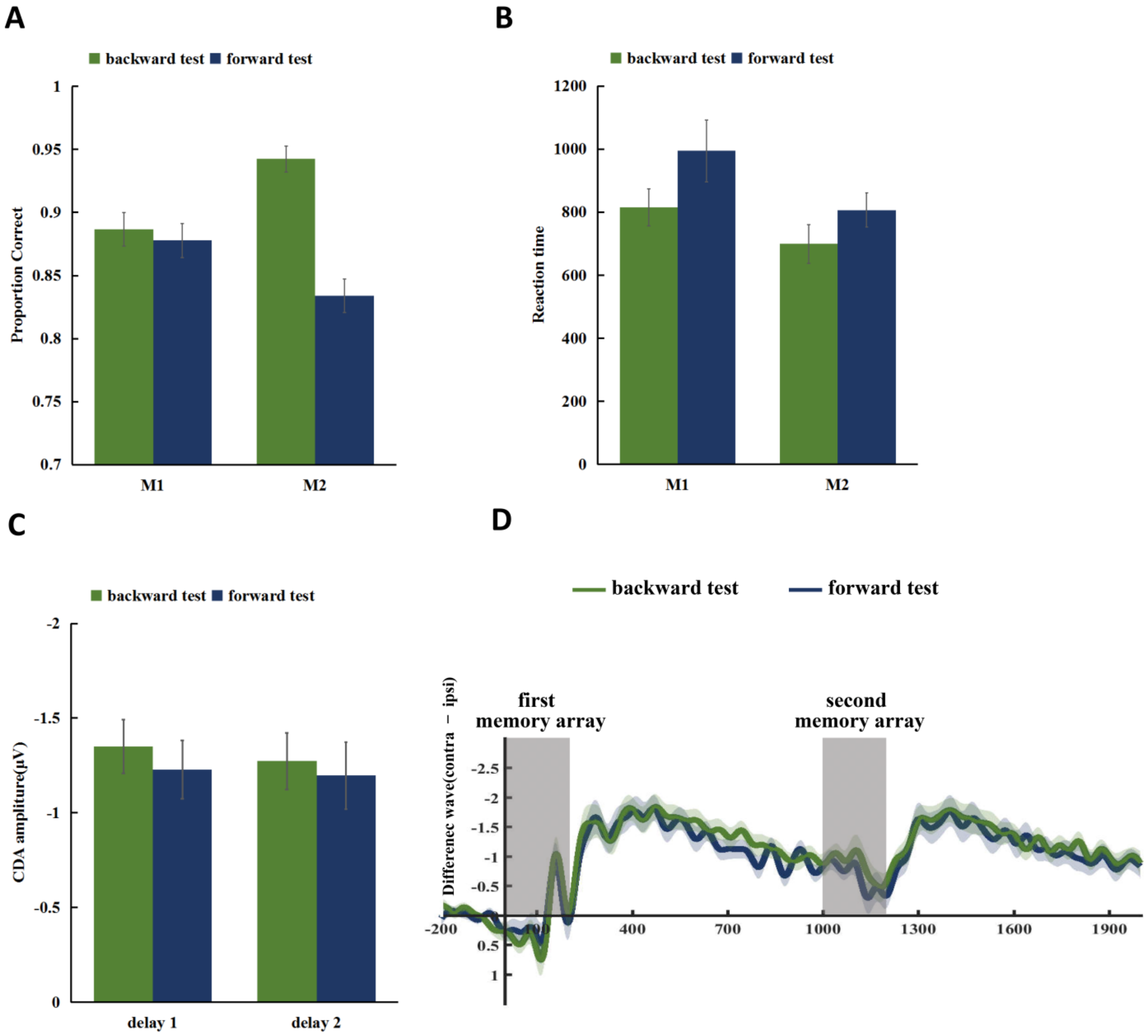
Figure 2



Experiment 1 Results

A, Memory accuracy in the different tests. Error bars indicate standard errors of the mean (SEM). B, Reaction times in the different tests. Error bars indicate the SEM. C, The averaged CDA amplitude in the intervals following the memory arrays in the two different test manners. Error bars indicate the SEM. D, The grand average of the CDA (PO7/8 electrodes) waves in the two different test manners (*backward test* vs. *combined test*). Shaded error bars represent one SEM.

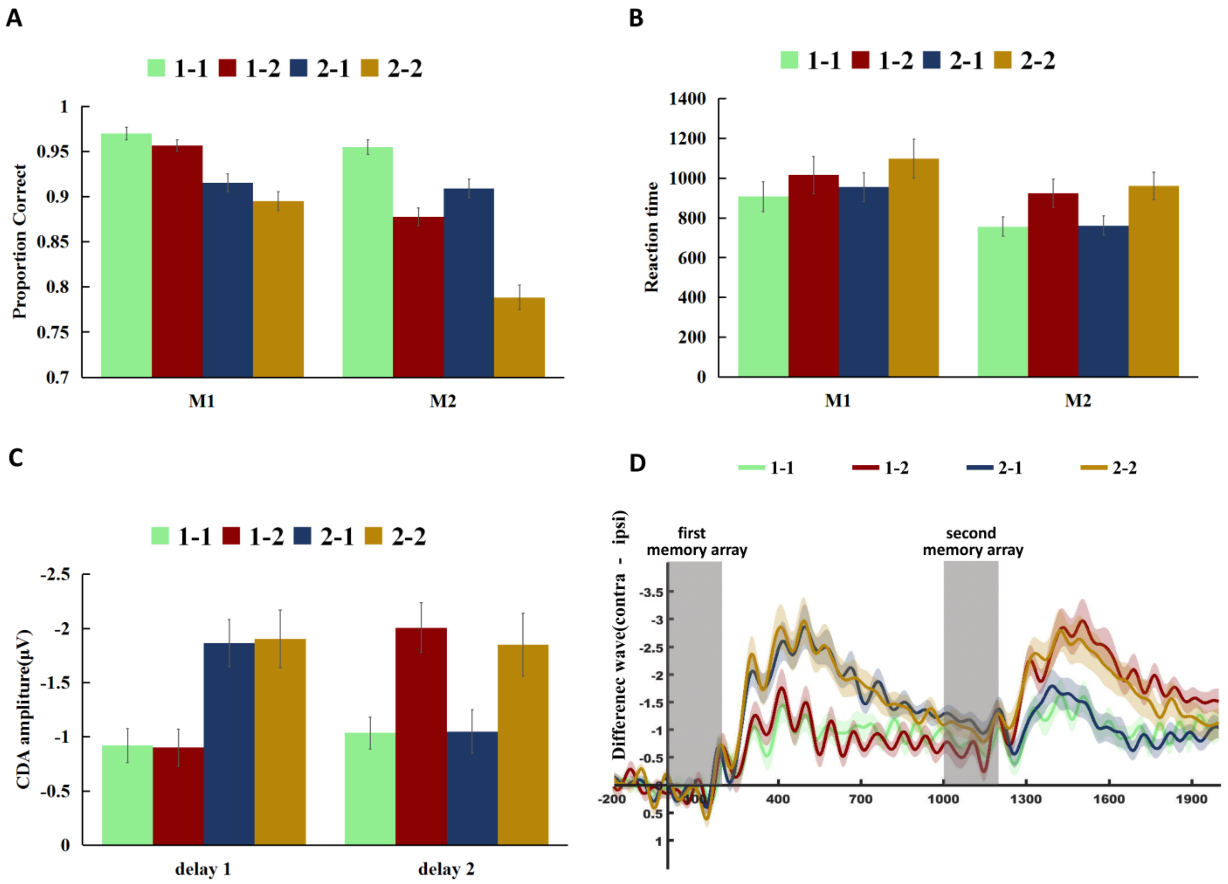
Figure 3



Experiment 2 Results

A, Memory accuracy in the different tests. Error bars indicate the SEM. B, Reaction times in the different tests. Error bars indicate the SEM. C, The averaged CDA amplitude in the intervals following the memory arrays in the two different test manners. Error bars indicate the SEM. D, The grand average of the CDA (PO7/8 electrodes) waves in the two different test manners (*backward test* vs. *forward test*). Shaded error bars represent one SEM.

Figure 4



Experiment 3 Results

A, Memory accuracy in the different tests. Error bars indicate the SEM. B, Reaction times in the different tests. Error bars indicate the SEM. C, The averaged CDA amplitude in the intervals following the memory arrays. Error bars indicate the SEM. D, The grand average of the CDA

(PO7/8 electrodes) waves in the four different tasks (condition 1-1, condition 1-2, condition 2-1, condition 2-2). Shaded error bars represent one SEM.