Comparing retro-cue benefit mechanisms in visual working memory: Completely valid vs. highly valid retro-cues

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Abstract

Visual working memory (VWM) plays a crucial role in temporarily maintaining and manipulating visual information. Retro-cue benefit (RCB) refers to enhancement in memory performance when attention is directed toward a subset of items within VWM after their initial encoding. Our recent EEG studies have indicated that cue validity can influence the mechanisms underlying RCB formation, but previous research has not investigated whether differences exist in the RCB formation mechanisms between completely valid and highly valid cue conditions. This study aims to examine the consistency of RCB mechanisms when retro-cues are completely valid (100% cue validity), compared with highly valid (80% cue validity). We manipulated retro-cue validity in our experiments and examined cognitive processing mechanisms under different cue validity conditions using EEG technology. We focused on the N2pc component, reflecting attentional resource allocation, and the contralateral delay activity (CDA) component, reflecting quantity of information retained in VWM. The results, encompassing both behavioral and event-related potential (ERP) findings, demonstrate that participants in both the 100% and 80% cue validity conditions exhibit robust RCB. Notably, the degree of RCB remains consistent between these conditions, indicating that participants utilize retro-cues to enhance VWM performance to the same extent. In the 80% cue validity condition, a significant retro-cue cost (RCC) is observed, suggesting that participants selectively eliminate uncued items from VWM. In invalid trials of this condition, response accuracy drops to chance levels, supporting the removal hypothesis. ERP results reveal that attentional resource allocation patterns (N2pc) and the quantity of information retained in VWM (CDA) remain uniform across cue validity conditions. The mechanism responsible for RCB formation appears to involve an all-or-nothing process of discarding uncued information rather than a flexible resource allocation strategy. This study provides insights into the attention allocation and information-processing mechanisms in VWM, suggesting that conclusions drawn from tasks with completely valid retro-cues can be integrated with findings from highly valid cue tasks. These findings also shed light on internal attentional resource allocation flexibility during RCB formation, as well as contribute to our understanding of attention processes in VWM.

Keywords: Visual working memory; Retro-cue benefit; Cue validity; Electroencephalography; Attention allocation; contralateral delay activity; N2pc

1. Introduction

Visual working memory (VWM), which plays an essential role in cognitive processing, functions as a cognitive system geared toward transiently storing and manipulating visual information to meet concurrent cognitive task demands (Luck & Vogel, 1997, 2013). Its well-known constraint lies in its ability to retain typically only three to four representations concurrently (Lewis‐Peacock et al., 2018; Luck & Vogel, 1997; Schneegans et al., 2020; Vogel et al., 2001; Zhang & Luck, 2011). However, VWM can allocate resources flexibly to task-related information while filtering out irrelevant information, thereby compensating for its limited capacity (Liesefeld et al., 2014; Maniglia & Souza, 2020; Plebanek & Sloutsky, 2019; Ye et al., 2023; Ye et al., 2018). In recent years, a burgeoning body of research has delved into the mechanisms underpinning VWM, revealing its adaptive and dynamic nature, as opposed to a rigid construct (Christophel et al., 2018; Christophel et al., 2017; Ma et al., 2014; Myers et al., 2018; Wolff et al., 2017; Ye et al., 2017; Ye et al., 2020; Ye et al., 2019). This often entails a reallocation of VWM resources toward these specific representations during the maintenance phase (Griffin & Nobre, 2003; Kuo et al., 2011; Landman et al., 2003; Li et al., 2020; Matsukura et al., 2014; Matsukura et al., 2007; Matsukura & Vecera, 2015; Murray et al., 2013; Myers et al., 2015; Niklaus et al., 2019; Pertzov et al., 2013; Souza & Oberauer, 2016; Zhang et al., 2022). Consequently, internal attention mechanisms become imperative in regulating access to VWM and prioritizing extant VWM representations for behavioral output.

The influence of internal attention on VWM has been examined extensively through the use of retro-cues (Souza & Oberauer, 2016). In a typical retro-cue experiment (Griffin & Nobre, 2003; Landman et al., 2003), participants are instructed to retain a memory array for subsequent recall. During the interval between presentation of the memory array and the test array, a retro-cue is presented to indicate the most likely probed item from the memory array. This effect on VWM performance is known as the retro-cue effect (RCE), comprising retro-cue benefit (RCB) and retro-cue cost (RCC). RCB signifies that in the valid retro-cue condition (indicating the item's location to be tested), memory performance outperforms that of the no-cue or neutral-cue conditions. Conversely, RCC denotes that in the invalid retro-cue condition (pointing to an item that will not be tested), memory performance is worse than that of the no-cue or neutral-cue conditions. Interestingly, recent studies have found that the RCE phenomenon does not occur exclusively when retro-cues direct internal attention toward specific memory items, but can manifest when cues steer attention toward a particular memory feature (e.g., color or orientation) across all memory items (Hajonides et al., 2020; Liu et al., 2023; Niklaus et al., 2017; Park et al., 2017; Ye et al., 2016; Ye et al., 2021). This underscores the complexity of the impact of internal attention on VWM. Therefore, investigating the mechanisms underlying RCE can contribute to a deeper understanding of the cognitive processes involved in attention during VWM maintenance.

Regarding the mechanisms underlying the RCE, several hypotheses have attempted to explain it, among which two influential ones emerged: the prioritization hypothesis and the removal hypothesis. The prioritization hypothesis suggests that the performance enhancement of a cued item in RCE results from elevating the cued representation to a prioritized state during maintenance without excluding non-cued representations from VWM. The cued representation is enhanced/protected while in the prioritized state, reducing competition with non-cued representations and consequently improving memory performance of the cued item. According to this hypothesis, non-cued representations are maintained continuously in VWM, but are less accessible than cued representations (Myers et al., 2018; Nobre et al., 2007; Rerko & Oberauer, 2013). However, the removal hypothesis posits that the retro-cue serves to reduce memory load by expelling non-cued items from VWM, thereby granting participants more available VWM resources to maintain cued representation. This reduction in inter-representation interference and resource competition is believed to improve memory performance (Goddertz et al., 2018; Kuo et al., 2012; Poch et al., 2018; Souza et al., 2014; Williams et al., 2013). Consequently, the removal hypothesis predicts that retro-cue benefits for cued representation should be accompanied by significant RCC for non-cued representation. Conversely, the prioritization hypothesis predicts that RCC would not be observed theoretically, as the status of the non-cued representations remains unchanged. Therefore, presence or absence of RCC is crucial to discerning between the hypotheses explaining the RCE phenomenon.

Interestingly, RCC has been observed in some studies (Gressmann & Janczyk, 2016; Griffin & Nobre, 2003; Pertzov et al., 2013). However, when using very similar retro-cue paradigms, other studies have failed to find such costs (Gozenman et al., 2014; Myers et al., 2018; Shimi & Astle, 2013). Consequently, while the prioritization and removal hypotheses initially may seem mutually exclusive, they actually may reflect automatic processing strategies that participants employed under different circumstances. Günseli et al. (2015) study suggests that whether non-cued representations are removed from VWM could depend on the expectation of retro-cue validity (Günseli et al., 2015). They discovered that retro-cue benefits were observed consistently regardless of retro-cue validity, but retro-cue costs became prominent when the retro-cue had high validity (i.e., 80% cue validity). Furthermore, retro-cue costs were absent for memory performance when the retro-cue had low validity (i.e., 50% cue validity). These findings suggest that participants strategically controlled how they implemented the retro-cue in the VWM task. When the cue is relatively unreliable, participants prioritize the cued representation for maintenance without excluding non-cued representations. Conversely, when the cue is highly reliable, participants not only prioritize, but also discard, non-cued representations during maintenance, resulting in notable retro-cue costs when a non-cued item is tested. However, previous studies related to retro-cue benefits often overlooked the impact of cue validity on the mechanisms of retro-cue benefits. While Günseli et al. (2015) study has directed attention towards the role of retro-cue validity, due to the inherent limitations of behavioral experiments in providing direct evidence regarding whether individuals retain non-cued representations in VWM, the results from behavioral experiments could not yield sufficiently compelling conclusions.

Given the advantages of direct brain activity observation and the high temporal resolution that electroencephalogram (EEG) technology has provided, researchers have employed event-related potential (ERP) measurements to measure VWM storage. The EEG technique has been applied extensively in investigating RCB (Goddertz et al., 2018; Kuo et al., 2012; Nobre et al., 2007; Poch et al., 2017; Poch et al., 2018; Schneider et al., 2017). A frequently employed ERP component in RCB is contralateral delay activity (CDA), a sustained negative potential reflecting the information currently held in VWM (Feldmann-Wustefeld et al., 2018; Gao et al., 2009; Gao et al., 2011; Ikkai et al., 2010; Vogel & Machizawa, 2004; Vogel et al., 2005; Ye et al., 2014). This ERP component also has been utilized to investigate the impact of retro-cue validity on RCB mechanisms (Fu et al., 2022; Günseli et al., 2019). For example, in our recent study employing CDA as an index of VWM storage, we manipulated retro-cue validity, examining the fate of non-cued representations in VWM when retro-cue validity was set at 80% (high retro-cue validity) and 20% (low retro-cue validity). The results revealed that although participants shifted their attention based on the cue in both high and low retro-cue validity conditions, they only maintained non-cued representations in the low retro-cue validity condition, but removed non-cued representations from VWM in the high retro-cue validity condition (Fu et al., 2022). This study supports Günseli et al. (2015) hypothesis and provides more direct evidence than behavioral experiments, suggesting that retro-cue validity may impact the mechanisms underlying RCB.

While our recent research has provided insights into the influence of retro-cue validity on RCB mechanisms (Fu et al., 2022), a comprehensive understanding of how retro-cue validity impacts RCB mechanisms remains an ongoing pursuit. Notably, previous research on RCB mechanisms has employed retro-cues that consistently were 100% valid, with no consideration of invalid cue conditions. Moreover, many existing hypotheses regarding RCB mechanisms have been proposed under the assumption of 100% retro-cue validity (Kuo et al., 2012; Landman et al., 2003; Matsukura et al., 2014; Murray et al., 2013; Myers et al., 2015). However, cognitive processes may exhibit qualitative distinctions between performing a retro-cue task with 100% retro-cue validity and one with high retro-cue validity, such as 80% cue validity. In the 80% retro-cue valid task, participants still may have the incentive to retain uncued items during the test phase, as they might be tasked with recalling these uncued items. However, in the 100% retro-cue valid task, participants lack any motivation to retain uncued representations. This motivational divergence could lead to disparities in RCB mechanisms observed in these two retro-cue validity conditions. While our previous research found that participants can remove uncued representations to some extent in high retro-cue validity (e.g., 80% cue validity) conditions, it remains uncertain whether this removal process aligns with the mechanisms governing RCB when retro-cues are 100% valid. Only by scrutinizing distinctions in mechanisms between high retro-cue validity tasks and tasks with completely valid retro-cues can we integrate the findings obtained from high retro-cue validity tasks with those from previous tasks involving completely valid retro-cues.

Consequently, the present study employed ERP techniques to investigate retro-cue validity's influence on RCB mechanisms further. We examined RCB mechanisms in both high retro-cue validity (i.e., 80% cue validity) and completely valid retro-cue (i.e., 100% cue validity) tasks and made comparisons between the similarities and differences in these RCB mechanisms under these two retro-cue validity conditions. In terms of ERP components, we used the CDA component, which serves as an indicator of VWM storage, and the

N2-posterior-contralateral (N2pc) component, which reflects attentional allocation. The N2pc component has been employed widely in extant research to examine deployment of attention and the onset of attentional engagement (Eimer, 1996; Hopf et al., 2000; Liu et al., 2016; Luck & Hillyard, 1994a, 1994b; Zhao et al., 2011). Both of these ERP components have been utilized in our previous studies that examined the impact of retro-cue validity on RCB mechanisms (Fu et al., 2022). In the present study, we anticipated two potential outcomes. First, notable distinctions in RCB mechanisms may occur between the high retro-cue validity condition and the completely valid retro-cue condition. While participants in the high retro-cue validity condition can eliminate uncued representations partially, this removal may not be as comprehensive as in the completely valid retro-cue condition. Consequently, participants in the high retro-cue validity condition may retain more VWM information following the retro-cue, resulting in a greater CDA amplitude compared with the completely valid retro-cue condition. Conversely, the second possibility is that no differences exist in RCB mechanisms between the high retro-cue validity condition and the completely valid retro-cue condition. Participants in both retro-cue validity conditions possessed the ability to eliminate uncued representations entirely. In this case, we expected to observe identical CDA components in both retro-cue validity conditions.

2. Materials and methods

2.1. Participants

Adequate statistical power for the t-test comparison was ensured by conducting an a priori power analysis. This analysis, performed using G*Power 3.1.9.2 (Faul et al., 2007), was based on the predicted effect size derived from our previous study (Fu et al., 2022). Anticipating a large effect size (Cohen's d = 0.80) for our experimental design, and setting a statistical power of 80% alongside an alpha level of 0.05, the analysis recommended a total sample size of 15 participants.

All participants in this study volunteered and were university students from Liaoning Normal University between the ages of 18 and 26, with an average age of 23.12 ± 1.58 years. The sample comprised 18 participants (six males and 12 females, all right-handed) who all possessed normal-color vision and either uncorrected or corrected normal vision. Following completion of the experiment, each participant received compensation at a rate of ¥30 per hour. Notably, the data from three participants, whose behavioral performance fell below chance levels, were excluded from the overall analysis. Consequently, data from the remaining 15 participants were analyzed for the study. Prior to the experiment, written informed consent was obtained from each participant. All procedures adhered to the Declaration of Helsinki guidelines and were approved by Liaoning Normal University’s ethics committees.

2.2. Experimental Materials

The experimental paradigm for the retro-cue task was developed using E-Prime 2.0 software. The memory array comprised eight colored squares, with their positions remaining constant throughout the experiment. These specific positions and sizes of these squares were in line with Kuo, Stokes, and Nobre's (2012) study. Eight positions were designated to display the memory array, with four positions in each hemifield. These positions were arranged based on two imaginary concentric circles with radii of approximately 3.06° and 5.44° of visual angle. Notably, squares positioned on the smaller circles measured 0.77° in size, while those on the larger circles measured 1.36°. The squares' colors were selected randomly from a pool of eight highly distinguishable colors: red; yellow; blue; green; magenta; purple; orange; and cyan. Stimuli were presented on a 19-inch CRT monitor, with participants seated 70 cm away from the monitor inside a quiet, noise-free experimental room.

2.3. Experimental Design

The participants needed to conduct a lateralized change-detection task. The experimental procedure commenced with the presentation of experimental instructions in the center of the screen, then the experimenter explained the study to participants to ensure that they fully comprehended the instructions. The experiment was divided into practice and formal trials. Participants first completed 30 practice trials with retro-cues that were 100% valid. Once participants were familiar with the experimental procedure through practice trials, they initiated formal trials by pressing the "Q" key. As illustrated in Figure 1, a black background screen initially displayed a fixation point for 800 ms, followed by a left- or right-pointing arrow for 100 ms, indicating which side of the fixation point participants were required to remember the colored squares. The left or right arrow was presented with equal probability and randomized. After a blank screen interval lasting 500–700 ms, a memory array appeared on the screen, comprising four colored squares on each side. However, participants were instructed to remember only the four squares on the side indicated by the preceding arrow cue. The memory array was presented for 100 ms, followed by a 400 ms blank screen interval. Subsequently, a retro-cue was presented for 200 ms, which could be a spatial cue or neutral cue, both presented with equal and random probabilities. The spatial cue (pointing to the upper left, upper right, lower left, or lower right) directed attention toward two of the four squares that needed to be remembered. Following the disappearance of the retro-cue, a blank screen interval of 1500 ms ensued, after which a probe stimulus was presented. Participants were tasked to determine whether the colors of the squares in corresponding positions matched those in the memory array. The probe array in the cued hemifield had a different color than the memory array on 50% of the trials and was identical in the remaining trials. Participants responded by pressing the "F" key for "same" or the "J" key for "different." After participants responded, the probe stimulus disappeared, and the subsequent trial commenced.

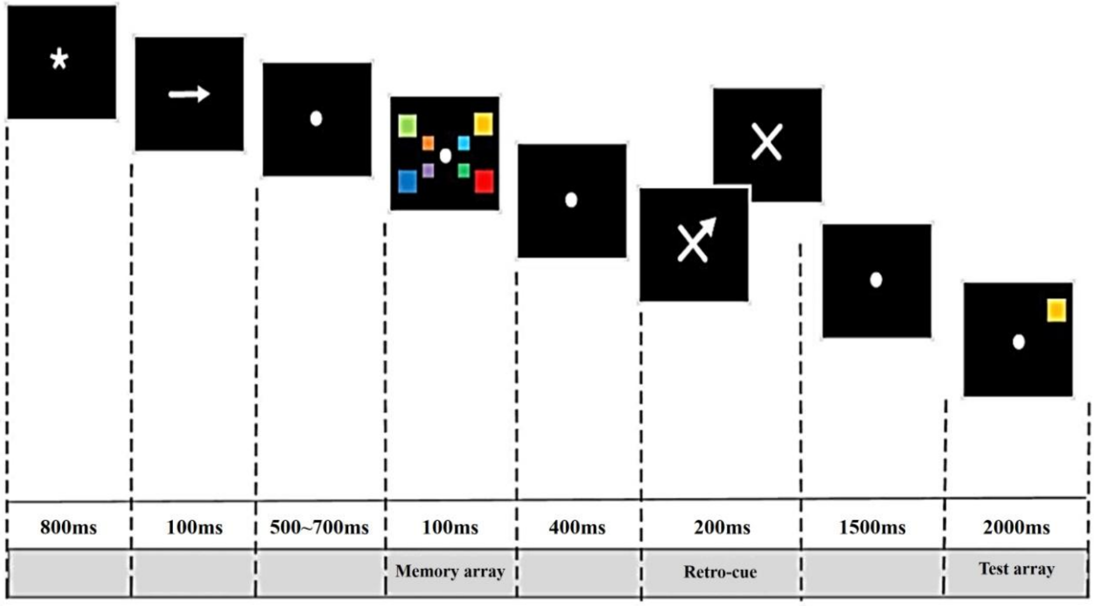

Figure 1. Experimental procedure. The lateralized change detection task involved presenting participants with a memory array comprising four colored squares on each side (100 ms), a retro-cue (200 ms), and a test array (2,000 ms). During the retro-cue trials, a spatial cue (with either 80% or 100% validity) was presented after the memory array. During the neutral trials, a neutral cue without spatially informative orientation was presented after the memory array. Participants were required to determine whether the colors of the squares in the test array in corresponding positions matched those in the memory array.

The experiment comprised two conditions: one with cues being completely valid (100% cue validity) and the other with cues being highly valid (80% cue validity). Based on these conditions, the experiment was divided into two blocks, each comprising 240 trials. The block with completely valid cues contained 120 trials with valid spatial cues and 120 trials with neutral cues, but the block with highly valid cues contained 96 trials with valid spatial cues, 24 trials with invalid spatial cues, and 120 trials with neutral cues. Based on our previous research (Li et al., 2020), which suggests that the sequence of experimental blocks can impact participants' memory strategies and performance outcomes, we took measures to ensure that participants placed complete trust in cue validity in the block with completely valid cues. To achieve this, all participants completed the experiment first in this condition (100% cue validity) before proceeding to the block with highly valid cues (80% cue validity). Prior to commencing the block with highly valid cues, participants were informed explicitly that cue validity in the upcoming experimental block would be reduced to 80%. Furthermore, during the formal experiment, participants were provided with three breaks (one after every 120 trials), each lasting at least 30 seconds.

2.4. Data Recording and Analysis

Behavioral data were recorded automatically ~~recorded~~ using E-Prime 2.0 software. EEG data were collected using a 64-electrode cap, following the international 10-20 system extended with left and right mastoid references. Electrodes F7 and F8 were positioned approximately 1 cm from the outer canthi of the eyes to monitor eye movements. EEG signals were digitized at a 24-bit resolution and a sampling rate of 512 Hz without online filtering.

Behavioral data were analyzed, initially involving computation of accuracy and reaction times using E-Prime 2.0 software. A repeated-measures ANOVA with validity condition (100% cue validity, 80% cue validity) and cue type (valid, neutral), similar to within-subject factors, was conducted for accuracy and reaction times. Paired-sample t-tests then were conducted to assess differences between valid and neutral cues in the completely valid cue (100% cue validity) condition, as well as between valid, neutral, and invalid cues in the highly valid cue (80% cue validity) condition.

EEG data analysis was conducted using Matlab and Letswave7. The EEG data underwent preprocessing, which included applying a 30 Hz low-pass filter and re-referencing the data to the average of the left and right mastoid electrodes (M1 and M2). The time window of interest for EEG analysis extended from 200 ms before presentation of the memory array to the presentation of the probe stimulus, encompassing a range of -200 to 2,200 ms. After eliminating ocular artifacts through ICA component analysis, thresholds of $\pm 100\ \mu V$ were applied for artifact rejection at electrodes PO7/PO8. Subsequently, based on the research objectives, more analyses were conducted using the preprocessed waveforms. EEG data were averaged separately for different conditions, and PO7/PO8 electrodes were selected as the region of interest. To isolate neural activity associated with the squares requiring memorization, waveforms from the contralateral side were subtracted from those on the ipsilateral side. The results on difference waves were corrected for multiple comparisons using false discovery rate (FDR) correction (Benjamini & Hochberg, 1995) at a statistical threshold of $p < .05$. For statistical significance within the FDR-corrected time windows, fewer than five consecutive time-sampling points were deemed nonsignificant, while more than five consecutive time points were deemed significant.

3. Results

3.1. Behavioral Results

The behavioral results are presented in Figure 2. For accuracy, a significant main effect of validity condition on accuracy was observed ($F(1,14) = 15.871$, $p = 0.001$, $\eta^2 = 0.959$). Similarly, a notable main effect of cue type on accuracy was found ($F(1,14) = 22.113$, $p < 0.001$, $\eta^2 = 0.992$). However, the interaction between condition and cue type on accuracy was not statistically significant ($F(1,14) = 0.338$, $p = 0.570$, $\eta^2 = 0.084$). Follow-up comparisons revealed that under the 100% cue validity condition, accuracy for valid cue trials was significantly higher than that for neutral cue trials (valid cue: 0.74 ± 0.03, neutral cue: 0.64 ± 0.03; $t(14) = 3.812$, $p = 0.002$). Similarly, under the 80% cue validity condition, accuracy for valid cue trials was significantly greater than that for neutral cue trials (valid cue: 0.77 ± 0.03, neutral cue: 0.69 ± 0.02; t(14) = 4.13, p = 0.01), while accuracy for neutral cue trials was higher than that for invalid cue trials (invalid cue: 0.50 ± 0.02; t(14) = 5.59, p < 0.001).

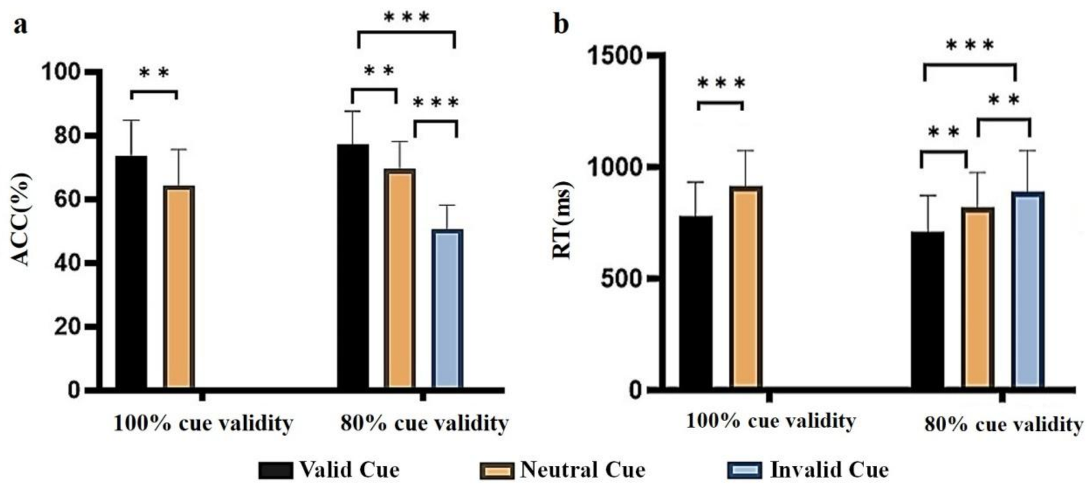

Figure 2. Behavioral results on accuracy (ACC) and reaction time (RT) in each condition. (a) Mean ACC and standard error in 100% and 80% cue validity conditions were separated based on cue type factors. (b) Mean RT and standard error in 100% and 80% cue validity conditions were separated based on cue type factors. The error bars indicate SE. ** = p < 0.010, *** = p < 0.001.

As for reaction time, a significant main effect of validity condition on reaction time was found ($F(1,14) = 19.484$, $p = 0.001$, $\eta^2 = 0.984$), as well as a significant main effect of cue type ($F(1,14) = 28.781$, $p < 0.001$, $\eta^2 = 0.999$). However, the interaction between condition and cue type on reaction time did not reach statistical significance ($F(1,14) = 2.659$, $p = 0.125$, $\eta^2 = 0.33$). Follow-up comparisons demonstrated that under the 100% cue validity condition, reaction times for valid cue trials were significantly shorter than those for neutral cue trials (valid cue: 779.7 ± 39.5, neutral cue: 914.6 ± 41.6; t(14) = 3.812, p 0.002). Similarly, under the 80% cue validity condition, reaction times for valid cue trials were significantly shorter than those for neutral cue trials (valid cue: 710 ± 42.2, neutral cue: 819.6 ± 40.6; t(14) = 4.487, p = 0.001), whereas reaction times for neutral cue trials were shorter than those for invalid cue trials (invalid cue: 889.2 ± 48.3; t(14) = 3.549, p = 0.003). Furthermore, a significant difference in reaction times between valid and invalid cue trials was found (t(14) = 6.606, p < 0.001).

Crucially, under the 100% cue validity condition, the extent of retro-cue benefit in accuracy (t(14) = 0.5814, p = 0.5702) and reaction time (t(14) = 1.631,p = 0.1253) did not significantly differ from the extent of retro-cue benefit under the 80% cue validity condition (see Figure 3).

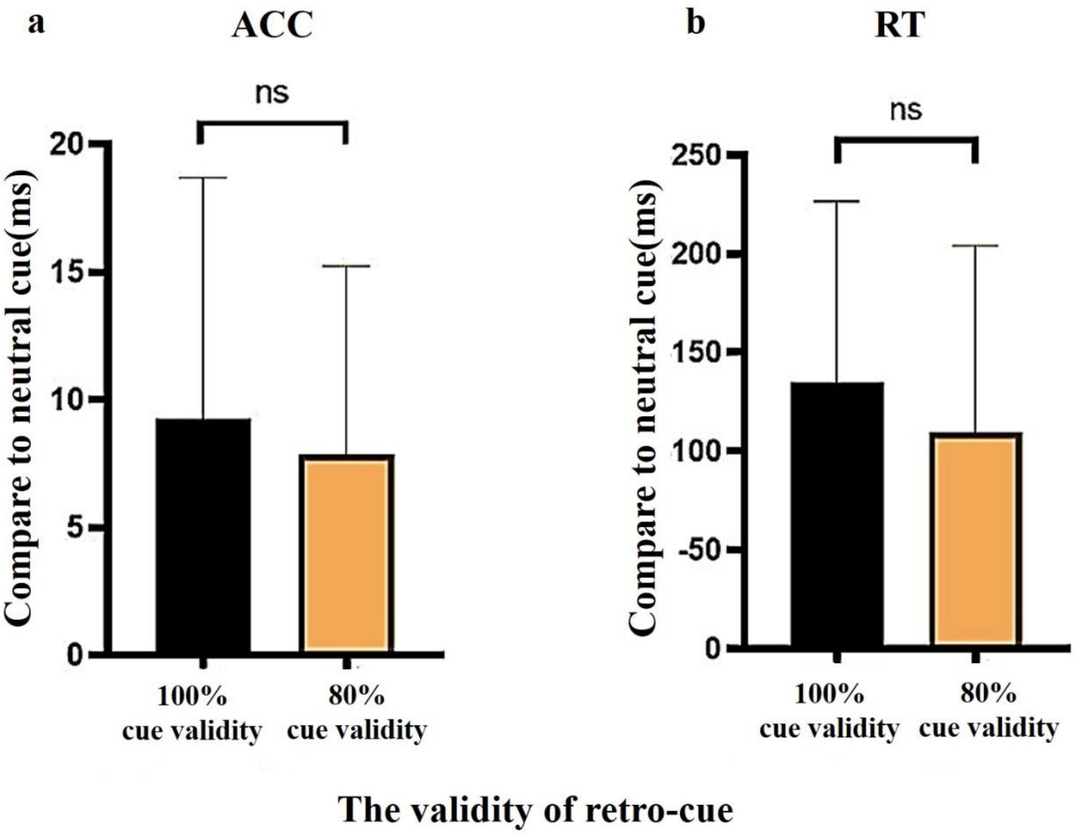

Figure 3. Retro-cue benefit (RCB) under different cue validity conditions. (a) RCB on mean accuracy (ACC) under the 100% and 80% cue validity conditions. (b) RCB on mean reaction time (RT) under 100% and 80% cue validity conditions. Error bars indicate SE. n.s. = not significant.

3.2. EEG Results

The EEG findings are presented in Figure 4. The upper segment displays average waveforms at electrodes PO7 and PO8 for contralateral and ipsilateral responses under the conditions of 100% and 80% cue validity conditions in spatial cues. Contralateral and ipsilateral references are with respect to the visual field containing the array of colored squares to be memorized. The lower part showcases the difference waves obtained by subtracting contralateral from ipsilateral responses for spatial cues in both conditions. Notably, distinct N2pc and CDA waveforms can be observed within specific temporal windows. The sharp negative peak occurring around 200 ms following stimulus onset (memory array or retro-cue) is identified as N2pc, while the slow negative wave appearing from 400 ms to 800 ms is referred to as CDA. FDR testing was employed to confirm the presence of significant CDA for spatial cues in both conditions over an extended period following the retro-cue appearance and preceding the probe stimulus presentation (as indicated by the green line on the difference wave in Figure 3: $p < 0.05$, FDR corrected, one-tailed test). Based on the defined criteria for these two metrics, time windows of interest were selected at 170–220 ms post retro-cue onset (N2pc) and 300–1000 ms post retro-cue onset (CDA). Average wave amplitudes of the difference waves for spatial cues in both conditions within these time windows were computed, and paired-sample t-tests were conducted to compare these measures (N2pc and CDA) between the two conditions.

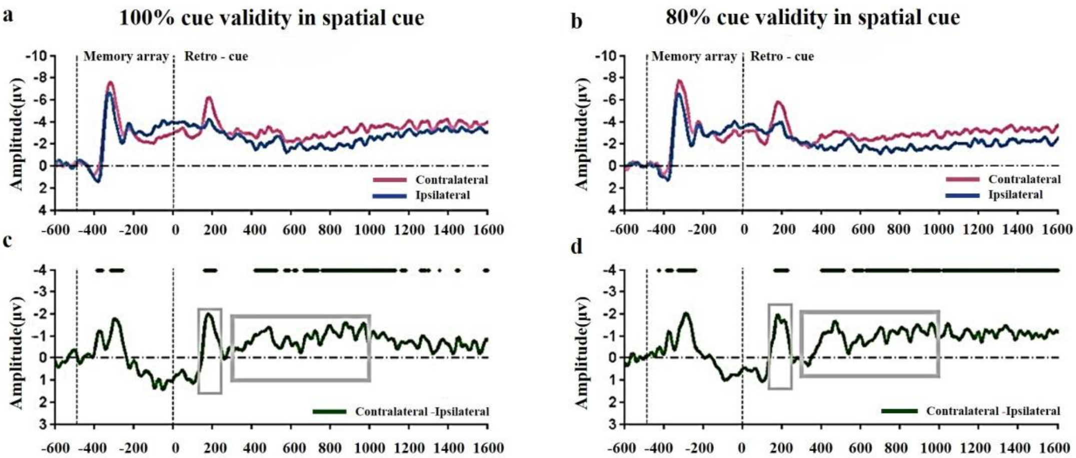

Figure 4. Grand average ERPs and difference waves time-locked to the onset of the retro-cue array. (a) Grand average ERPs for the valid cue condition under the 100% cue validity condition. Pink lines represent activity contralateral to, and blue lines represent activity ipsilateral to, the lateralized memory stimuli. (b) Grand average ERPs for the valid cue condition under the 80% cue validity block. (c) Mean ERP difference wave form for the valid cue condition under the 100% cue validity block. The black lines above the waveforms indicate amplitudes significantly larger than zero throughout the entire duration. The gray-boxed areas denote the analysis time window used to compute the mean N2pc (170–220 ms) and CDA amplitude (300–1000 ms). (d) Mean ERP difference wave form for the valid cue condition under the 80% cue validity block. The gray-box areas denote the analysis time window used to compute the mean N2pc and CDA amplitude.

The comparison of average wave amplitude within the windows of interest is presented in Figure 5. The comparison results indicated no significant differences in the average wave amplitude of N2pc between the 100% and 80% cue validity conditions (100% cue validity: -1.82 ± 0.53; 80% cue validity: -2.12 ± 0.47; $t(14) = 0.902$, $p = 0.383$). Furthermore, no significant differences were found in average CDA wave amplitude between the 100% and 80% cue validity conditions (100% cue validity: -1.02 ± 0.28; 80% cue validity: -1.09 ± 0.39; $t(14) = 0.161$, $p = 0.874$). These results indicated no significant differences in average wave amplitude of difference waves between the two conditions within the two time windows of interest.

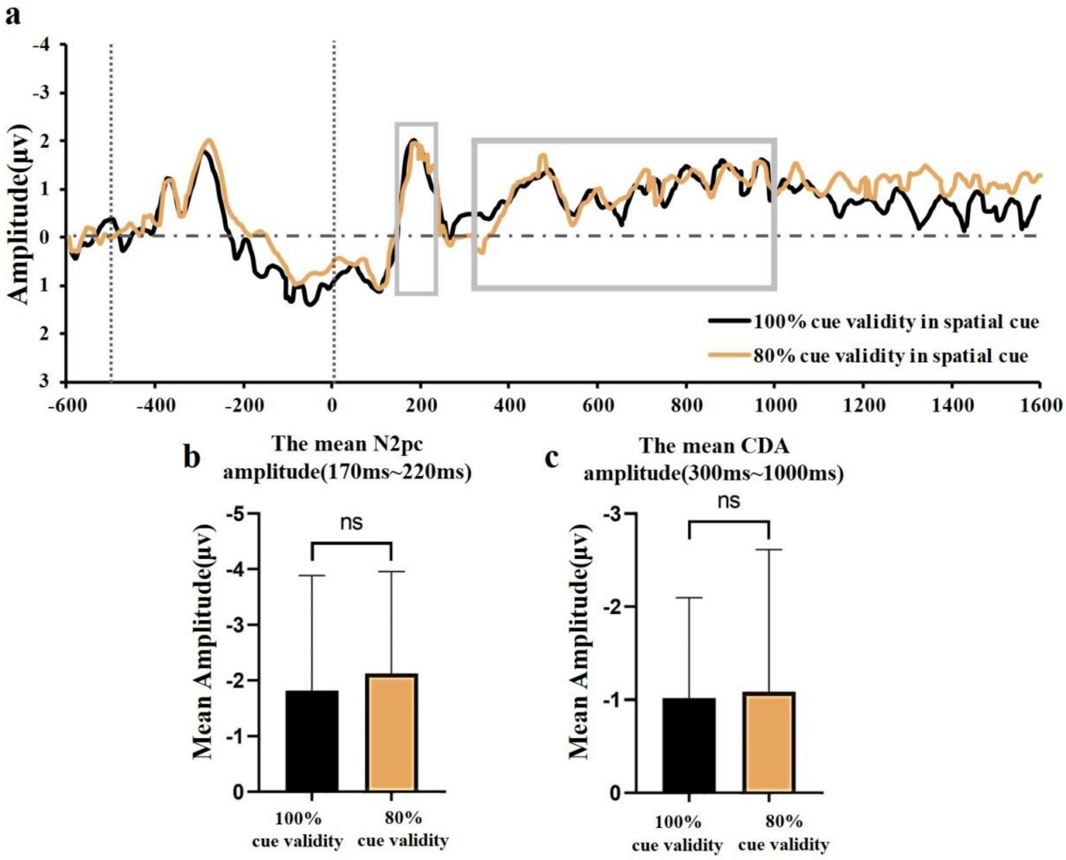

Figure 5. Difference waves during the entire time window and the ERP results. (a) Difference wave forms (contralateral waves minus ipsilateral waves) of average ERPs are depicted under different cue validity. The gray-box areas indicate the analysis time window used to calculate the mean N2pc amplitude (170ms ~220ms) and mean CDA amplitude (300ms ~ 1,000ms). (b) Mean N2pc amplitude and standard error for valid cue trials in 100% and 80% cue validity conditions. (c) Mean CDA amplitude and standard error for valid cue trials in 100% and 80% cue validity conditions. Error bars indicate SE. n.s. = not significant.

4. Discussion

This study investigated whether the mechanisms responsible for the emergence of RCB remain consistent when the retro-cue is completely valid vs. when it is highly valid. Our findings, including both behavioral and ERP results, revealed that participants, under both 100% and 80% cue validity conditions, were capable of eliciting a reliable RCB effect. Notably, the mechanisms involved in RCB generation, allocating attentional resources and the processing of stored information, exhibited no discernible differences across these two levels of retro-cue validity.

Our behavioral findings reveal that both the 100% and 80% cue validity conditions exhibit robust RCB. Importantly, the extent of RCB is entirely equivalent across these two cue validity conditions, signifying that participants in both conditions use the retro-cue to enhance their memory performance to the same degree. Furthermore, within the 80% cue validity condition, significant RCC is observed, indicating that participants selectively abandon uncued items within their VWM. Notably, in the invalid trials of the 80% cue validity condition, participants' response accuracy plummets to chance levels. These behavioral outcomes collectively suggest that in the context of the 80% cue validity condition, participants fully discard uncued items in their VWM. This observation aligns harmoniously with prior behavioral experiments that support the removal hypothesis (Goddertz et al., 2018; Kuo et al., 2012; Poch et al., 2018; Souza et al., 2014; Williams et al., 2013), and also is in line with findings from our previous EEG study (Fu et al., 2022).

Turning to our EEG results, our N2pc findings indicate that regardless of the cue validity condition, participants consistently allocate heightened attention to the cued location following the retro-cue. Importantly, the patterns and extent of attentional resource allocation remain uniform between the two cue validity conditions. Furthermore, our CDA results demonstrate that the quantity of VWM information retained following cue utilization is identical between these two cue validity conditions. This outcome aligns seamlessly with our expectation that no differences exist in RCB mechanisms between the high and completely valid retro-cue conditions. These findings emphasize that the fundamental mechanisms underpinning RCB emergence remain consistent for participants in both the completely valid and high retro-cue validity conditions.

By combining our behavioral and EEG findings, we have uncovered a pivotal insight: Once retro-cue validity reaches a certain threshold, individuals begin employing a complete removal mechanism, effectively dropping uncued representations out of their VWM to secure a stable RCB. Notably, the degree of RCB achievement remains consistent as cue validity escalates from 80% to 100%. Furthermore, the decrease in cue validity from 100% to 80% does not result in a significant decrease in additional allocation of attentional resources to the cued region. This indicates that in the mechanism responsible for RCB formation, the expulsion of uncued information operates as an all-or-nothing process, rather than a malleable, statistically optimized continuum of resource allocation dependent on cue validity. Future research could examine the flexibility of internal attentional resource allocation during RCB formation by incorporating a wider range of cue validity conditions.

Notably, the experimental paradigm employed in this study diverges from our previous investigations into cue validity effects. In our previous study (Fu et al., 2022), participants were tasked with memorizing information presented bilaterally across the visual field. Conversely, in the present study, participants were instructed only to retain information from one side of the visual field based on the initial arrow cue. This experimental arrangement aligns with the paradigm utilized in previous research examining the RCB effect through the CDA component (Kuo et al., 2012). The rationale for adopting a unilateral memory paradigm in this study, rather than persisting with our previous paradigm probing cue validity within the bilateral visual field, primarily was to investigate whether participants in the high cue validity condition also would completely forget uncued representations within a unilateral memory context. This prospect emerged from earlier research demonstrating superior performance in VWM when visual items are allocated across both left and right visual fields, predominantly due to participants' more efficient allocation of attentional resources (Delvenne, 2005; Delvenne & Holt, 2012; Zhang et al., 2018). However, our study ascertained that even in the context of unilateral visual presentation, participants in the high cue validity condition, akin to our previous findings within the bilateral visual field context, could discard uncued representations entirely (Fu et al., 2022). This underscores that the mechanism for discarding uncued representations through cues remains unaffected by whether memory stimuli are presented unilaterally or bilaterally.

Our finding of no discernable distinctions in the fundamental mechanisms underlying formation of the RCB between the high retro-cue validity condition and completely valid retro-cue condition carries significant implications. It enables us to extend many of the conclusions drawn from tasks with a completely valid retro-cue to findings in tasks involving a highly valid retro-cue, essentially harmonizing these two bodies of research. For instance, in previous research that employed a completely valid retro-cue, it was concluded that the emergence of object-based RCB does not necessitate sustained attention (Hollingworth & Maxcey-Richard, 2013; van Moorselaar et al., 2014). This conclusion now can be integrated seamlessly with findings from tasks with a highly valid cue, suggesting that when individuals utilize a highly valid retro-cue, they will drop uncued representations out of VWM, which occurs without the requirement for sustained attention. Consequently, this study establishes a bridge for the smooth amalgamation of conclusions derived from diverse cue validity tasks.

5. Conclusions

The results of this study revealed that the mechanisms responsible for RCB formation indicate remarkable consistency between conditions of high and completely valid retro-cues. This suggests that conclusions drawn from tasks with completely valid retro-cues can be integrated seamlessly with findings from tasks involving highly valid cues. Specifically, individuals tend to employ a complete removal mechanism, effectively discarding uncued representations from their VWM when retro-cue validity reaches a certain threshold. Importantly, the degree of RCB remains consistent as cue validity decreases from 100% to 80%. Furthermore, cue validity augmentation from 100% to 80% does not result in a discernible increase in the additional allocation of attentional resources to the cued region. This indicates that the mechanism responsible for RCB formation involves an all-or-nothing process of expelling uncued information, rather than a flexible, statistically optimized continuum of resource allocation dependent on cue validity. These findings provide valuable insights into attention allocation and information-processing mechanisms in VWM.

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