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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

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### Introduction

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Short-term maintenance of information is a critical component of cognitive processing.

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Human beings can temporarily maintain and manipulate information for advanced cognitive

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processing via the visual working memory (VWM) system (Baddeley, 2012; Luck & Vogel,

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2013). Previous research has established that VWM interacts with many essential cognitive

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processes, including attention and long-term memory (LTM) (Cowan, 1995). Understanding the

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mechanisms that support short-term maintenance is an essential aim of cognitive psychology.

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Traditionally, researchers have asserted that information can be maintained in VWM for a

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short time via persistent neural activity (Curtis & D'Esposito, 2003; Goldman-Rakic, 1995;

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Sreenivasan et al., 2014). That is, individuals can temporarily hold VWM representations in an

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active or online state (herein, we refer to this state as the *online state*). Recently, however,

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cognitive and neural evidence has suggested that the representations of short-term maintenance

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could also be stored in a passive state without any accompanying persistent neural activity

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(LaRocque et al., 2013; Lewis-Peacock et al., 2012; Rose et al., 2016). For the passive state,

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short-term maintenance of information might be accomplished via weight-based changes in

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synaptic connectivity; thus, standard recording methods would not allow for direct observation

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of maintenance in the passive state (Stokes, 2015; Wolff et al., 2017). Some researchers have

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also proposed that the LTM system assists in the storage of representations in the passive state

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(Foster et al., in press; Rose, 2020).

63

Although research shows that representations can be stored in the passive state, it remains

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unclear whether VWM representations stored in the passive state are prone to interference and

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decay . For example, Cowan (1995, 2005) proposed that representations stored in the passive

66 state (also called the activated part of LTM) are likely to be forgotten due to decay over time and  
67 interference (e.g., perceptual interference, interference from other cognitive processes, and  
68 competition among memory representations). However, some researchers have proposed that  
69 memory representations in the passive state could be protected from decay and shielded from  
70 interaction with the current task to minimize interference from the currently prioritized cognition  
71 or activity-based representations (de Vries et al., 2020; Muhle-Karbe et al., 2021; Stokes, 2015;  
72 Stokes et al., 2020). Thus, the passive state could be regarded as being protective, preventing  
73 information loss of the VWM representations.

74 To investigate the storage mechanism of the passive state, researchers have tried to  
75 manipulate the storage states of VWM representations. For instance, researchers have adopted a  
76 double retro-cue paradigm to guide participants to store the memory representations in either the  
77 online state or the passive state (LaRocque et al., 2013; Lewis-Peacock et al., 2012; Rose et al.,  
78 2016). In these double retro-cue studies, two retro-cues appear sequentially and point to the  
79 to-be-tested items after the memory array disappears. When the first retro-cue appears,  
80 participants store the cued representation in the online state and the uncued representations in the  
81 passive state. After the first cued item has been detected, the second retro-cue appears to indicate  
82 the representation which was initially stored in the online state (repeat retro-cue) or the passive  
83 state (switch retro-cue). These studies showed that VWM performance under the switch  
84 retro-cue condition was worse than under the repeat retro-cue condition. The inferior  
85 performance under the switch retro-cue condition implies that representations stored in the  
86 passive state are impaired compared to those stored in the online state. Actually, the inferior  
87 performance under the switch retro-cue condition might be due to the comparison between the

88 representations stored in the passive state and the online state. Because the representations in the  
89 passive state suffered state-switching from the online state into the passive state for transient  
90 maintenance and from the passive state to the online state again for the probe, the cost of VWM  
91 performance under the switch retro-cue condition compared to the repeat retro-cue condition  
92 may be derived from the transferring process between different states instead of impairment in  
93 the passive state. However, previous studies did not directly manipulate the interference or delay  
94 conditions to compare the representations in the passive state (LaRocque et al., 2013;  
95 Lewis-Peacock et al., 2012; Rose et al., 2016). One possible way to investigate the effect of the  
96 passive state on VWM representations is to directly compare the memory performance of the  
97 items in the passive state over different retention periods and to manipulate the factors of  
98 interference (e.g., perceptual interference and judging decision interference). Research on the  
99 single retro-cue paradigm has manipulated the stimulus-onset asynchrony between the retro-cue  
100 and the probe array (Astle et al., 2012; Gressmann & Janczyk, 2016; Pertzov et al., 2013; van  
101 Moorselaar et al., 2015); however, the retro-cue validity in these studies using the single  
102 retro-cue paradigm was fairly high (usually > 65%). There was a much lower probability of  
103 retrieving the uncued items, and the participants tended to forget the uncued representations  
104 rather than maintain them in the passive state. Therefore, these studies did not provide direct  
105 insight into whether the information in the passive state is prone to interference and decay. The  
106 current study addresses this issue.

107         In the current study, participants were required to perform a new modified sequential  
108 encoding version of the change detection paradigm during an Electrophysiology (EEG)  
109 recording, in which two memory arrays were presented in sequence (M1 and M2). The key

110 manipulation of the experiment was using a setup of probe arrays. Participants were encouraged  
111 to store the memory arrays in different ways: (1) a *combined test*—change detection was  
112 required for test stimuli when both arrays were combined; (2) a *forward test*—change detection  
113 was required first for the test stimuli for M1, then for the test stimuli for M2; and (3) a *backward*  
114 *test*—change detection was required first for the test stimuli for M2, then for the test stimuli for  
115 M1. M1 and M2 were tested separately in the *forward test* and the *backward test*; thus, the two  
116 tests fell into the same general category: the *separate test*.

117         We expected that for the task requiring sequential retrieval of the two arrays (the *separate*  
118 *test*), participants would first retain M1 in the online state, then put it into the passive state when  
119 M2 appeared. To identify whether the memory state indeed changed, we recorded the  
120 contralateral delay activity (CDA), a widely used marker in event-related potential. CDA tracks  
121 the number of visual representations stored in the online state during the maintenance phase. Its  
122 amplitude increases with the number of memory representations, approaching an asymptote once  
123 approximately 3–4 representations are stored, reflecting the limit of VWM capacity (Luria et al.,  
124 2016; Vogel & Machizawa, 2004; Vogel et al., 2005).

125         The aim of Experiment 1 was to examine whether the M1 representations in the  
126 *backward test* were stored in the passive state. By using a blocked design, participants were  
127 required to perform a VWM task in the *backward test* and the *combined test*. In Experiment 2,  
128 participants performed a VWM task in the *backward test* and the *forward test*. The same  
129 memory load (two items) in M1 and M2 enabled us to directly compare the memory  
130 performance of representations stored in the different states. By comparing the memory  
131 performance of the items in M1 between the *forward test* and the *backward test*, we could assess

132 whether the representations stored in the passive state were prone to interference and decay. In  
133 Experiment 3, we varied the load of the two memory arrays to investigate whether the CDA  
134 component following the onset of M2 only tracked the M2 representations independently of M1  
135 in the *forward test*.

### 136 **Experiment 1**

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



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

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

## 169 **Method**

### 170 ***Sample Size***

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

### 175 ***Participants***

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

### 185 *Stimuli*

186 Memory items ( $0.65^\circ \times 0.65^\circ$ ) were randomly selected from seven easily distinguishable  
187 colored squares. The RGB values of these colors were red (255, 0, 0); orange (255, 125, 0);  
188 yellow (255, 255, 0); green (0, 255, 0); blue (0, 0, 255); indigo (0, 255, 255); and violet (255, 0,  
189 255). All memory items were randomly presented within two imaginary  $4^\circ \times 7.3^\circ$  rectangular  
190 regions symmetrically positioned  $3^\circ$  to the left and right of a blank central fixation cross ( $0.2^\circ \times$   
191  $0.2^\circ$ ) on a gray screen. The positions of the memory items between M1 and M2 did not overlap,  
192 and the center distance of any two memory items was greater than  $2^\circ$ .

### 193 **Procedure**

194 Figure 1 shows a schematic illustration of a sample trial. Participants were seated in front  
195 of the screen at a distance of 70 cm. Each trial began with a display of the central fixation cross  
196 for 1 500 ms. Then, an arrow cue (200 ms) asked the participants to memorize the stimuli on the  
197 left or right field of the fixation cross. After a random interval (100–300 ms), the first memory

198 array (M1) was presented for 200 ms, followed by a retention interval of 800 ms. Then, the  
199 second memory array (M2) was presented for 200 ms, also followed by a retention interval of  
200 800 ms. The probe array was then be presented after the second retention interval. There were  
201 two kinds of detection conditions.

202         In the *backward test*, participants first detected M2 (probe 2) and then detected M1  
203 (probe 1). When probe 2 appeared, if the memory items in the cued visual field of M2 were  
204 identical to probe 2, the participants should choose the “same” response (pressing the *F* key);  
205 otherwise, they should select the “different” response (pressing the *J* key). Following a delay of  
206 800 ms, probe 1 appeared. Similarly, if the memory items in the cued visual field of M1 were  
207 identical to probe 1, participants were to choose the “same” response (pressing the *F* key);  
208 otherwise, they should select the “different” response (pressing the *J* key). In the *combined test*,  
209 the participants had to mentally combine both the M1 and M2 items and compare them with the  
210 test display in the cued visual field (combined probe), selecting the “same” or “different”  
211 response. The proportion of “same” and “different” responses was 50% in each condition. In  
212 addition, the “different” item in the probe array was a “new” item that was never presented in the  
213 memory field of the two memory arrays. The probe arrays (probe 1, probe 2, or the combined  
214 probe) disappeared following the response.

215         Participants received a practice block of 16 trials to understand the experimental  
216 procedure before starting either the *backward test* (four blocks, each consisting of 64 trials) or  
217 the *combined test* (four blocks, each consisting of 64 trials) to finish the formal experiment. Half  
218 of the participants experienced sequence 1. They practiced the *backward test* and then completed  
219 the formal *backward test*; they then practiced the *combined test* before taking the formal

220 *combined test*. The other half of the participants finished the experiment by experiencing  
221 sequence 2. They practiced the *combined test* and then completed the formal *combined test*. They  
222 then practiced the *backward test* before taking the formal *backward test*. Their accuracy had to  
223 be at least 75% in the practice block before participating in the formal experiment (the trial was  
224 correct only when both of the probes were correct in the *backward test*). Therefore, participants  
225 knew what kind of probe condition they were to perform before the formal experiment.  
226 Participants were encouraged to adopt different memory techniques according to the two test  
227 manners. In the *backward test*, participants were encouraged to remember the two memory  
228 arrays using two separate representations rather than an integrated visual array combining the  
229 two memory arrays; however, this technique was not emphasized in the *combined test*. In  
230 addition, we strongly emphasized accuracy over response speed in the instructions. On average,  
231 it took 80 minutes to finish the entire experiment.

232

233 **INSERT FIGURE 1 ABOUT HERE**

234

### 235 *Electrophysiology (EEG) Recording and Analyses*

236 The EEG signals were recorded using a 64-channel amplifier (ANT Neuro EEGO)  
237 mounted in a cap using a 10/20 montage, including Fp1, Fp2, Fpz, AF3, AF4, GND, AF7, AF8,  
238 F1, F2, F3, F4, F5, F6, F7, F8, Fz, FT7, FT8, FC1, FC2, FC3, FC4, FC5, FC6, FCz, T7, T8, C1,  
239 C2, C3, C4, C5, C6, Cz, TP7, TP8, CP1, CP2, CP3, CP4, CP5, CP6, CPz, P1, P2, P3, P4, P5, P6,  
240 P7, P8, Pz, PO3, PO4, PO7, PO8, POz, O1, O2, and two mastoid electrodes. In these electrodes,  
241 CPz served as the online reference, and GND served as the ground electrode. The O2 was not

242 recorded because it was broken. The horizontal EOG was recorded from electrodes placed 1 cm  
243 to the left and right of the external canthi; the vertical EOG was recorded from the electrodes  
244 above and below the left eye. All electrode impedances were kept below 10 K $\Omega$ . The data were  
245 collected at a sampling rate of 500 Hz.

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

256 The contralateral delay activity (CDA) was evident in electrode PO7/PO8 (Luria et al.,  
257 2010; Luria et al., 2016; Luria & Vogel, 2014; Vogel & Machizawa, 2004). The CDA was  
258 calculated by subtracting the ipsilateral side from the contralateral side with the memory items  
259 (Williams & Woodman, 2012). The CDA mean amplitude was calculated using a window of  
260 300–900 ms after the onset of the learning stimulus. For visualization purposes, we adopted a  
261 low-pass filter (“eegfilt.m”) (Delorme & Makeig, 2004) of 17 Hz to smooth the CDA waveforms;  
262 this practice aligned with previous studies (Adam et al., 2018; Gao et al., 2009; Gao et al., 2011;

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

### 265 ***Data Analysis***

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

### 275 **Results**

#### 276 ***Behavioral Results***

277 Figure 2A shows the memory accuracy. We employed a one-sample *t*-test and determined  
278 that the accuracy of the memory arrays under each condition was greater than chance (50%) (all  
279 with a  $p < .001$ ). We then conducted a 2 (test manner: *backward test*, *combined test*) $\times$ 2 (memory  
280 array: M1, M2) repeated measures ANOVA to analyze memory accuracy (Figure 2A). The main  
281 effect of test manner was significant ( $F(1,21) = 36.456$ ,  $p < .001$ ,  $\eta_p^2 = 0.635$ ), as was the main  
282 effect of memory array ( $F(1, 21) = 18.889$ ,  $p < .001$ ,  $\eta_p^2 = 0.474$ ). Additionally, there was a  
283 significant interaction between test manner and memory array ( $F(1,21) = 13.071$ ,  $p = .002$ ,  $\eta_p^2 =$   
284 0.384).

285            Simple effect analysis and the Bayesian paired samples *t*-test revealed that the accuracy  
286 of M2 was higher than M1 in the *backward test* ( $F(1,21) = 26.27, p < .001, \eta_p^2 = 0.556$ , Cohen's  
287  $d = 1.093$ ,  $BF_{01} = 0.002$ ). However, the difference in accuracy between M1 and M2 was not  
288 significant in the *combined test* ( $F(1,21) = 1.17, p = .292, \eta_p^2 = 0.053$ , Cohen's  $d = 0.230$ ,  $BF_{01} =$   
289  $2.673$ ). For M1, the difference in accuracy between the *backward test* and the *combined test* was  
290 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,  
291 however, the participants' accuracy in the *backward test* was significantly higher than in the  
292 *combined test* ( $F(1,21) = 40.94, p < .001, \eta_p^2 = 0.661$ , Cohen's  $d = 1.315$ ,  $BF_{01} = 1.255 \times 10^{-4}$ ).

293            Figure 2B shows the reaction time results. To analyze the reaction time results, we  
294 conducted a 2 (test manner: *backward test*, *combined test*) $\times$ 2 (memory array: M1, M2) repeated  
295 measures ANOVA. The main effect of test manner was significant ( $F(1,21) = 32.420, p < .001,$   
296  $\eta_p^2 = 0.607$ ), as was the main effect of memory array ( $F(1,21) = 68.962, p < .001, \eta_p^2 = 0.767$ ).  
297 There was also a significant interaction between test manner and memory array ( $F(1,21) =$   
298  $25.792, p < .001, \eta_p^2 = 0.551$ ).

299            Simple effect analysis and the Bayesian paired samples *t*-test revealed that the reaction  
300 time of M2 was significantly lower than M1 in the *backward test* ( $F(1,21) = 51.84, p < .001, \eta_p^2$   
301  $= 0.712$ , Cohen's  $d = 1.534$ ,  $BF_{01} = 2.550 \times 10^{-5}$ ). The reaction time of M2 significantly lower  
302 than M1 in the *combined test* ( $F(1,21) = 8.87, p = .007, \eta_p^2 = 0.297$ , Cohen's  $d = 0.638$ ,  $BF_{01} =$   
303  $0.152$ ). For M1, the reaction time in the *backward test* was significantly lower than in the  
304 *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,  
305 the reaction time in the *backward test* was also lower than in the *combined test* ( $F(1,21) = 47.69,$   
306  $p < .001, \eta_p^2 = 0.694$ , Cohen's  $d = 1.472$ ,  $BF_{01} = 4.538 \times 10^{-5}$ ).

307

308 **INSERT FIGURE 2 ABOUT HERE**

309

310 *Electrophysiological Results*

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

318 Simple effect analysis and the Bayesian paired samples *t*-test revealed that the difference  
319 in CDA amplitude between delay 2 and delay 1 was not significant in the *backward test* ( $F(1,21)$   
320  $= 0.49$ ,  $p = .494$ ,  $\eta_p^2 = 0.023$ , Cohen's  $d = 0.148$ ,  $BF_{01} = 3.604$ ). However, the CDA amplitude of  
321 delay 2 was greater than delay 1 in the *combined test* ( $F(1,21) = 27.06$ ,  $p < .001$ ,  $\eta_p^2 = 0.563$ ,  
322 Cohen's  $d = 1.109$ ,  $BF_{01} = 0.002$ ). In addition, for delay 1, the CDA amplitude in the *combined*  
323 *test* was greater than in the *backward test* ( $F(1,21) = 7.46$ ,  $p = .013$ ,  $\eta_p^2 = 0.262$ , Cohen's  $d =$   
324  $0.582$ ,  $BF_{01} = 0.242$ ). For delay 2, the CDA amplitude in the *combined test* was also greater than  
325 the *backward test* ( $F(1,21) = 15.01$ ,  $p = .001$ ,  $\eta_p^2 = 0.417$ , Cohen's  $d = 0.826$ ,  $BF_{01} = 0.025$ ).

326 We then focused on delay 1 during the earlier versus later phase following stimulus  
327 presentation: early-CDA (300–600 ms) and late-CDA (600–900 ms) segments. We found that  
328 there was no significant difference in early-CDA between the *combined test* and the *backward*



329 *test* ( $t(21) = 1.580, p = .129$ , Cohen's  $d = 0.337$ ,  $BF_{01} = 1.528$ ). However, the *combined test* had a  
330 significantly higher late-CDA than the *backward test* ( $t(21) = 2.908, p = .008$ , Cohen's  $d = 0.619$ ,  
331  $BF_{01} = 0.174$ ).

332 We also analyzed the effect of the ordering of the conditions (half of the participants did  
333 the *backward test* first and then the *combined test*; the other half did the *combined test* first and  
334 then the *backward test*). We used mixed ANOVA to measure the accuracy, reaction time, and  
335 CDA. We used group (*backward-combined*, *combined-backward*) as the between-subject factor.  
336 For the accuracy and the reaction time, we utilized test manner (*backward test*, *combined test*)  
337 and memory array (M1, M2) as the within-subject factors. For the CDA, we used test manner  
338 (*backward test*, *combined test*) and delay (delay 1: 300–900 ms; delay 2: 1300–1900 ms) as the  
339 within-subject factors. In terms of accuracy, there were no significant main effects of group  
340 ( $F(1,20) = 0.533, p = .474, \eta_p^2 = 0.026$ ) and no significant interaction between group, memory  
341 array and test manner ( $F(1,20) = 0.304, p = .588, \eta_p^2 = 0.015$ ). For the reaction time, there were  
342 no significant main effects of group ( $F(1,20) = 0.007, p = .933, \eta_p^2 = 0.000$ ) and no significant  
343 interaction between group, memory array, and test manner ( $F(1,20) = 1.410, p = .249, \eta_p^2 =$   
344  $0.066$ ). For the CDA, there were no significant main effects of group ( $F(1,20) = 0.030, p = .865,$   
345  $\eta_p^2 = 0.001$ ) and no significant interaction between group, delay, and test manner ( $F(1,20) =$   
346  $1.078, p = .312, \eta_p^2 = 0.051$ ).

## 347 Discussion

348 The results of Experiment 1 show that, in the *backward test*, M1 accuracy was much  
349 higher than the level of chance alone. Meanwhile, the CDA amplitude was comparable following  
350 M2 and M1 in the *backward test*, while the CDA amplitude following M2 was significantly

351 greater than that following M1 in the *combined test*. These results suggest that, in the *combined*  
352 *test*, both M1 and M2 were stored together in the online state (four items). Notably, although the  
353 participants have enough storage space to store both the M1 and M2 representations in the online  
354 state (as shown by the results in the *combined test*), they still transferred the M1 representations  
355 to the passive state in the *backward test*. In addition, there was a significant difference in CDA  
356 amplitude between the *backward test* and the *combined test* during the late period (600–900 ms)  
357 of M1 and the entire period of M2. This finding might suggest that the information retention  
358 declined in the online state to some extent. Of course, it was also possible that in some  
359 proportion of trials (not all trials), participants transferred all of the M1 representations into the  
360 passive state before the onset of M2.

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

369         The accuracy of M2 was lower in the *combined test* than in the *backward test*. There was  
370 no difference in accuracy between M1 and M2 in the *combined test*. These results were  
371 consistent with the general notion that accuracy decreases as the stimulus set size increases in the  
372 online state (Ikkai et al., 2010). In addition, the reaction time was longer in the *combined test*

373 than the *backward test* for M2. It is possible that M1 and M2 interfered with each other in the  
374 online state under the *combined test* (Postle, 2006; Bettencourt & Xu, 2016), resulting in lower  
375 accuracy and a longer reaction time in both memory arrays. In the *backward test*, M1 was stored  
376 in the passive state, so the M1 representations could not interfere with the M2 representations  
377 that were stored in the online state. Thus, there was higher accuracy and a shorter reaction time  
378 for M2 in the *backward test* than the *combined test*. In addition, in the *backward test*, the  
379 accuracy of M1 was significantly lower than that of M2. These results could suggest an  
380 impairment for the M1 representations in the *backward test*.

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

**Experiment 2**

394  
395 We confirmed that the participants stored the M1 representations in the passive state in  
396 the *backward test* in Experiment 1. An impairment for the M1 representations was found in the  
397 *backward test*. In Experiment 2, we investigated the mechanisms underlying the impairment. In  
398 the *backward test*, the M1 VWM representations were transferred from the online state to the  
399 passive state. The information was then retrieved from the passive state back to the online state.  
400 The M2 representation was not subject to this transferring process because M2 detection was  
401 performed right after retention. Therefore, the first possible reason for the decline in memory  
402 representation is the transferring process for representation between states. In addition to the  
403 process of switching between memory states, the impairment might also occur after the  
404 representation has been transferred to the passive state. In the *backward test*, the probe for M1  
405 was performed later than it was for M2; thus, the difference in accuracy between M1 and M2  
406 might result from the information in the passive state simply decaying over time. Alternatively,  
407 the probe for M2 (appearance of the M2 probe as well as the decision process for the M2 change  
408 detection) might also cause extra interference for the representations stored in the passive state.  
409 Therefore, it was unclear whether the loss of the M1 representations occurred during the  
410 switching of states or the maintenance in the passive state (due to decay over time or interference  
411 from the M2 probe).

412 In Experiment 2, we manipulated the retrieval order in the *forward test* and the *backward*  
413 *test*. In the *forward test*, the change detection was required for M1 and then for M2. Specifically,  
414 during the test phase, participants were first required to retrieve the M1 representations from the  
415 passive state at the onset of the M1 probe array; they then had to do the same for M2. This

416 process represented a reversal of test order from that of the *backward test*, where they would  
417 retrieve the M1 representations *after* completing the M2 probe.

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

428 The reasons for the performance impairment of the M1 representations (relative to M2) in  
429 the *backward test* could be examined by measuring accuracy. If the performance cost occurred  
430 only due to the switching of states, we would expect to find no difference in M1 accuracy  
431 between the *backward test* and the *forward test* as the same switching process occurred in both  
432 tests. Conversely, if, following switching, storage in the passive state was easily impaired due to  
433 decay or interference from the M2 probe, we would expect higher M1 accuracy in the *forward*  
434 *test* compared to the *backward test*. This expectation rests on the fact that M1 was tested firstly  
435 and without interference from the M2 probe in the *forward test* compared to the *backward test*.  
436 Therefore, it should exhibit a smaller effect for delay and interference. Of course, there was a

437 long retention time and interference in the *backward test* for M1 storage in the passive state, but  
438 Experiment 2 did not differentiate between these two factors.

## 439 **Method**

### 440 *Participants*

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

### 445 *Procedure*

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

## 452 **Results**

### 453 *Behavioral Results*

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

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

462         Simple effect analysis and the Bayesian paired samples  $t$ -test revealed that the accuracy  
463 of M2 was higher than M1 in the *backward test* ( $F(1,21) = 22.32$ ,  $p < .001$ ,  $\eta_p^2 = 0.515$ , Cohen's  
464  $d = 1.007$ ,  $BF_{01} = 0.004$ ), but the accuracy of M2 was lower than M1 in the *forward test* ( $F(1,21)$   
465  $= 8.69$ ,  $p = .008$ ,  $\eta_p^2 = 0.293$ , Cohen's  $d = 0.628$ ,  $BF_{01} = 0.161$ ). For M1, the difference in  
466 accuracy between the *forward test* and the *backward test* was not significant ( $F(1,21) = 0.27$ ,  $p$   
467  $= .611$ ,  $\eta_p^2 = 0.013$ , Cohen's  $d = 0.110$ ,  $BF_{01} = 3.974$ ). Meanwhile, for M2, the accuracy in the  
468 *backward test* was higher than that in the *forward test* ( $F(1,21) = 55.26$ ,  $p < .001$ ,  $\eta_p^2 = 0.725$ ,  
469 Cohen's  $d = 1.584$ ,  $BF_{01} = 1.624 \times 10^{-5}$ ).

470         Figure 3B shows the reaction time results. We conducted a 2 (test manner: *backward test*,  
471 *combined test*) $\times$ 2 (memory array: M1, M2) repeated measures ANOVA to analyze the reaction  
472 time. The main effect of test manner was significant ( $F(1,21) = 6.418$ ,  $p = .019$ ,  $\eta_p^2 = 0.234$ ), as  
473 was the main effect of memory array ( $F(1,21) = 26.488$ ,  $p < .001$ ,  $\eta_p^2 = 0.558$ ). The interaction  
474 between test manner and memory array was not significant ( $F(1,21) = 1.846$ ,  $p = .189$ ,  $\eta_p^2 =$   
475  $0.081$ ).

476

477 **INSERT FIGURE 3 ABOUT HERE**

478

479 *Electrophysiological Results*

480 We conducted a 2 (test manner: *backward test*, *combined test*) $\times$ 2 (delay: delay1, delay2)  
481 repeated measures ANOVA to analyze the CDA amplitude (Figure 3C and Figure 3D). The main  
482 effect of test manner was not significant ( $F(1, 21) = 0.804$ ,  $p = .380$ ,  $\eta_p^2 = 0.037$ ), and the main  
483 effect of delay was not significant ( $F(1, 21) = 0.619$ ,  $p = .440$ ,  $\eta_p^2 = 0.029$ ). To some extent, the  
484 information in M1 was removed from the online state in both the *forward test* and the *backward*  
485 *test*. The interaction between test manner and delay was not significant ( $F(1,21) = 0.185$ ,  $p$   
486  $= .672$ ,  $\eta_p^2 = 0.009$ ).

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

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



501 0.248,  $p = .624$ ,  $\eta_p^2 = 0.012$ ) and no significant interaction between group, memory array, and  
502 test manner ( $F(1,20) = 0.086$ ,  $p = .773$ ,  $\eta_p^2 = 0.004$ ). For the reaction time, there was no  
503 significant main effect of group ( $F(1,20) = 2.922$ ,  $p = .103$ ,  $\eta_p^2 = 0.127$ ) and no significant  
504 interaction between group, memory array, and test manner ( $F(1,20) = 0.846$ ,  $p = .369$ ,  $\eta_p^2 =$   
505 0.041). For CDA, there was no significant main effect of group ( $F(1,20) = 2.497$ ,  $p = .130$ ,  $\eta_p^2 =$   
506 0.111) and no significant interaction between group, delay, and test manner ( $F(1,20) = 3.359$ ,  $p$   
507  $= .082$ ,  $\eta_p^2 = 0.144$ ).

## 508 **Discussion**

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

515       Superficially, it seems contradictory that a previous study also used the *forward test* but  
516 did not find the same CDA pattern (Ikkai et al., 2010). We believe that this discrepancy can be  
517 explained by their short (400 ms) interval between M1 and M2 (Ikkai et al., 2010). Previous  
518 research has demonstrated that the two array representations are combined when the  
519 interstimulus interval is below 500 ms (Ikkai et al., 2010; Jiang & Kumar, 2004; Li et al., 2020)  
520 but separated if the interval is 500 ms or longer (Jiang & Kumar, 2004). In the current work, the  
521 interval between the two memory arrays was 800 ms—long enough for switching between the  
522 two states. None of the participants had completed any memory experiments prior to the current

523 study to avoid the formation of a particular memory mindset. Participants were also encouraged  
524 to remember the two memory arrays with two separate mental images rather than an integrated  
525 visual array. Thus, it was not surprising to see a different pattern of results in our *forward test*  
526 than in Ikkai and colleagues' (2010) study. In addition, some studies from the sequential change  
527 detection paradigm found no increase in the CDA amplitude after the onset of M2 if the item  
528 locations differed between the probe and memory arrays (Feldmann-Wustefeld et al., 2018) or if  
529 the two memory arrays appeared in different fields (Berggren & Eimer, 2016). Therefore, it  
530 should not be surprising to see separate storage in the current study using the sequential change  
531 detection paradigm. Future studies can systematically investigate this issue by manipulating the  
532 factors mentioned above.

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

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

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

### 555 **Experiment 3**

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

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

571 **Method**

572 ***Participants***

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

576 ***Procedure***

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

586 **Results**587 ***Behavioral Results***

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

593 Figure 4A shows the accuracy results. For M1, the main effect of M1 load was significant  
594 ( $F(1, 21) = 62.898, p < .001, \eta_p^2 = 0.750$ ). The main effect of M2 load was significant ( $F(1, 21) =$   
595  $18.180, p < .001, \eta_p^2 = 0.464$ ), but the interaction between M1 load and M2 load was not  
596 significant ( $F(1, 21) = 1.192, p = .287, \eta_p^2 = 0.054$ ). For M2, the main effect of M1 load was  
597 significant ( $F(1, 21) = 148.227, p < .001, \eta_p^2 = 0.876$ ); the main effect of M2 load was significant  
598 ( $F(1, 21) = 113.247, p < .001, \eta_p^2 = 0.844$ ), and the interaction between M1 load and M2 load  
599 was significant ( $F(1, 21) = 13.416, p = .001, \eta_p^2 = 0.390$ ). Simple effect analysis and the  
600 Bayesian paired samples *t*-test revealed that the accuracy was significant lower when the load of  
601 M2 was 2 than when the load of M2 was 1 in both the conditions that the load of M1 was 1 ( $F(1,$   
602  $21) = 47.49, p < .001, \eta_p^2 = 0.693, \text{Cohen's } d = 1.469, \text{BF}_{01} = 4.673 \times 10^{-5}$ ) and 2 ( $F(1, 21) =$   
603  $124.68, p < .001, \eta_p^2 = 0.856, \text{Cohen's } d = 2.383, \text{BF}_{01} = 2.701 \times 10^{-8}$ ).

604 Figure 4B shows the reaction time results. For M1, the main effect of M1 load was  
605 significant ( $F(1, 21) = 8.927, p = .007, \eta_p^2 = 0.298$ ), the main effect of M2 load was significant  
606 ( $F(1, 21) = 12.658, p = .002, \eta_p^2 = 0.376$ ), but the interaction between M1 load and M2 load was  
607 not significant ( $F(1, 21) = 2.531, p = .127, \eta_p^2 = 0.108$ ). For M2, the main effect of M1 load was

608 significant ( $F(1, 21) = 6.315, p = .020, \eta_p^2 = 0.231$ ); the main effect of M2 load was significant  
609 ( $F(1, 21) = 33.905, p < .001, \eta_p^2 = 0.618$ ), but the interaction between M1 load and M2 load was  
610 not significant ( $F(1, 21) = 3.262, p = .085, \eta_p^2 = 0.134$ ).

611

612 **INSERT FIGURE 4 ABOUT HERE**

613

### 614 *Electrophysiological Results*

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

618 For delay 1, only the main effect of M1 load was significant ( $F(1, 21) = 40.224, p < .001,$   
619  $\eta_p^2 = 0.657$ ). The main effect of M2 load was not significant ( $F(1, 21) = 0.007, p = .936, \eta_p^2 =$   
620  $0.000$ ), and the interaction between M1 load and M2 load was not significant ( $F(1, 21) = 0.189,$   
621  $p = .668, \eta_p^2 = 0.009$ ).

622 For delay 2, only the main effect of M2 load was significant ( $F(1, 21) = 34.419, p < .001,$   
623  $\eta_p^2 = 0.621$ ). The main effect of M1 load was not significant ( $F(1, 21) = 0.302, p = .588, \eta_p^2 =$   
624  $0.014$ ), and the interaction between M1 load and M2 load was not significant ( $F(1, 21) = 1.519,$   
625  $p = .231, \eta_p^2 = 0.067$ ).

626

### 627 **Discussion**

628 In Experiment 3, the CDA amplitude during delay 2 only varied with the M2 load,  
629 suggesting that the CDA amplitude during delay 2 exclusively tracked the M2 representations in

630 the *forward test*. Varying the M1 load caused, corresponding changes in CDA amplitude only  
631 during delay 1. In addition, the accuracy of M1 in all the test manners was much higher than the  
632 chance level (50%). These results confirmed that the M1 representations were constantly kept in  
633 the passive state during delay 2.

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

648

649

### **General Discussion**

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

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

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

672 Experiment 3 afforded the opportunity to explore how the switching cost occurs. The  
673 results of Experiment 3, which showed that the memory load of M2 had an impact on the



674 memory performance of M1, motivates the conclusion that in the sequential encoding task, the  
675 switching cost might be derived from the concurrent encoding of the M2 representations which  
676 would compete for resources with the state switching of the M1 representations. Namely, when  
677 more M2 representations were concurrently encoded during the state switching of the M1  
678 representations, the performance cost might be greater. In addition, some researchers have  
679 proposed that the online state can retain representations with high-fidelity via persistent neural  
680 activity in the sensory processing areas (de Vries, Slagter, & Olivers, 2020; Sreenivasan, Curtis,  
681 & D’Esposito, 2014); in contrast, the items stored in the passive state do not accompany  
682 persistent neural activity (Myers, Stokes, & Nobre, 2017), possibly producing low fidelity of the  
683 passive representations. Thus, some details might be lost when memory representations are  
684 transferred into the passive state for transient retention.

685         The switching cost can be also found in previous retro-cue study. In the double retro-cue  
686 condition, the participants transferred the uncued items from the online state into the passive  
687 state after indication from the first retro-cue, so it was natural to observe that, when the uncued  
688 items were cued by the second retro-cue for probing, the memory performance was lower than in  
689 the single retro-cue condition (LaRocque et al., 2013; Lewis-Peacock et al., 2012; Matsukura et  
690 al., 2007; van Moorselaar et al., 2015), displaying a switching cost for the uncued items.  
691 However, some researchers found no difference in accuracy between a double retro-cue  
692 condition and a single retro-cue condition (Landman et al., 2003; Rerko & Oberauer, 2013). In  
693 these double-cue conditions (Landman et al., 2003; Rerko & Oberauer, 2013), there was no  
694 probe between the first and second retro-cues. As a result, the participants might be hesitant to  
695 move the uncued items to the passive state after the first retro-cue (see van Moorselaar et al.,

696 2015), thus resulting in no cost in switching states. Of course, it should be noted that participants  
697 possibly utilize the first retro-cue to strengthen the cued item, rather than change the state of the  
698 uncued items.

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

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

718 Hinrichs, 1968; Hulme et al., 1997; Li & Lewandowsky, 1995; St Clair-Thompson & Allen,  
719 2013). In the *forward test* (Experiment 2-3), if the loads of M1 and M2 were equal, the accuracy  
720 was higher for M1 that was first retrieved than in M2, which was consistent with the results of  
721 forward serial recall tasks (Farrand & Jones, 1996; Hulme et al., 1997; Li & Lewandowsky,  
722 1995). For the sequential encoding memory task, it has been shown that participants generally  
723 store the first memory item in the activated long-term memory (or secondary memory) system  
724 but store the last memory item in focal attention (“short-term storage” or primary memory)  
725 (Atkinson & Shiffrin, 1968; Nee & Jonides, 2013a, 2013b). Combined with the current CDA  
726 results that found participants retained M1 representations in the passive state after the onset of  
727 M2, we can speculate that the LTM system assists in the storage of representations in the passive  
728 state (Foster et al., in press; Rose, 2020).

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

732

### 733 **Author Contributions**

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

738

### 739 **Declaration of Conflicting Interests**

740 The author(s) declared that there were no conflicts of interest with respect to the authorship or  
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742

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747

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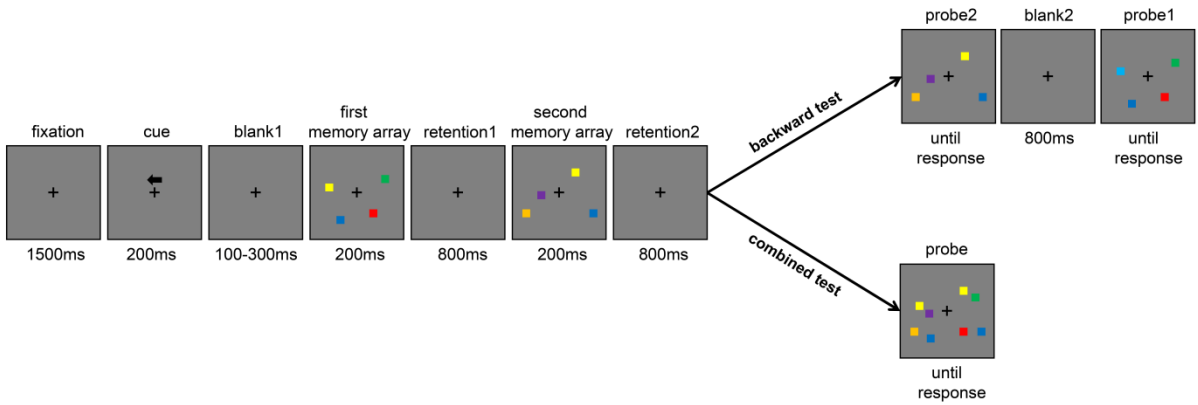
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907

908 **Figure captions**

909 **Figure 1**

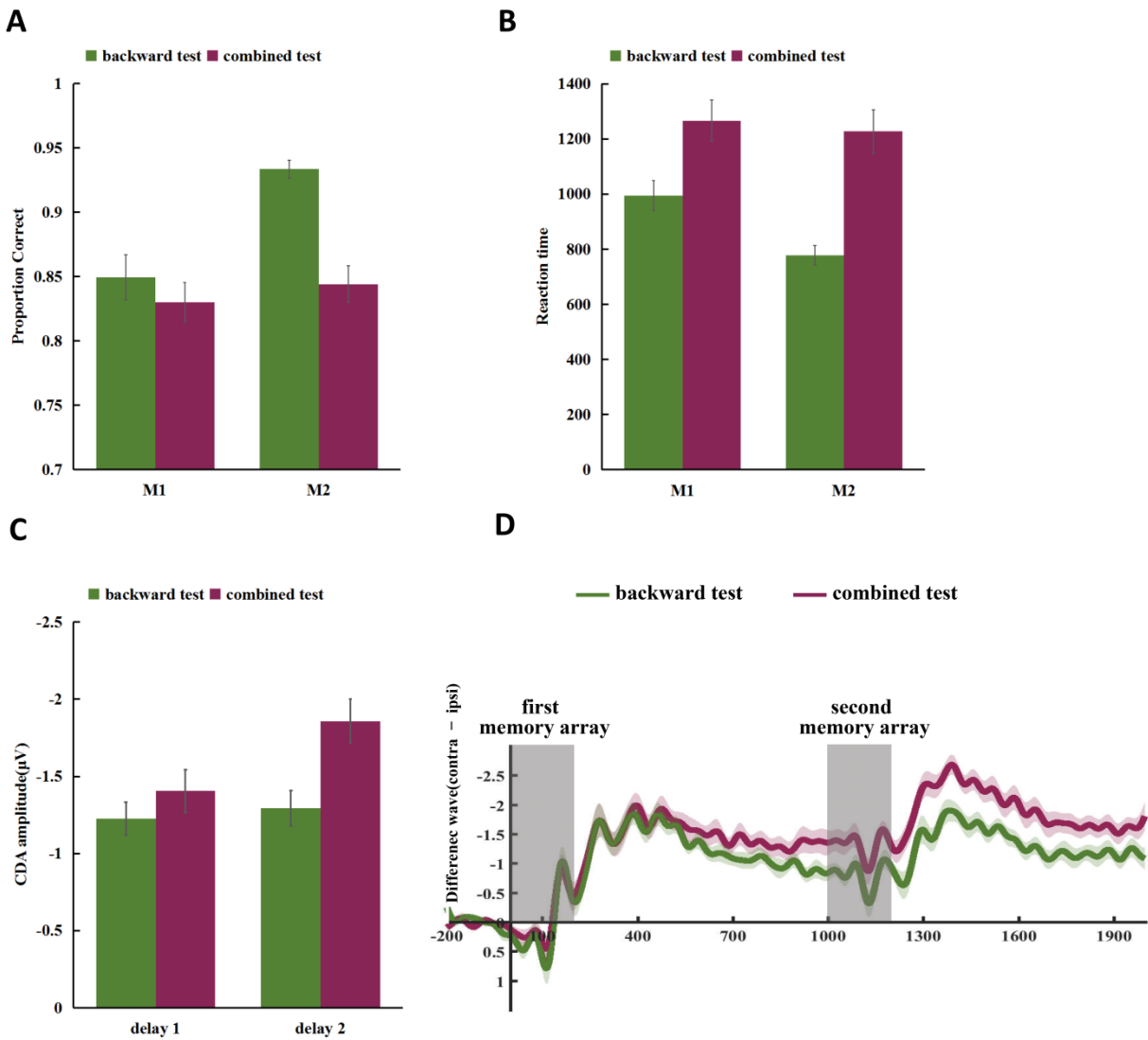


910

911 *Experiment 1 Procedure*

912

913 **Figure 2**



914

915 *Experiment 1 Results*

916 A, Memory accuracy in the different tests. Error bars indicate standard errors of the mean (SEM).

917 B, Reaction times in the different tests. Error bars indicate the SEM. C, The averaged CDA

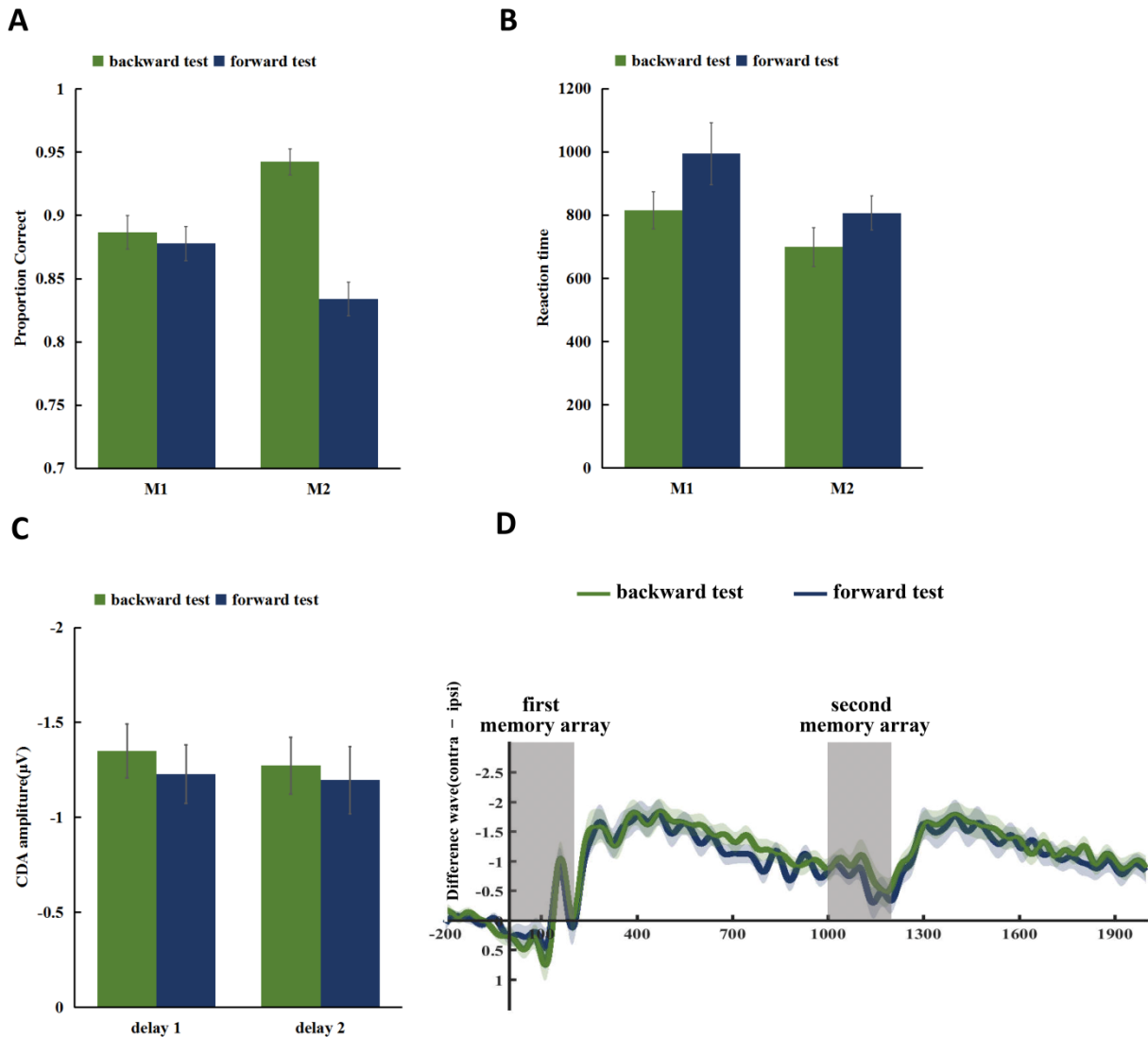
918 amplitude in the intervals following the memory arrays in the two different test manners. Error

919 bars indicate the SEM. D, The grand average of the CDA (PO7/8 electrodes) waves in the two

920 different test manners (*backward test* vs. *combined test*). Shaded error bars represent one SEM.

921

922 **Figure 3**



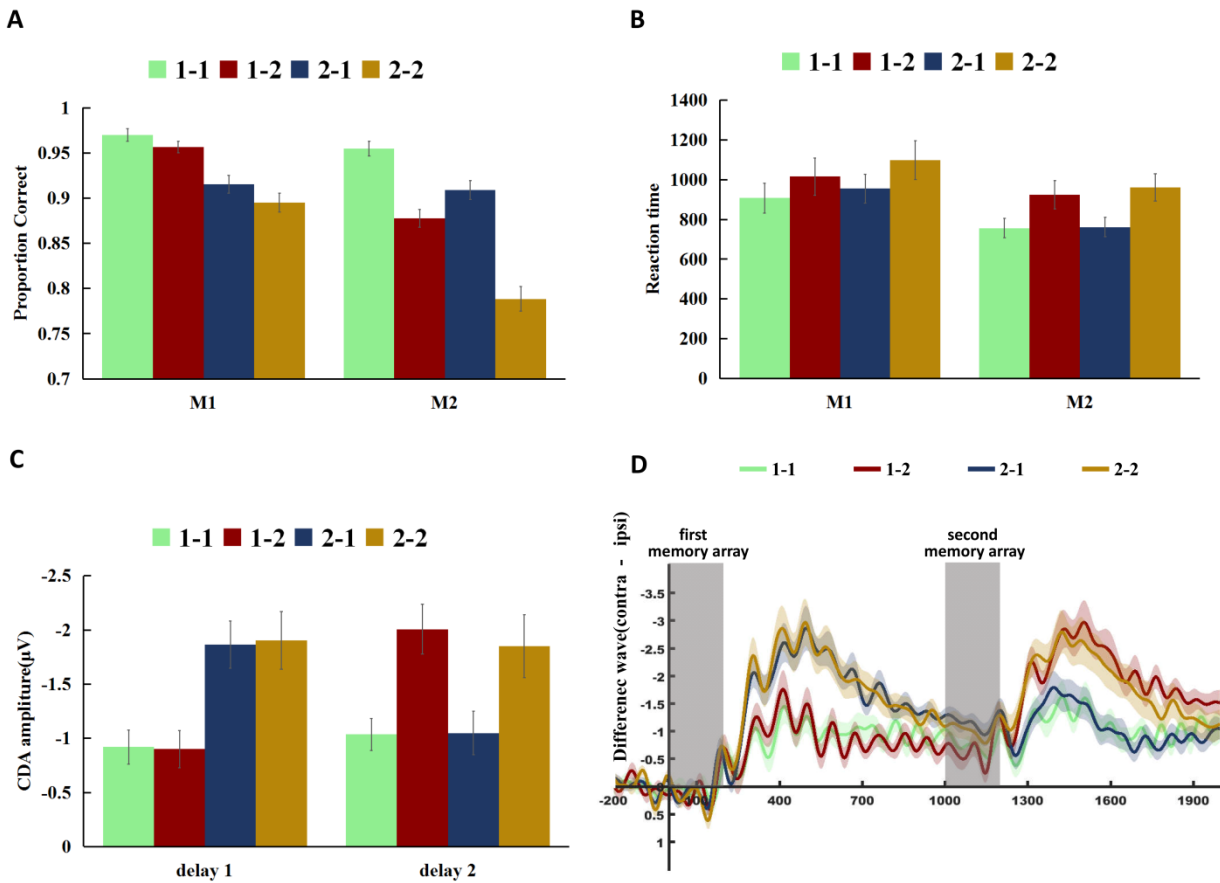
923

924 *Experiment 2 Results*

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

930

931 **Figure 4**



932

933 *Experiment 3 Results*

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

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

939

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942