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21 **1. Introduction**

22 Visual working memory (VWM) plays an essential role in cognitive processing and
23 performance. VWM has been proposed as a cognitive system that temporarily stores and
24 manipulates visual information to meet the needs of ongoing cognitive tasks (Luck & Vogel,
25 1997, 2013). In recent years, a growing body of research has explored the mechanisms of
26 VWM, and researchers now suggest that VWM is a flexible, dynamic process rather than a
27 fixed one (Christophel, Iamshchinina, Yan, Allefeld, & Haynes, 2018; Christophel, Klink,
28 Spitzer, Roelfsema, & Haynes, 2017; Ma, Husain, & Bays, 2014; Myers, Chekroud, Stokes,
29 & Nobre, 2018; Wolff, Jochim, Akyurek, & Stokes, 2017; Ye et al., 2017; Ye et al., 2020; Ye
30 et al., 2019). However, the VWM capacity is extremely limited, so the visual system is often
31 exposed to demanding tasks that exceed its limits. Thus, mechanisms of selective attention
32 are needed to control access to VWM and to prioritize the existing VWM representations for
33 behavioral output.

34
35 Attentional prioritization in VWM has been extensively studied using retro-cues (Souza &
36 Oberauer, 2016). In a typical retro-cue experiment (Griffin & Nobre, 2003; Landman,
37 Spekrijse, & Lamme, 2003), participants are asked to remember a memory array for
38 subsequent reporting. During the interval between the memory array and the probe array, a
39 retro-cue is presented to indicate which item of the memory array is most likely to be tested.
40 The effect of the retro-cue on VWM performance is called the retro-cue effect and includes
41 retro-cue benefits and retro-cue costs. A retro-cue benefit refers to improved memory
42 performance resulting from a valid retro-cue condition (i.e., the location of the to-be-tested

43 item is indicated), and this can be calculated by the difference in behavioral performance
44 between the valid retro-cue condition and the neutral retro-cue condition. Conversely, a
45 retro-cue cost refers to impaired memory performance resulting from an invalid retro-cue (i.e.,
46 the location of an item that will not be tested is indicated), and this can be calculated as the
47 difference in behavioral performance between an invalid retro-cue condition and a neutral
48 retro-cue condition.

49

50 Recent studies have investigated the underlying mechanisms of the retro-cue effect by
51 examining whether this effect is modulated by the validity of the retro-cue (calculated as

52
$$\frac{\text{number of trials of valid cue condition}}{\text{number of trials of valid cue condition} + \text{number of trials of invalid cue condition}}$$
) (Günseli et al., 2019;

53 Günseli, van Moorselaar, Meeter, & Olivers, 2015). For example, by manipulating the
54 retro-cue validity, one behavioral study showed that retro-cue benefits were clearly observed
55 regardless of the retro-cue validity (Günseli et al., 2015). However, the retro-cue costs could
56 only be unambiguously identified when the retro-cue had high validity (i.e., 80% validity).

57 The retro-cue costs were minor for raw deviations (a metric for memory quality) and absent
58 for memory precision and memory probability when the retro-cue had low validity (i.e., 50%
59 validity). Based on the behavioral results, Günseli et al. (2015) suggested that when the cue
60 was relatively unreliable, the participants would prioritize the cued representation for
61 maintenance without dropping the non-cued representations. By contrast, when the cue was
62 highly reliable, in addition to prioritizing, the participants would drop the non-cued
63 representations during maintenance, thereby incurring obvious retro-cue costs when a
64 non-cued item was tested. That is, the mechanisms underlying retro-cue effects can be

65 strategically (or automatically) adjusted by the participants; therefore, the removal of the
66 non-cued representations from VWM will depend on the expected validity of the retro-cue.

67

68 A potential problem arises with the behavioral results of the retro-cue studies because many
69 additional innate processing stages, such as encoding, retrieval, and decision-making, may
70 also possibly affect the behavioral results of the VWM task. These extra processing stages
71 could potentially contribute to a behavioral outcome, thereby corrupting the measurement of
72 VWM storage (Keshvari, van den Berg, & Ma, 2013). Therefore, behavioral results may not
73 provide sufficiently strong evidence to confirm that retro-cue validity affects selective
74 attention and storage during VWM maintenance before the test probe. These behavioral
75 results complicate the unambiguous detection of the retro-cue effect in VWM.

76

77 One technique for tracking the VWM process online without potential contamination by other
78 processes is to use electroencephalograms (EEGs), and several researchers have previously
79 used EEGs to investigate the retro-cue effect (Goddertz, Klatt, Mertes, & Schneider, 2018;
80 Kuo, Stokes, & Nobre, 2012; Poch, Valdivia, Capilla, Hinojosa, & Campo, 2018; Schneider,
81 Barth, Getzmann, & Wascher, 2017). For example, lateralized alpha powers (8–14 Hz) and
82 contralateral delay activity (CDA) have been used as indicators of attention and VWM
83 maintenance. The lateralized alpha power is widely accepted as being able to track the locus
84 of covert visuospatial attention (Bacigalupo & Luck, 2019; Ikkai, Dandekar, & Curtis, 2016;
85 Klatt, Getzmann, Wascher, & Schneider, 2018; Poch, Capilla, Hinojosa, & Campo, 2017;
86 Poch et al., 2018; Sauseng et al., 2005; Thut, Nietzel, Brandt, & Pascual-Leone, 2006;

87 Worden, Foxe, Wang, & Simpson, 2000). The alpha power over the parietal-occipital
88 electrodes in the hemisphere contralateral to the attended item is reduced relative to the
89 ipsilateral electrodes, both during and after the perception, within VWM. Conversely, CDA is
90 an accepted metric for tracking VWM storage (Feldmann-Wustefeld, Vogel, & Awh, 2018;
91 Luria, Balaban, Awh, & Vogel, 2016; Vogel & Machizawa, 2004; Vogel, McCollough, &
92 Machizawa, 2005). CDA appears as a sustained negative waveform over the parietal-occipital
93 electrodes in the hemisphere contralateral to the remembered stimuli. The CDA amplitude is
94 thought to track the number of stored items in an online maintenance state within VWM.

95

96 A follow-up study on retro-cue validity by Günseli et al. (2019) used EEGs to measure the
97 VWM process during maintenance after retro-cue onset. The authors manipulated the validity
98 of retro-cues and asked participants to conduct a continuous report task. Their memory array
99 contained three different orientations: one presented on the vertical midline and the other two
100 presented left and right from the center. Two retro-cue validity conditions (80% validity and
101 50% validity) were included in their study. The behavioral results showed that the retro-cue
102 effect (error on the invalid cue trials – error on the valid trials) was larger under the
103 high-validity condition than under the low-validity condition. The EEG results showed
104 obvious lateralized alpha powers under both the high-validity and low-validity conditions, but
105 no difference was evident between the validity conditions at the beginning of the task.
106 However, at about 700 ms from the onset of the retro-cue, the lateralized alpha power under
107 the low-validity condition returned to baseline, resulting in a significant difference between
108 the low-validity and high-validity conditions in the latter part of the interval period.

109

110 These results suggested that participants paid attention to the cued item when the retro-cue
111 was presented under both low-validity and high-validity conditions, but they sustained
112 attentional prioritization for a longer period in the high-validity condition than in the
113 low-validity condition. The researchers also noted the emergence of an obvious CDA early
114 after the retro-cue in the high-validity state, whereas CDA in the low-validity state appeared
115 only later in the trial, just before the onset of the probe array. Importantly, this difference in
116 the CDA amplitude under conditions of high and low validity generally became apparent
117 early in the interval period, rather than later. The study by Günseli et al. (2019) requires that
118 the participants remember the stimuli of both the left and right hemifields simultaneously;
119 therefore, CDA could serve as an index for measuring asymmetrical maintenance in VWM.
120 That is, CDA should not be found when items are encoded/maintained equally in both
121 hemifields, whereas obvious CDA should appear if participants drop the non-cued
122 representations from online memory (unequal memory load in two hemifields). Thus, the
123 CDA results reported by Günseli et al. (2019) suggested that, although the process time
124 course may differ, the non-cued representations were eventually dropped from VWM under
125 both high-validity and low-validity conditions. This result seems inconsistent with the results
126 of the same group's earlier study (Günseli et al. 2015), which had suggested that participants
127 would continue to maintain the non-cued items when the retro-cue validity is low.

128

129 We propose two potential explanations for the evidence suggesting the prolonged
130 maintenance of non-cued items under the low-validity conditions, as observed by Günseli et

131 al. (2019). One is that those researchers used a continuous report task to measure VWM
132 performance. Consequently, their participants needed to memorize, with high precision,
133 orientations that were considered more complex than simple materials (e.g., colors) (Hao,
134 Becker, Ye, Liu, & Liu, 2018; Stevanovski & Jolicoeur, 2011; Vogel, Woodman, & Luck,
135 2006). The imposed task required that the participants report the target item as precisely as
136 possible, thereby encouraging the participants to concentrate all their VWM resources on one
137 item to maintain its representation with high precision. Thus, the participants had a strong
138 motivation to drop the non-cued representations from VWM.

139
140 The second explanation may be that Günseli et al. (2019) used a 50% valid retro-cue as the
141 low-validity condition. Compared to the chance level of 33% for memorizing three items and
142 detecting one of them, the participants could obtain the benefit of an extra 17% chance under
143 the low-validity condition if they used a retro-cue to remove the non-cued representations
144 from VWM. The choice of whether to maintain a non-cued representation in VWM may
145 represent a strategic control (or a result of implicit statistical learning); however, individual
146 differences exist in the control of these strategies adopted by participants under the 50%
147 validity condition. Quite possibly, even under a 50% validity condition, the participants could
148 use the same strategy (resource allocation mechanism) that they use under the high-validity
149 condition (80% validity). This would lead to the eventual removal of the non-cued
150 representations from VWM under the 50% validity condition. In that case, the retro-cue effect
151 would be caused by both retro-cue benefits (i.e., the strengthening of the cued representation)
152 and retro-cue costs (i.e., the loss of non-cued representations) under both the low-validity (50%

153 validity) and the high-validity (80% validity) conditions. Günseli et al. (2019) did not
154 establish a neutral cue condition in their study; consequently, they could not confirm this
155 second possibility because they could not identify whether the retro-cue effect was due to the
156 contribution of retro-cue benefits or retro-cue costs.

157

158 The aim of the present study was to test whether retro-cue validity affects the fate of
159 non-cued representations in VWM. We used EEGs to investigate how non-cued
160 representations are handled in VWM under different cue validity conditions. We also used an
161 improved experimental design to minimize the pitfalls apparent in the study by Günseli et al.
162 (2019). In our study, the participants conducted a change-detection task to remember four
163 colored squares that were symmetrically distributed on both the left and right visual fields.
164 We manipulated the validity of the retro-cue and recorded the EEG signals to explore the
165 prolonged selective attention and memory storage process after the onset of the retro-cue. The
166 impact of retro-cue validity was investigated by setting the validity of the retro-cue to 80%
167 valid (the high-validity state) and 20% valid (the low-validity state; this was slightly below
168 the chance level of 25%) across the experimental blocks. We set the cue validity to 20% valid
169 as the low-validity condition because we did not want participants to gain extra performance
170 benefits by allocating additional attention/memory resources to the cued item under the
171 low-validity condition. Therefore, under the low-validity condition, the participants should
172 not have a conscious motivation to allocate more resources to the cued item. On the contrary,
173 they should have a stronger motivation to allocate resources to the non-cued items under the
174 low-validity condition. In this case, if a retro-cue effect is still obvious under the low-validity

175 condition, this would suggest that the retro-cue effect may be partly driven by bottom-up
176 processes.

177

178 We also established the cause of the retro-cue effect by setting neutral cue trials to identify
179 the retro-cue benefit (i.e., better performance in valid cue trials than in neutral cue trials) and
180 the retro-cue cost (i.e., worse performance in valid cue trials than in neutral cue trials). Under
181 both the high-validity and low-validity conditions, we used lateralized alpha power to track
182 the prolonged selective attention and CDA to index VWM storage, as described by Günseli et
183 al. (2019). We determined the prolonged selective attention to the cued item by observing
184 whether a sustained lateralized alpha power emerged (i.e., whether a smaller alpha power
185 contralateral to the cued item was evident). For memory, we assumed that because
186 participants needed to encode and maintain the items in both hemifields at the same time, no
187 asymmetry would be apparent in the EEG signal (i.e., no CDA would emerge) if the
188 participants continued to maintain all items in VWM. By contrast, when non-cued items
189 (particularly those from the hemifield opposite the cued item) were dropped from memory,
190 CDA would be expected to emerge (i.e., a stronger negativity contralateral to the cued item
191 should be evident). We anticipated that the retro-cue would redirect selective attention to a
192 cued item under both the low-validity and high-validity conditions; however, the participants
193 would maintain the non-cued representations during the interval under the low-validity
194 condition while dropping them from VWM under the high-validity condition. Thus, we
195 expected to observe lateralized alpha power after the retro-cue appeared under both the
196 low-validity and high-validity conditions. We also expected to observe CDA only under the

197 high-validity condition and not under the low-validity condition.

198

199 **2. Methods**

200 **2.1. Participants**

201 Adequate power for the t-test comparison was ensured by a priori determination of the
202 sample size by a power analysis based on the predicted effect size using G*Power 3.1.9.2
203 (Faul, Erdfelder, Lang, & Buchner, 2007). According to the study by Berryhill, Richmond,
204 Shay, and Olson (2012), the difference between different cue conditions has a medium effect
205 size (e.g., Cohen's $d = 0.49$, for Experiment 3, Ignore mixed) for accuracy. Thus, we assumed
206 a medium effect size (Cohen's $d = 0.50$) for our experimental design. For a statistical power
207 of $(1 - \beta) = 0.80$ and a significance level of 0.05, the suggested total sample size was 34
208 participants. The suggested sample size in our study is slightly larger than the sample size
209 used in previous similar studies (i.e., 22 participants in the study by Günseli et al. (2015); 30
210 participants in the study by Günseli et al. (2019)).

211

212 In total, 38 students (16 males and 22 females) volunteered to take part in our experiment for
213 compensation. All participants were healthy and right-handed, with normal or
214 corrected-to-normal vision. No individuals reported achromatopsia, anomalous trichromatism,
215 or psychiatric disorders. Two of these 38 participants were excluded from further analysis
216 because of a ceiling effect in their behavioral performance (accuracy close to 100% in the
217 neutral cue), and another two were excluded because of extreme artifacts in their EEG data
218 (the number of available trials was less than 50 on either side of each validity). Ultimately,

219 data from 34 participants (19 females and 15 males) were used for the final statistical
220 analyses (mean age: 20.59 ± 1.76 years; range 18 to 25 years). All participants provided
221 written consent before enrollment in the study and received a monetary reward (25 CNY per
222 hour). All procedures in our study were conducted in accordance with the Declaration of
223 Helsinki (2008) and were approved by the Ethics Committee of Liaoning Normal University.

224

225 **2.2. Materials**

226 The experiment was programmed using E-prime software (E-prime 2.0, Psychology Software
227 Tools, Inc.). The color stimuli were four colored squares (each $1^\circ \times 1^\circ$), randomly chosen
228 from red (255,0,0), green (0,255,0), blue (0,0,255), yellow (255,255,0), white (255,255,255),
229 magenta (255,0,255), purple (128,0,128), orange (255,125,0), and turquoise (64,224,208). All
230 stimuli were displayed on a 19-inch CRT monitor (60 Hz) on a gray (128,128,128)
231 background at a viewing distance of 70 cm.

232

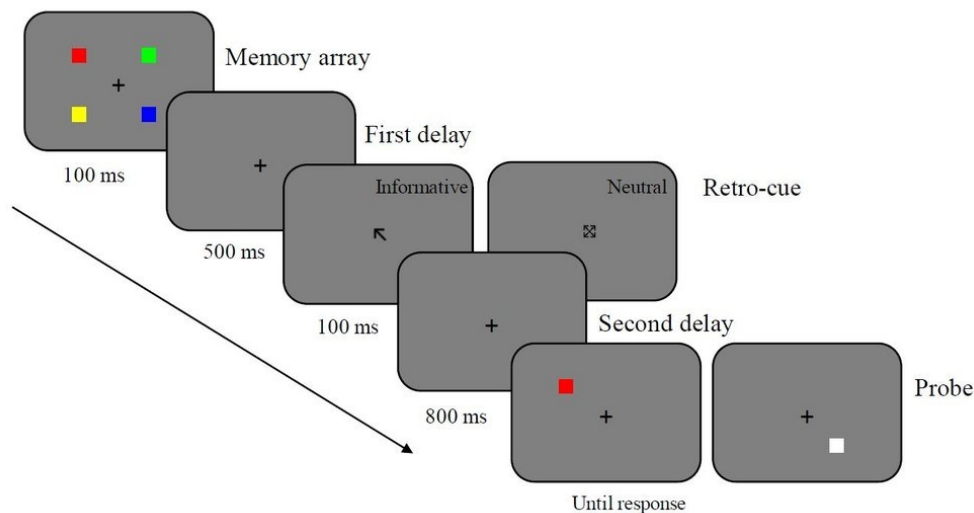
233 **2.3. Procedure**

234 The participants were asked to perform a change-detection task with a retro-cue. Two
235 different retro-cue types were used: an informative cue that pointed to the location of one
236 memory item and a neutral cue that pointed to all four locations of the memory items. The
237 validity (80% validity or 20% validity) of the informative retro-cue was manipulated under
238 different blocks for each participant.

239

240 The trial structures are depicted in Figure 1. Each trial began with a central fixation that

241 appeared for 200 ms. A memory array of colored squares was then presented at the corners of
 242 an invisible square ($5^\circ \times 5^\circ$) for 100 ms. The participants were instructed to memorize the
 243 colors of the four colored squares. After 500 ms had elapsed from the offset of the memory
 244 array (first delay), an informative retro-cue or a neutral cue was presented at the center for a
 245 duration of 100 ms. The cue was then followed by the rest of the retention interval (second
 246 delay), with a duration of 800 ms. After that interval, the participants were asked to indicate
 247 whether the probe stimulus was identical to the memory item (50%) or if the color had
 248 changed to a new color that had not appeared in the presented memory array at the
 249 corresponding location (50%). The next trial started at 800–1400 ms after the response.
 250 Before the task, participants were instructed to stare at the fixation, to minimize eye blinks,
 251 and to respond as accurately as possible. The retro-cue type was selected at random during
 252 each trial, based on the validity condition.



253
 254 **Fig. 1.** *Retro-cue experimental design. At the beginning of each trial, a new memory array,*
 255 *including four color items, was presented symmetrically. The participants were requested to*
 256 *remember the items and complete the change-detection task after a retro-cue. These*

257 *retro-cues came in two forms: informative (66.7%) and neutral (33.3%). The informative*
258 *retro-cue was divided into a valid cue and an invalid cue. The whole experiment consisted of*
259 *a high-validity (e.g., 80% validity) condition and a low-validity (20% validity) condition in*
260 *separate blocks.*

261

262 For each participant, the first half of the experiment consisted of one validity condition and
263 the other half consisted of the other validity condition. The high-validity and low-validity
264 conditions were blocked, and the order of the blocks was counterbalanced across participants.

265 A 2×3 repeated-measures design, including the within-subject factors of cue validity (high
266 vs. low) and cue type (neutral vs. valid vs. invalid), was employed in our experiment. We
267 manipulated the retro-cue validity (high-validity vs. low-validity) in two different blocks. The
268 total number of trials of each block was the same, but the ratio of valid cue trials (i.e.,
269 pointing to the location of the to-be-tested item) and invalid cue trials (i.e., pointing to the
270 location of a not-to-be-tested item) differed under different validity blocks.

271

272 Overall, 360 trials were run for each validity condition in the formal experiment. Each block
273 was divided into six mini-blocks of 60 trials each, with a break of at least 30 s between
274 mini-blocks and 2 min between blocks. Each mini-block consisted of 20 neutral trials and 40
275 informative retro-cue trials (32 valid cue trials and 8 invalid cue trials in the high-validity
276 condition; 8 valid cue trials and 32 invalid cue trials in the low-validity condition). We
277 ensured that participants were familiar with the formal experiment by informing them of the
278 validity of the retro-cues (80% validity for the high-validity condition and 20% validity for

279 the low-validity condition) and having them perform a practice block of 50 trials (including
280 10 neutral trials) before each validity block with the same validity as the block. In the
281 practice block, feedback about whether the response was correct or wrong was given after
282 each trial. In the formal experiment, feedback was provided regarding the overall accuracy
283 during each break. The participant was required to show an accuracy in the practice block
284 that exceeded 75% for the experiment to continue. The experiment took approximately 1 h.

285

286 **2.4. EEG recording**

287 The EEG data were recorded from a 64-electrode cap (BioSemi ActiveTwo, BioSemi Inc.,
288 Amsterdam, the Netherlands) using the International 10/20 System. Two additional electrodes
289 on both sides around the vertex (Cz) were used as the online reference and ground electrodes.
290 Electrodes were also placed on the right and left mastoid as off-line references. F7/F8 were
291 placed at the left and right outer corners, 1 cm away from the eyes, to monitor horizontal eye
292 movements (HEOG). Fpz was used to monitor vertical eye movements (VEOG). EEG signals
293 were amplified and digitized at a sampling rate of 512 Hz, with 24-bit resolution and no
294 online filter. Electrode impedances were kept below 5 k Ω .

295

296 **2.5. Data analysis**

297 A significance level of $p < 0.05$ was used for all tests. A repeated-measures ANOVA was
298 applied to test the effects of validity and cue type on accuracy. The assumption of sphericity
299 was assessed by Mauchly's tests, and the Greenhouse-Geisser correction was applied to
300 adjust the degrees of freedom for violations of sphericity. Partial eta squared (η^2_p) measures

301 were used for effect size estimations for the ANOVAs. The t-tests were conducted using a
302 bootstrapping method (SPSS Statistics Version 23; 10,000 permutations with 95% confidence
303 intervals). Cohen's d was used as an estimator of the effect size for the t-tests. We also used
304 JASP software (Version 0.16, JASP Team, 2021) to conduct Bayes factor analyses (Bayesian
305 t-test) to show whether the results favored the alternative hypothesis or the null hypothesis
306 (Rouder, Speckman, Sun, Morey, & Iverson, 2009). The default priors in JASP were used
307 (Schmalz, Biurrun Manresa, & Zhang, 2021). The Bayes factor (BF_{10}) provides an odds ratio
308 for the alternative/null hypotheses (values < 1 favor the null hypothesis and values > 1 favor
309 the alternative hypothesis). For example, a BF_{10} of 4 would indicate that the alternative
310 hypothesis is 4 times more likely than the null hypothesis to be correct, while a BF_{10} of 0.2
311 would indicate that the null hypothesis is 5 times more likely than the alternative hypothesis
312 to be correct. The results of CDA and lateralized alpha power were corrected for multiple
313 comparisons using false discovery rate (FDR) correction (Benjamini & Hochberg, 1995) at a
314 statistical threshold of $p < .05$ (MATLAB 2015b, MathWorks, Inc., Natick, MA). We also
315 calculated the two-tailed Pearson's correlation coefficients between the ERP indicators (CDA,
316 lateralized alpha power) and behavioral indicators (accuracy of each cue type, retro-cue
317 benefit index, and retro-cue cost index under high-validity condition or low-validity
318 condition).

319

320 *2.5.1. Behavioral data analysis*

321 The accuracy of three different cue types (valid, invalid, and neutral) in two validity blocks
322 was calculated to assess memory performance. A repeated-measures ANOVA with validity

323 condition (high-validity, low-validity) and cue type (valid, neutral, invalid) as within-subject
324 factors was conducted for accuracy. The interaction effects found in ANOVAs were followed
325 up using paired-samples *t*-tests (two-tailed) conducted for pairwise comparison of the
326 different cue types under both the high-validity and the low-validity conditions using
327 Bonferroni correction.

328

329 *2.5.2. EEG data preprocessing.*

330 We analyzed the EEG data from trials with neutral, valid, and invalid cues during VWM
331 maintenance. Off-line EEG data were processed in MATLAB (2015b, MathWorks, Inc.,
332 Natick, MA) using the EEGLAB toolbox 14.1.2 (Delorme & Makeig, 2004) and scripts. As
333 in the study by Günseli et al. (2019), the scalp EEG was band-pass filtered (cutoff
334 frequencies: 0.01 Hz and 40 Hz) and re-referenced off-line to the average of the left and right
335 mastoids. Continuous EEG data were epochal, from -500 ms to 2000 ms around the memory
336 array onset in each trial. Trials in which the EEG amplitude exceeded $\pm 50 \mu\text{V}$ at HEOG
337 (F7/F8) and $\pm 75 \mu\text{V}$ at PO7/PO8 and VEOG (Fpz) during the 0 to 1500 ms interval
338 (time-locked to the memory array onset) were deemed to contain artifacts and were rejected.
339 Additional blinks and eye or head movements were rejected based on visual inspection.
340 Subsequently, the epoch was based on the direction of the retro-cue (pointed to the left or
341 right side). Two participants were excluded from the final sample because they had fewer
342 than 50 trials on either side in each condition after artifact rejection. On average, we retained
343 91 ± 19 left-side epochs and 91 ± 18 right-side epochs per participant under high-validity
344 conditions and 92 ± 17 left-side epochs and 94 ± 16 right-side epochs per participant under

345 low-validity conditions for further analysis. We also investigated the effects of eye
346 movements on the EEG measures of interest and determined that eye movements were
347 unlikely to spuriously generate the EEG dynamics (CDA and lateralized alpha power) effect
348 we observed in the present study. More details are provided in the Supplementary Materials.

349

350 In the main text, we have mainly focused on the results of valid cue trials and invalid cue
351 trials. Upon further analysis, we reported only the EEG data of trials with informative
352 retro-cues in the Results section. The EEG results of neutral cue trials under different validity
353 conditions (which is not the focus of this paper) can be found in the Supplementary Materials.

354

355 *2.5.3. Analysis of CDA amplitudes*

356 As with some recent CDA studies (Feldmann-Wustefeld & Vogel, 2019; Feldmann-Wustefeld
357 et al., 2018; Hakim, Feldmann-Wüstefeld, Awh, & Vogel, 2020), we chose the PO7/PO8
358 electrodes for the analyses of CDA amplitudes, using a 200 ms prior to memory array onset
359 as the baseline (-200 to 0 ms, time-locked to the memory array onset). However, since CDA
360 has been shown to be present and large at many electrode pairs (McCollough, Machizawa, &
361 Vogel, 2007), many studies have used multiple electrode pairs for data analysis when
362 investigating the CDA component (Günseli et al., 2019; Günseli, Meeter, & Olivers, 2014;
363 Günseli, Olivers, & Meeter, 2014; Gao, Xu, et al., 2011; Gao, Yin, Xu, Shui, & Shen, 2011;
364 Hao et al., 2018; Ikkai, McCollough, & Vogel, 2010; Liang et al., 2020; Ngiam, Adam, Quirk,
365 Vogel, & Awh, 2021; Peterson, Gozenman, Arciniega, & Berryhill, 2015; Wang, Rajsic, &
366 Woodman, 2019; Ye et al., 2018; Ye, Zhang, Liu, Li, & Liu, 2014). We also chose the

367 multiple parietal-occipital electrode pairs (P5/P6, P7/P8, and PO7/PO8) to reanalyze our data
368 in the Supplementary Materials; the result pattern using multiple electrode pairs was highly
369 consistent with the result using the PO7/PO8 electrodes. More details are provided in the
370 Supplementary Materials. Hence, we only reported the results using the PO7/PO8 electrodes
371 in the main text.

372

373 For CDA, the contralateral waveforms were computed as the average of the activity recorded
374 at the left hemisphere electrode sites when the retro-cues (including valid and invalid cues)
375 pointed to the right side of the memory array and the average of the activity recorded from
376 the right hemisphere electrode sites when they pointed to the left side. The ipsilateral
377 waveforms were computed by averaging the left and right hemisphere sites when the cues
378 pointed to the left or the right side of the memory array, respectively. CDA was defined by
379 subtracting the ipsilateral activity from the contralateral activity.

380

381 We assumed that other memory and cognitive processes were present before the retro-cue
382 appeared. Thus, we chose to use the memory array onset with baseline correction during the
383 EEG analysis, as was done in some previous studies (Goddertz et al., 2018; Schneider et al.,
384 2017), and we focused on the stage of VWM maintenance after the onset of the retro-cue.
385 During the period before the probe array appeared, the participants did not know whether the
386 retro-cue in the trial was valid. The validity of the retro-cue in each trial was determined by
387 the probe array. The use of this design meant that we did not need to analyze the valid
388 retro-cue trials or the invalid retro-cue trials in the EEG data. Instead, we analyzed all trials

389 with an informative retro-cue (both valid and invalid) and compared the differences in the
390 EEG results between the informative retro-cue trials under the high-validity and low-validity
391 conditions.

392

393 Previous studies have shown that CDA can be observed 300–400 ms after retro-cue onset and
394 that it persists throughout maintenance (Günseli et al., 2019; Vogel & Machizawa, 2004;
395 Williams & Woodman, 2012). This established a time window of interest between 900 and
396 1500 ms (300–900 ms after retro-cue onset) in this study. The amplitudes of the different
397 waves (cue contralateral – cue ipsilateral) at each time point over the whole time window
398 (0–1500 ms) were calculated under high-validity or low-validity conditions. For the
399 within-condition testing, we conducted a two-tailed one-sample *t*-test against zero (Groppe,
400 Urbach, & Kutas, 2011) with false discovery rate (FDR) correction (Benjamini & Hochberg,
401 1995) at each time point to test for the presence of a significant lateralized component. The
402 mean amplitudes of CDA across the time window of interest (900–1500 ms) under the
403 high-validity and low-validity conditions were compared with the zero value by a one-sample
404 *t*-test.

405

406 Subsequently, for the between-condition testing, the *t*-tests (two-tailed, FDR correction) were
407 applied at each time point to compare the amplitude of the different waves under the
408 high-validity and low-validity conditions. The mean amplitudes of CDA across the time
409 window of interest (900–1500 ms) under the high-validity and low-validity conditions were
410 compared with the paired-samples *t*-test.

411

412 *2.5.4. Analysis of lateralized alpha power*

413 Similar to the analysis of the CDA component, we chose the PO7/PO8 electrodes for the
414 analyses of lateralized alpha power. As shown in the Supplementary Materials, we also chose
415 parietal-occipital electrode pairs (P5/P6, P7/P8, and PO7/PO8) to reanalyze our data; the
416 result pattern using multiple electrode pairs was highly consistent with the result using the
417 PO7/PO8 electrodes. We maintained consistency in the EEG analyses by only reporting the
418 results obtained using the PO7/PO8 electrodes here in the main text. We conducted a
419 time–frequency analysis of the alpha-band power by convoluting the trials that were the same
420 as the CDA analysis with a complex Morlet wavelet transform (width: seven cycles, from 1 to
421 30 Hz in 1 Hz increments). We used –300 to 0 ms relative to the memory array onset as the
422 baseline (L. Zhang, Peng, Zhang, & Hu, 2013; Z. G. Zhang, Hu, Hung, Mouraux, & Iannetti,
423 2012). As with the CDA analysis, the lateralized alpha power was calculated as the difference
424 between the contralateral and ipsilateral dB-normalized power values. The power values were
425 averaged across the alpha band (8–14 Hz), and we selected a time window of interest of
426 900–1500 ms (300–900 ms after retro-cue onset). The power of the lateralized alpha band at
427 each time point was calculated under both conditions and analyzed by a one-sample *t*-test
428 (two-tailed) with FDR correction over the time window. The power difference of the
429 lateralized alpha band between the high-validity and low-validity conditions was compared
430 by paired-samples *t*-tests (two-tailed, FDR correction). The mean power of the lateralized
431 alpha band during the time window under the high-validity and low-validity conditions was
432 compared with the zero value by a one-sample *t*-test, whereas the difference between the two

433 validity conditions was compared with the paired-samples t-test.

434

435 We also replicated the analysis of previous studies (L. Zhang et al., 2013; Z. G. Zhang et al.,
436 2012) by providing an extra analysis of CDA and the lateralized alpha power using the time
437 window prior to retro-cue onset for baseline correction (see Supplementary Material). We
438 generally observed highly consistent results for both CDA and the lateralized alpha power,
439 regardless of the baseline correction analysis employed.

440

441 *2.5.5. Correlation analysis*

442 We assessed the ability of the EEG signal (CDA/lateralized alpha power) to predict
443 behavioral performance and whether CDA and lateralized alpha power influenced each other
444 or were independent during VWM. We first calculated the mean CDA amplitude and the
445 mean lateralized alpha power under each validity condition in the time window of interest
446 (900–1500 ms) for each participant. We then applied Pearson correlation (two-tailed) analysis
447 to investigate the relation between behavioral indicators (the accuracy of the valid cue and
448 invalid cue types, the retro-cue benefit index [valid – neutral], and the retro-cue cost index
449 [neutral – invalid]) and EEG indicators (CDA amplitude and lateralized alpha power). We
450 also calculated the Pearson’s correlation (two-tailed) between CDA amplitude and the
451 lateralized alpha power.

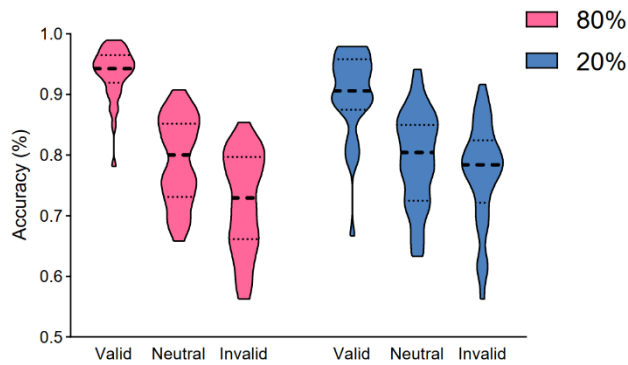
452

453 **3 Results and discussion**

454 *3.1. Behavioral results*

455 The accuracies in each cue type for the high-validity and low-validity conditions are shown in
456 Figure 2. The ANOVA showed a significant main effect of cue type ($F(1.586, 52.345) =$
457 $146.765, p < .001, \eta_p^2 = .816$) and a significant interaction between the cue type by validity
458 condition ($F(2, 66) = 18.237, p < .001, \eta_p^2 = .356$), but we found no significant main effect of
459 validity condition ($F(1, 33) = 0.617, p = .438, \eta_p^2 = .018$). The paired-samples t -tests revealed
460 significantly higher accuracy for the valid cue trials (0.935 ± 0.043 for high validity; $0.902 \pm$
461 0.068 for low validity) than for the neutral cue trials (0.792 ± 0.071 for high validity; $0.794 \pm$
462 0.079 for low validity) under both the high-validity condition ($t(33) = 14.200, p < .001, 95\%$
463 $CI [0.123, 0.164], d = 2.434, BF_{10} > 10000$) and the low-validity condition ($t(33) = 7.837, p$
464 $< .001, 95\% CI [0.080, 0.136], d = 1.344, BF_{10} > 10000$). The accuracy was significantly
465 greater for the neutral cue trials than for the invalid cue trials (0.722 ± 0.082 for high validity;
466 0.770 ± 0.084 for low validity) under both the high-validity condition ($t(33) = 6.246, p < .001,$
467 $95\% CI [0.047, 0.092], d = 1.071, BF_{10} > 10000$) and the low-validity condition ($t(33) =$
468 $2.636, p = .038, 95\% CI [0.005, 0.041], d = 0.452, BF_{10} = 3.529$). By contrast, the accuracy
469 was significantly greater for the valid cue trials under the high-validity condition than under
470 the low-validity condition ($t(33) = 3.850, p = .0015, 95\% CI [0.016, 0.051], d = 0.660, BF_{10}$
471 $= 57.824$), whereas the accuracy was significantly lower for the invalid cue trials under the
472 high validity condition than under the low validity condition ($t(33) = 3.535, p = .0037, 95\%$
473 $CI [-0.075, -0.020], d = 0.606, BF_{10} = 26.585$). No significant difference was noted in the
474 accuracy of the neutral cue trials between the high-validity and the low-validity condition (t
475 $(33) = 0.211, p = .834, 95\% CI [-0.018, 0.015], d = 0.036, BF_{10} = 0.188$). These results
476 indicated that significant retro-cue benefits were obtained from the valid cues and significant

477 retro-cue costs were incurred from the invalid cues under both the high-validity and
478 low-validity conditions. The retro-cue benefits and the retro-cue costs were also larger under
479 the high-validity condition than under the low-validity condition.



480 **Fig. 2.** *Violin plots of the behavioral performance for the high-validity condition (80%*
481 *validity, pink) and the low-validity condition (20% validity, blue). The dashed line and two*
482 *dotted lines indicate the median and the two quartiles.*

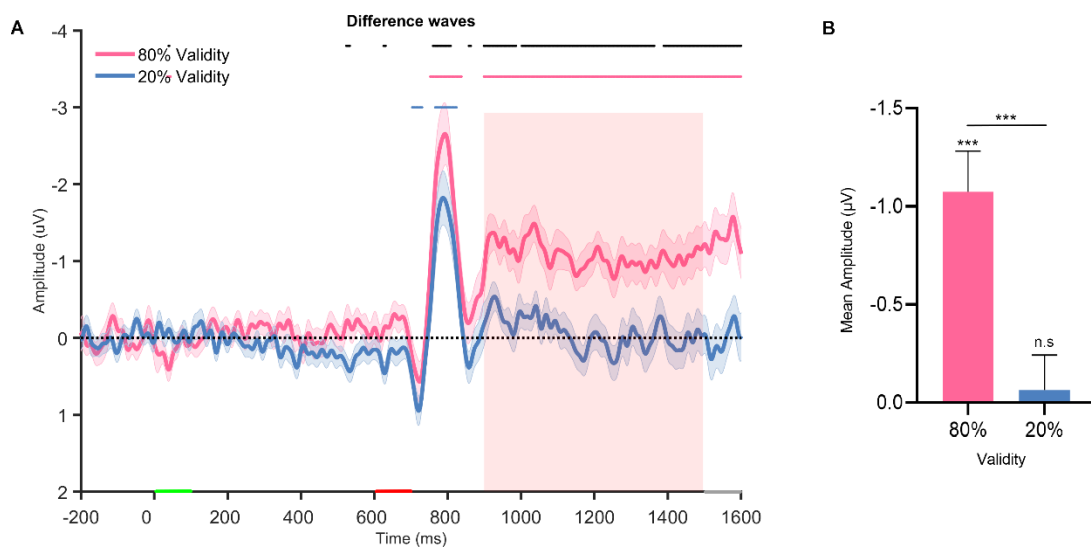
484 3.2. CDA results

485 Figure 3 shows the CDA amplitude results and the grand-averaged difference waveform of
486 the retro-cue trials under the high-validity and low-validity conditions. For the
487 within-condition testing, each time point from 0–1600 ms was corrected against zero using
488 the false discovery rate (FDR) at a statistical threshold of $p < .05$. No significant difference
489 was observed for the waves under either validity condition or between conditions before the
490 retro-cue onset, indicating that no lateralized ERP component was present before the
491 retro-cue under either validity condition. Significant CDA was observed after a retro-cue with
492 a high-validity (898–1600 ms, FDR-corrected of $p < .05$) rather than a low-validity retro-cue.
493 Studying the time window of interest of 900–1500 ms revealed that the mean CDA amplitude

494 under the high-validity condition was significantly different from zero ($t(33) = 5.174$, p
 495 $<.001$, 95% CI [-1.483, -0.671], $d = 0.887$, $BF_{10} = 1890.109$), suggesting that CDA was
 496 present under the high-validity condition during the entire retaining period after the retro-cue.
 497 However, the mean CDA amplitude did not differ from zero under the low-validity condition
 498 ($t(33) = 0.362$, $p = .720$, 95% CI [-0.428, 0.299], $d = 0.062$, $BF_{10} = 0.195$), suggesting the
 499 absence of any obvious CDA component under the low-validity condition.

500

501 For the between-condition testing, the FDR-corrected results for the time window from
 502 900–1600 ms also showed a statistically significant difference (shown as the black bar,
 503 FDR-corrected of $p < .05$) in CDA amplitude between the two validity conditions over the
 504 time courses of 898–986 ms, 1002–1063 ms, and 1389–1600 ms. The mean CDA amplitude
 505 was larger under the high-validity condition than under the low-validity condition ($t(33) =$
 506 3.748 , $p = .001$, 95% CI [-1.525, -0.471], $d = 0.643$, $BF_{10} = 44.886$). These results suggested
 507 that the participants maintained the non-cued items during the interval under the low-validity
 508 condition but dropped them from VWM under the high-validity condition, as expected.



509

510 **Fig. 3** *Difference waves during the entire time window and the CDA amplitude results. (A)*
511 *Mean ERP difference waveforms time-locked to the onset of the memory array under the*
512 *high-validity condition (80% validity) and the low-validity condition (20% validity). The*
513 *green, red, and gray rectangles on the x-axis show the timing of the memory array (0–100*
514 *ms), retro-cue (600–700 ms), and probe (1500–1600 ms), respectively. The red shadow shows*
515 *the time window of interest (900–1500 ms). The shadow of the curve indicates the standard*
516 *error of the estimate. The black lines along the tops of the waves indicate a significant*
517 *difference in amplitude over the entire time course between the 80% validity and 20% validity*
518 *conditions. The pink lines along the top of the waves indicate an amplitude significantly*
519 *larger than zero under the 80% validity condition over the entire course. The blue lines along*
520 *the top of the waves indicate an amplitude significantly larger than zero under the 20%*
521 *validity condition over the entire time course; (B) The mean CDA amplitude results*
522 *(900–1500 ms) under the high-validity and the low-validity conditions are displayed as pink*
523 *and blue bars, respectively (Error bar: SE). ** = $p < .01$; *** = $p < .001$; n.s. = not*
524 *significant.*

525

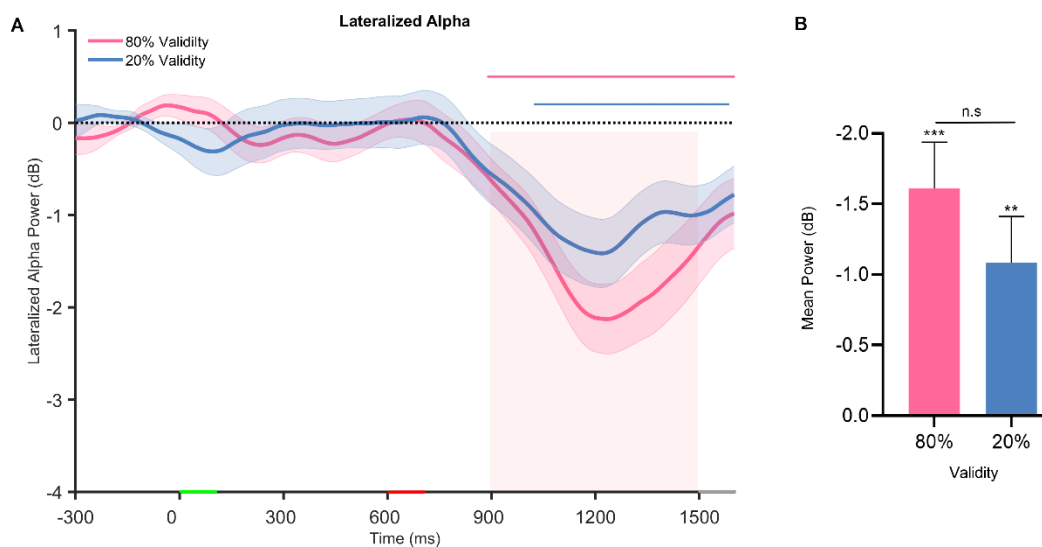
526 **3.3. Lateralized alpha power results**

527 Figure 4 illustrates the lateralized alpha power results and the grand-averaged lateralized
528 alpha power of the retro-cue trials under the high-validity and low-validity conditions. For the
529 within-condition testing, the lateralized alpha power was detected over the entire maintenance
530 period after the retro-cue under the high-validity condition (890–1600 ms, one-sample t-test
531 with an FDR-corrected p-value of 0.05). Most time points after the retro-cue appeared under

532 the low-validity condition (1025–1600 ms, one-sample t-test with an FDR-corrected p-value
533 of 0.05). Studying the time window of 900–1500 ms revealed that the mean lateralized alpha
534 power across the time window was significantly different from zero under both the
535 high-validity condition ($t(33) = 4.923, p < .001, 95\% \text{ CI} [-2.275, -1.006], d = 0.844, \text{BF}_{10} =$
536 957.937) and the low-validity condition ($t(33) = 3.316, p = .002, 95\% \text{ CI} [-1.750, -0.419], d$
537 $= 0.569, \text{BF}_{10} = 15.782$), suggesting an obvious lateralized alpha power under both the
538 high-validity and low-validity conditions.

539

540 For the between-condition testing, no difference in lateralized alpha power was detected
541 between the high-validity and low-validity conditions at any time point (FDR-corrected of p
542 $< .05$). For the mean lateralized alpha power, no significant difference was detected over the
543 time window of interest (900–1500 ms) between the two validity conditions ($t(33) = 1.295, p$
544 $= .204, 95\% \text{ CI} [-1.359, 0.243], d = 0.222, \text{BF}_{10} = 0.395$). As expected, these results
545 suggested that retro-cues redirect selective attention to the cued item under both the
546 low-validity and the high-validity conditions.



547

548 **Fig. 4.** *The lateralized alpha power waves and their mean power during the time window of*
549 *interest. (A) Mean lateralized alpha power time-locked to the onset of the memory array for*
550 *the high-validity condition (80% validity) and the low-validity condition (20% validity). The*
551 *green, red, and gray rectangles on the x-axis show the timing of the memory array (0–100*
552 *ms), retro-cue (600–700 ms), and probe (1500–1600 ms), respectively. The red shadow shows*
553 *the time window of interest (900–1500 ms). The shadow of the curves is the standard error of*
554 *the estimate. The black lines along the top of the waves indicate a significant difference in*
555 *amplitude over the time course between the 80% validity and 20% validity conditions (the*
556 *absence of a black line indicates no significant difference). The pink lines along the top of the*
557 *waves indicate that the amplitude under the 80% validity condition is significantly larger*
558 *than zero over the time course. The blue lines along the top of the waves indicate that the*
559 *amplitude under the 20% validity condition is significantly larger than zero over the time*
560 *course. (B) The mean power of the lateralized alpha band (900–1500 ms) under the*
561 *high-validity and low-validity conditions is displayed as pink and blue bars, respectively*
562 *(Error bar: SE). ** = $p < .01$; *** = $p < .001$; n.s = not significant.*

563

564 **3.4. Correlation results**

565 The EEG results showed no correlation between the CDA amplitude and the lateralized alpha
566 power under either validity condition ($r(34) = -0.023$, $p = .899$ for high validity; $r(34) =$
567 0.115 , $p = .519$ for low validity). Similarly, no significant correlation was detected between
568 the CDA amplitude and the mean accuracies among the valid and invalid cues under either
569 validity condition (high-validity: all $p > .338$; low-validity: all $p > .052$) or between the

570 lateralized alpha power and the mean accuracies under either validity condition (high-validity:
571 all $p > .318$; low-validity: all $p > .234$). The results showed no significant correlation between
572 the retro-cue benefit/cost index and the CDA amplitude (high-validity: all $p > .510$;
573 low-validity: all $p > .258$). Similarly, no significant correlation was detected between the
574 lateralized alpha power and the retro-cue benefit/cost index under either validity condition
575 (high-validity: all $p > .556$; low-validity: all $p > .466$). Taken together, our findings provided
576 no evidence of any significant correlation between the behavioral performance, CDA
577 amplitude, and lateralized alpha power under either the high-validity or the low-validity
578 conditions. That is, the correlation analyses did not show any evidence that the CDA
579 amplitude could be predicted by the alpha-band power or by behavioral performance.

580

581 *3.5. Exploratory analysis*

582 A visual inspection of the difference waveforms (Fig 3A) suggested that an N2pc component
583 was elicited after the onset of a retro-cue under both validity conditions. An N2pc is usually
584 observed at the posterior electrode on the contralateral side of the target position at 200 ms
585 after the lateralization stimulus onset, and it reflects the spatial attention placed on the target
586 location. Previous work has shown that an N2pc is more negative when elicited by the target
587 item than by the non-target items when multiple items are presented (Eimer, 1996; Luck &
588 Hillyard, 1994a, 1994b; Zhao et al., 2011). A relatively common practice is to interpret the
589 N2pc (180–320 ms) as an index of the deployment of covert lateraled visual attention (Kiss,
590 Van Velzen, & Eimer, 2008) or of the onset of attentional engagement (Zivony, Allon, Luria,
591 & Lamy, 2018). Therefore, based on our visual inspection, and similar to previous studies

592 using CDA (Allon & Luria, 2019; Feldmann-Wustefeld & Vogel, 2019), we conducted
593 exploratory analyses to explore the N2pc components under our different conditions.

594

595 The preprocessing and calculation of the amplitudes of the difference waveforms of the N2pc
596 component were conducted essentially as described for the CDA component. In the present
597 study, the FDR-corrected results showed that the N2pc was averaged from the difference
598 wave at the PO7/PO8 electrodes during the 780–880 ms after the memory array onset
599 (180–280 ms after the retro-cue onset) for each condition. One-sample t-tests were applied to
600 detect whether a significant N2pc was elicited, and a paired-samples t-test was applied to
601 detect whether the N2pc amplitude showed a significant difference under the different
602 validity conditions. The correlation between the N2pc and the CDA/lateralized alpha power
603 was also analyzed using the Pearson correlation. Note that we have no a priori assumptions
604 about the N2pc in this research; therefore, these findings should be interpreted with caution.

605

606 The N2pc was also measured under the high-validity and low-validity conditions (i.e., 80%
607 validity and 20% validity, respectively) as the difference in the mean amplitude between the
608 ipsilateral and contralateral waveforms recorded at the analyzed electrodes (PO7/PO8)
609 (Feldmann-Wustefeld & Vogel, 2019; Luck & Hillyard, 1994a, 1994b) at 780–880 ms after
610 memory array onset (180–280 ms after the retro-cue onset).

611

612 Significant N2pc components were found after the high-validity retro-cue ($M = -1.277 \pm$
613 1.543 ; $t(33) = 4.822$, $p < .001$, 95% CI $[-1.797, -0.770]$, $d = 0.827$, $BF_{10} = 730.289$) and the

614 low-validity retro-cue ($M = -0.674 \pm 1.186$; $t(33) = 3.315$, $p = .002$, 95% CI [-1.103, -0.312],
615 $d = 0.568$, $BF_{10} = 15.750$), suggesting that the N2pc component was reliably observed under
616 both validity conditions. The N2pc amplitude was significantly larger under the high-validity
617 condition than under the low-validity condition ($t(33) = 2.549$, $p = .016$, 95% CI [-1.046,
618 -0.134], $d = 0.437$, $BF_{10} = 2.960$). These results indicated that a retro-cue could redirect the
619 participants' attention to the cued hemifield, regardless of the validity of the retro-cue. By
620 contrast, more attention resources were allocated to cued items after a more reliable retro-cue
621 appeared.

622
623 Significant positive correlations were detected between the N2pc amplitude and the CDA
624 amplitude in the 80% validity ($r = .536$, $p = .001$) and 20% validity conditions ($r = .473$, p
625 $= .005$), whereas no significant correlation was found between the N2pc and the lateralized
626 alpha power under either validity condition (all $p > .055$). We also did not find any significant
627 correlation between the N2pc amplitude and memory recognition performance (all $p > .323$)
628 or between the N2pc amplitude and the retro-cue benefit/retro-cue cost index (all $p > .140$)
629 for either validity condition.

630

631 **4. General discussion**

632 In the present study, we tested whether the retro-cue validity affects the fate of non-cued
633 representations in VWM. We found significant retro-cue benefits and retro-cue costs for the
634 behavioral results under both the high-validity and low-validity conditions. More importantly,
635 for the EEG results, although the retro-cue could redirect selective attention to the cued

636 hemifield under both low-validity and high-validity conditions, the participants maintained
637 the non-cued items during the interval under the low-validity condition, whereas they
638 dropped them from VWM under the high-validity condition.

639

640 *4.1. Retro-cues work in both top-down and bottom-up processes*

641 Our behavioral results demonstrate the retro-cue effects occurring under both high-validity
642 and low-validity conditions. A previous study indicated that the retro-cue effect persists even
643 when the cue validity is set at the chance level (Berryhill et al., 2012). Similarly, our results
644 demonstrate a retro-cue benefit for a valid cue even when the cue validity was set below the
645 chance level (20%). This suggests that a retro-cue could automatically guide attention even
646 when the cue was disadvantageous (i.e., it cues an item that is likely to be irrelevant). Our
647 EEG results also support this suggestion. The retro-cue clearly could guide participants'
648 attention under the high-validity condition; however, an obvious lateralized alpha power and
649 the N2pc component were also observed after retro-cue appearance under the low-validity
650 condition, similar to those under the high-validity condition. These results indicate that the
651 retro-cue effect is not fully under optimal strategic control. Under the low-validity condition,
652 the optimal strategy was to allocate similar/fewer resources to the cued item compared to the
653 non-cued items, indicating an imperfect resource allocation mechanism. Our work revealed
654 that retro-cues can be used partly in a bottom-up manner (i.e., stimulus-driven).

655

656 A natural question also arises regarding the possibility that the impact of cue validity on the
657 retro-cue effect is also affected by top-down control. Our results showed that both the

658 retro-cue benefit and retro-cue cost were larger under the high-validity condition than under
659 the low-validity condition. That is, the expectation of cue validity had an impact on the
660 degree of the retro-cue effect. In addition, a difference was evident in the mechanisms
661 underlying the retro-cue effect between the high-validity and low-validity conditions. These
662 results suggest that the impact of cue validity on the retro-cue effect was at least partly caused
663 by top-down control.

664

665 Two possible top-down control methods could explain our results. One is strategic control. In
666 our experiment, the participants were informed in advance of the cue validity (i.e., 20% or
667 80%) in each validity condition, and they were allowed sufficient practice before performing
668 the formal experiment. Therefore, the expectation of cue validity can lead the participants to
669 use the retro-cue strategically. The other possible control method is implicit statistical
670 learning. In this case, the participants automatically carried out implicit statistical learning
671 during the experiment and formed an optimal memory mechanism (e.g., whether to keep the
672 non-cued items in VWM) to obtain better performance. Future studies can test these two
673 possibilities by intermixed vs. blocked reliability manipulation or by controlling whether the
674 participants are informed of the cue validity in advance.

675

676 **4.2. *Impact of retro-cue validity on EEG dynamics***

677 We noted discrepancies between the impact of retro-cue validity on CDA and the lateralized
678 alpha power. An obvious CDA component was found under the high-validity condition but
679 was absent under the low-validity condition. This demonstrates that, based on the expectation

680 of retro-cue validity, the participants could store only the cued representation in the online
681 maintenance state within VWM under the high-validity condition, whereas they could store
682 both the cued and the non-cued representations in VWM under the low-validity condition.
683 Thus, our CDA results can be regarded as supplementary EEG evidence for the EEG results
684 reported by Günseli et al. (2015).

685
686 For the lateralized alpha power results, although our results and those reported by Günseli et
687 al. (2019) suggest that the participants shifted their attention to the cued item after the
688 retro-cue appeared, regardless of the cue validity, some small differences are still apparent
689 between our results and the results reported by Günseli et al. (2019). In contrast to the
690 findings of Günseli et al. (2019), we found a similar and sustained lateralized alpha power
691 during VWM maintenance after the retro-cue onset and until the onset of the probe array
692 under both the high-validity and low-validity conditions. Günseli et al. (2019) reported that,
693 regardless of retro-cue validity, the lateralized alpha power disappeared before the probe
694 array onset under both the high-validity and low-validity conditions. The difference in the
695 duration of the lateralized alpha power between our study and theirs may reflect the
696 differences in experimental design. In our study, we used a change-detection task, which
697 required participants to allocate their attention to the location of the probe stimulus and then
698 compare it with the memory item after the probe array appeared. By contrast, Günseli et al.
699 (2019) used a continuous report task, which required participants to reallocate their attention
700 to the center of the screen to adjust the probe item after the probe array appeared. In our study,
701 the participants would focus steadily on the cued item's position to complete the task, leading

702 to sustained lateralized alpha power. Conversely, the participants in the study by Günseli et al.
703 (2019) would shift their attention back to the center of the screen after they had allocated
704 attention to the cued item. This would lead to a lateralized alpha power that would emerge
705 only during early maintenance and then vanish. Therefore, the differences observed in the
706 lateralized alpha power results between our study and that by Günseli et al. (2019) could be
707 due to differences in the setting of the probe array.

708

709 **4.3. *Attention and storage are two distinct processes in VWM***

710 In the present study, the lateralized alpha power reflects the selective attention of the
711 participants, while the N2pc component reflects the attention redirection of the participants.
712 However, we did not find any significant correlation between the lateralized alpha power and
713 the N2pc component. This result was in line with the findings of a recent study (Bacigalupo
714 & Luck, 2019), which found that the lateralized alpha power and the N2pc have different
715 time courses and influence mechanisms, suggesting that they reflect a related but distinct
716 attention mechanism. The lateralized alpha power was of greater interest in the present study
717 because of its similar time course to that of the CDA component.

718

719 The idea that attention can predict storage in VWM remains controversial. Some studies have
720 shown a correlation between CDA and lateralized alpha power (van Dijk, van der Werf,
721 Mazaheri, Medendorp, & Jensen, 2010), but a growing number of studies now suggest that
722 the neural mechanism of CDA and lateralized alpha power are separated within VWM (Bae
723 & Luck, 2018; Fukuda, Mance, & Vogel, 2015; Günseli et al., 2019; Hakim, Adam, Günseli,

724 Awh, & Vogel, 2019). Lateralized alpha power is considered a good metric for measuring
725 prolonged selective attention, and CDA reliably predicts representative storage levels.
726 Günseli et al. (2019) observed a dissociation between the CDA amplitude and lateralized
727 alpha power with the retro-cues of different reliabilities in a continuous report task. In
728 corroboration with their findings, we failed to observe any correlation between the CDA
729 amplitude and lateralized alpha power, regardless of the cue validity. Especially under the
730 low-validity condition, we detected obvious lateralized alpha power but no CDA component.
731 These results again support the idea that storage and prolonged selective attention in VWM
732 are two distinct processes that can operate differently, depending on the needs of the task.

733

734 In addition to indicating a relation between prolonged selective attention and storage, our
735 results showed a positive correlation between the N2pc amplitude and the CDA amplitude,
736 regardless of the cue validity. These results were in line with the findings reported by Salahub
737 and Emrich (2020). Our results demonstrate that an increased likelihood of dropping a
738 non-cued representation in VWM (as indicated by the CDA) is associated with an increased
739 reallocation of attention to the cued item (as indicated by the N2pc). Therefore, although
740 prolonged selective attention and storage are two distinct processes, the process of redirection
741 of attention could predict the process of VWM storage.

742

743 *4.4. Different mechanisms for the retro-cue effect under different expectations of cue* 744 *validity*

745 As predicted, the mechanisms underlying the retro-cue effect varied depending on the cue

746 validity. Previous studies have proposed different hypotheses to explain the cause of the
747 retro-cue effect (Souza & Oberauer, 2016). Our results suggest that, under the high-validity
748 condition, the participants redirected their attention to the cued item and allocated VWM
749 resources to it, while reducing or removing memory resources from the non-cued items.
750 Therefore, under the high-validity condition, the participants could gain significant retro-cue
751 benefits from the valid cue. This mechanism could be considered consistent with a removal
752 hypothesis, suggesting that retro-cues can help to reduce memory load by removing non-cued
753 items from VWM, thereby freeing up VWM resources to maintain the cued item (Goddertz et
754 al., 2018; Kuo et al., 2012; Poch et al., 2018; Williams, Hong, Kang, Carlisle, & Woodman,
755 2013).

756
757 By contrast, under the low-validity condition, although the participants in our study could
758 still redirect their selective attention to the cued item, they allocated equal VWM resources to
759 the cued item and to other non-cued items in an attempt to maintain all items to the greatest
760 extent possible. In this case, the participants could still significantly gain retro-cue benefits
761 from the valid cue. These results would appear to refute the removal hypothesis.

762
763 The mechanism of the retro-cue effect could instead be interpreted by an attentional
764 strengthening hypothesis, suggesting that attention is redirected to augment the accessibility
765 of cued representations in VWM (Goddertz et al., 2018; Kuo et al., 2012; Poch et al., 2018;
766 Williams et al., 2013). However, this attentional strengthening hypothesis does not
767 specifically state what happens to the non-cued representations. That is, the attentional

768 strengthening hypothesis does not preclude the possibility that an additional mechanism also
769 operates on the non-cued items. Thus, the maintenance of non-cued representations under the
770 low-validity condition does not conflict with the attentional strengthening hypothesis.

771

772 The key to testing the removal hypothesis is to investigate whether participants drop the
773 non-cued representations from VWM after the retro-cue appears. The study of Günseli et al.
774 (2019) showed ERP evidence (i.e., the CDA component) supporting the removal hypothesis
775 (i.e., the participants eventually dropped the non-cued representations from VWM) under
776 both high-validity and low-validity conditions. By contrast, we found ERP evidence
777 supporting the removal hypothesis only under the high-validity condition.

778

779 The difference between the findings of Günseli et al. (2019) and our results under the
780 low-validity condition may stem from the fact that we used a below-chance level (20%
781 validity) as the low validity to reduce strategy conflicts caused by ambiguous validity (50%
782 validity), thereby amplifying the underlying mechanism of low validity. This is in line with
783 the inference that participants might take a longer time to change the status of non-cued items
784 under a 50% valid condition (i.e., the low-validity condition used by Günseli et al. (2019)).

785

786 One point to consider is that we only found EEG evidence supporting or rejecting the
787 removal hypothesis at the group level. By contrast, at the individual level, we found no
788 significant correlation between EEG results and any of the behavioral measures. Thus, our
789 results did not really allow disentanglement of the extent to which the behavioral retro-cue

790 benefit/cost is due to prolonged selective attention (i.e., lateralized alpha power) or to
791 removal of non-cued items from VWM (i.e., a CDA effect). However, the lack of a
792 significant correlation between the EEG and behavioral results could have several
793 explanations. For example, the behavioral results in the change-detection task are affected by
794 the VWM process, but they are also influenced by the decision-making process. The need for
795 extra processing stages could potentially contribute to a behavioral outcome. This may
796 explain why behavioral indicators are less sensitive than EEG indicators (i.e., CDA) for
797 reflecting the representations of VWM storage. In addition, because our experimental design
798 mainly focuses on the results of group-level comparisons, the failure to find a significant
799 correlation may be due to the limited number of participants. Therefore, the findings
800 regarding a relationship between EEG results and the retro-cue benefit/cost should be
801 interpreted with caution.

802

803 We also found that although our participants maintained the non-cued representations in
804 VWM under the low-validity condition, the accuracy was significantly lower for the invalid
805 cue trials than for the neutral cue trials. Günseli et al. (2015) similarly found a minor
806 detriment in memory quality from invalid retro-cues under the low-validity condition. In our
807 study, the retro-cue costs under the low-validity condition could also be explained by the
808 protection-during-retrieval hypothesis (Makovski & Jiang, 2007, 2008; Makovski & Pertzov,
809 2015; Makovski, Sussman, & Jiang, 2008), which suggests that the redirection of selective
810 attention to the cued item makes VWM representations more resistant to visual interference
811 from the probe stimulus. Thus, the non-cued items that are not protected by prolonged

812 selective attention are more vulnerable to impairment after the probe stimulus appears,
813 resulting in retro-cue costs from the invalid cues. Notably, we used a change-detection task.
814 The probe stimulus was presented in the same position as the memory item, which led to new
815 visual interference when the probe array appeared (Makovski & Jiang, 2007).

816

817 Taken together, our study findings provide new EEG evidence for different mechanisms
818 underlying the retro-cue effect. Importantly, these mechanisms are determined by the
819 expectation of cue validity and by the chosen experimental parameters.

820

821 **5. Conclusion**

822 Our study results suggest that the maintenance of non-cued representations in VWM is
823 affected by the cue validity. When the retro-cue validity is high, individuals will drop the
824 non-cued items from VWM to strengthen their maintenance of the cued item. By contrast,
825 when the retro-cue validity is low, individuals are more likely to maintain both the cued and
826 non-cued items in VWM, but they prioritize the cued item by attention. The maintenance of
827 the non-cued representations in VWM may be driven in part by strategy or it may be a result
828 of implicit statistical learning. Our study provides new EEG evidence for the previous
829 hypotheses of the retro-cue effect and reconciles previous discrepant results. This research
830 provides an important theoretical basis for further exploration of the relationship between
831 attention and working memory.

832

833

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840

841 **Data Availability**

842 The datasets generated/analyzed during this study and experimental script have been added to
843 <https://osf.io/qtwc9/>.

844

845 **Author contributions**

846 **Xueying Fu:** Conceptualization, Methodology, Software, Validation, Formal analysis,
847 Investigation, Resources, Data curation, Visualization, Project administration, Writing -
848 Original Draft, Writing - Review & Editing; **Chaoxiong Ye:** Conceptualization, Methodology,
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850 acquisition, Writing - Original Draft, Writing - Review & Editing; **Zhonghua Hu:**
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853 Writing - Review & Editing.

854

855

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