Influence of presentation duration on filtering of irrelevant stimuli in visual working memory

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Author Note

This work was supported by grants from the National Natural Science Foundation of China (no. 31970989 to Qiang Liu) and Academy of Finland (no. 355369 to Chaoxiong Ye). All the authors had full independence from the funding sources. The authors have no conflicts of interest to disclose. The data that support the findings of this study are openly available at http://doi.org/10.17605/OSF.IO/VJPN4

Abstract

In an environment teeming with distractions, the ability to selectively focus on relevant information is crucial for advanced cognitive processing. Existing research utilizing event-related potential (ERP) technology has indicated active suppression of irrelevant stimuli during the consolidation phase of visual working memory (VWM). In previous studies, participants have always been given sufficient time to consolidate VWM while suppressing distracting information. However, a question remains as to whether the suppression of irrelevant distractors requires continuous effort throughout their presence or whether this suppression is only necessary after the consolidation of task-relevant information. To address this question, our study examines the necessity of distractor suppression processing in scenarios where consolidation time is limited. This research explores how varying the presentation duration affects the filtering of distractors in VWM. We tasked participants with memorizing two color stimuli while ignoring four distractors presented for either 50 ms or 200 ms. Utilizing ERP technology, we discovered that the distractor-induced distractor positivity (PD) amplitude is larger during longer presentation durations compared to shorter ones. These findings highlight the substantial influence of the presentation duration on the efficacy of distractor suppression in VWM, as prolonged exposure results in more significant distraction effects and a heightened need for suppression. This study illuminates the temporal dynamics of attention and memory, emphasizing the critical role of stimulus timing in cognitive tasks. It provides valuable insights into the mechanisms underlying VWM and has implications for models of attention and memory.

Keywords: Visual Working Memory; Distractor Suppression; Event-Related Potentials; Presentation Duration; Attentional Filtering

1 Introduction

Visual working memory (VWM) is a short-term memory system that acquires relevant information via visual pathways and retains and manipulates it even after the visual stimuli have disappeared (Baddeley, 2000, 2012; Baddeley & Hitch, 1974). This memory system plays a key role in facilitating various complex cognitive activities (Luck & Vogel, 2013; Wolfe, 2014); however, the capacity of VWM is notably limited (Awh et al., 2007; Luck & Vogel, 1997; Vogel et al., 2001; Ye et al., 2014; Zhang & Luck, 2008).This limited capacity not only restricts the quantity of information processed concurrently but it also impacts the efficiency of different higher-level cognitive activities. Given the stimulus-rich social environment that humans inhabit, where distraction is constant and unavoidable, the active mitigation of the impact of distractors on VWM emerges as a critical strategy for enhancing memory performance. This necessitates prioritizing target items and suppressing irrelevant ones during the encoding and consolidation phases within the VWM system (Cowan & Morey, 2006; Fukuda & Vogel, 2009; Vogel et al., 2005).

Due to the brief nature of encoding and consolidation processes in VWM, coupled with the potential overlap in the timeline of VWM resource allocation and the suppression of irrelevant items, traditional behavioral indicators (e.g., accuracy) have limitations in distinguishing individual resource allocation and filtering mechanisms. However, recent studies have used event-related potential (ERP) technology to investigate the filtering processes of distractors in VWM (Feldmann-Wustefeld & Vogel, 2019; Owens et al., 2012; Vogel et al., 2005; Ye et al., 2023; Ye et al., 2018). For instance, Feldmann-Wustefeld and Vogel (2019) utilized an ERP component called distractor positivity (PD) to detect the filtering processes of distractors during the consolidation phases of a VWM task. In their lateralized change detection task, participants were required to focus on remembering the location and color of the target items while disregarding distractors. Under these conditions, the unilateral memory of target items elicited a contralateral delay activity (CDA) component—an ERP marker tracking VWM load. Critically, the researchers observed that distractors elicited early PD and PD components, with amplitudes that increased as the number of distractors increased and correlated positively with the individual's VWM capacity. The early PD component was argued to reflect the initial processing of stimuli or to represent physical salience, which might also be linked to predefined feature-filtering weights that are influenced by the participants' task expectations (Fortier-Gauthier et al., 2012; Jannati et al., 2013; Weaver et al., 2017). By contrast, the PD component reflected the process used for suppression of to-be-ignored items, as well as the negative attentional weights on salience maps, thereby inhibiting the consolidation of distractors into the VWM system (Feldmann-Wustefeld & Vogel, 2019). This study compellingly demonstrated active suppression of irrelevant items during VWM consolidation and prevention of their entry into the VWM system.

The consolidation processes involved in VWM have been identified to include two distinct phases of resource allocation. During the early consolidation phase, individuals involuntarily allocate VWM resources in a stimulus-driven manner across visual stimuli. If the stimuli are presented for a sufficiently long duration, the individuals create low-resolution VWM representations for as many visual stimuli as possible. This initiates the transition into the late consolidation phase, wherein VWM resources are reallocated according to task demands, focusing on task-relevant visual stimuli (Ye et al., 2017, 2020, 2019). Moreover, previous research has revealed that information is sequentially consolidated into the system in a bandwidth-limited manner (Hao et al., 2018; Miller et al., 2014). In addition, Vogel et al. (2006), using a masked change detection paradigm, demonstrated that the number of memory items participants could retain increased with the stimulus presentation duration up to the limit of their VWM capacity. This finding indicates that consolidating a single color item requires roughly 50 ms.

The bandwidth-limited sequential consolidation pattern in VWM implies a progressive consolidation of task-related information, leading to an intriguing question: Do irrelevant distractors need continuous suppression throughout their presence, or is continuous suppression only required if the distractors persist post the consolidation of task-relevant information? A critical aspect in resolving this question is determining whether distractor suppression processing still occurs when consolidation time is inadequate. Feldmann-Wustefeld and Vogel (2019) did not provide a definitive answer in this context, given that their study utilized a fixed stimulus presentation duration of 200 ms. According to Vogel et al. (2006), this duration should be adequate for consolidation of more items than the two-color items required in the task used in the study by Feldmann-Wustefeld and Vogel (2019). Hence, the aim of the present study was to manipulate the stimulus presentation duration (i.e., short or long duration) to further explore the temporal dynamics between distractor suppression processing and the consolidation of task-relevant information.

Our research strategy was to present memory stimuli under two presentation duration conditions (50 ms and 200 ms) while recording the ERP components of distractors as participants completed the task. We hypothesized that 200 ms represents a sufficient duration for consolidating task-relevant information, whereas 50 ms does not. Under the 200 ms condition, we anticipated observing results consistent with those of Feldmann-Wustefeld and Vogel (2019). More importantly, if the suppression processing of distractors occurs only after the consolidation of task-relevant information, we expected that the PD component elicited by distractors would be observable only under the long presentation duration condition and not under the short presentation duration condition. Conversely, if distractor suppression processing is independent of consolidation completion, then we expected to see similar PD component magnitudes under both stimulus presentation durations.

2 Material and methods

2.1 Participants

We ensured sufficient statistical power for comparisons by conducting an a priori power analysis using G*Power 3.1.9.2 (Faul et al., 2007), referencing the effect sizes of the PD results reported in the study by Feldmann-Wustefeld and Vogel (2019) (η^2 = 0.274, 0.315, 0.367). We anticipated a similar effect size (η^2 = 0.274) in our experimental design (2-way repeated measures ANOVA); therefore, we aimed for a statistical power of $(1 - \beta) = 0.80$ at a significance level of 0.05. This analysis suggested a minimum sample size of 26 participants.

Thirty-five students from Sichuan Normal University were recruited for the study. After artifact rejection and the removal of trials with response errors, five participants were excluded for having fewer than 100 trials per condition. The remaining 30 participants (aged 18–27 years, M = 20.6, SD = 2.54, including 9 males) were included in the data analysis. This sample size aligned closely with the sample size (N = 26) used in the study by Feldmann-Wustefeld and Vogel (2019). All participants were right-handed, had normal or corrected-to-normal vision, no color blindness or weakness, no psychiatric disorders, and had not previously participated in similar experiments. Participation was voluntary, and all participants were compensated based on their performance upon completion of the study. Our study was approved by the ethical committee of Sichuan Normal University and followed the guidelines of the Declaration of Helsinki (2008).

2.2 Materials

The experiment was programmed in Matlab 2018b using the Psych Toolbox and the program was used for data collection. The lab's computer screen had a resolution of 1920 × 1080 and a refresh rate of 60 Hz. A 64-channel electroencephalography (EEG) cap was used to collect the EEG signals. During the experiment, the distance between the participant's eyes and the monitor was approximately 60 cm, with the participant's eyes directly facing the center of the screen. The experiment was conducted in a quiet room, with all light sources other than the monitor turned off, ensuring clear visibility of the stimuli.

The stimuli were presented on the memory display and included colored squares (0.9°×0.9°), colored circles, and gray circles (all circles 1° in diameter). The colors of the stimuli were randomly chosen from nine options (RGB values: red [255-0-0], green [0-255-0], blue [0-0-255], yellow [255-255-0], magenta [255-0-255], cyan [0-255-255], dark green [20-80-20], purple [50-0-100], or orange [255-128-0]), with no color repeats. The gray circles had an RGB value of 128-128-128. The stimuli were presented in four groups, which included two colored squares, four colored circles, and two groups of grey circles (each containing two and four circles), as shown in Figure 1A. Two groups of stimuli were positioned on the vertical median (above and below), and the other two were placed on the horizontal median (left and right), with their centers located 3.4° away from the screen center (measured from the center of the screen to the center of each group). The two colored squares represented the target items, the four colored circles represented the distractors, and the two groups of gray circles were neutral distractors. In the target lateral condition (50% of the trials), target items were presented on the horizontal median (either left or right, with equal probability), and the distractors were presented on the vertical median (either top or bottom, with equal probability). In the distractor lateral condition (the remaining 50% of the trials), the target items were presented on the vertical median (either top or bottom, with equal probability), and the distractors were presented on the horizontal median (either left or right, with equal probability). The remaining positions were filled with neutral distractor groups, with the set size of neutral distractors always matching the number of their opposite targets or distractors.

In the probe array, the location at which the memory stimulus appeared showed an outline, and only one of the target stimuli at that location was filled with color. In 50% of the trials, the color was identical to the color shown in the memory display at that location. In the remaining 50% of the trials, the color was chosen randomly from one of the other eight colors.

2.3 Experimental Procedure

As illustrated in Figure 1B, each trial began with a 500 ms fixation cross at the center of the screen, signaling the upcoming stimuli. To minimize the impacts of eye movements and blinks on the results, the participants were instructed to focus on the cross throughout the experiment and to blink, if necessary, only during key presses. After 500 ms, the memory array appeared for either 50 ms or 200 ms. Participants were tasked with remembering the color and position of the colored squares (targets) while ignoring the circles (distractors). During the probe phase, their task was to determine whether the color and position of the probe square matched that of a square in the memory array. The probe array had a different color than the memory array in 50% of the trials and was identical in the remaining trials. Responses were made by pressing "F" for a match and "J" for a non-match. The trials were separated by a jittered interval of 800–1000 ms.

The experiment comprised 20 blocks, each containing 32 trials, totaling 640 trials. The stimulus presentation durations (50 ms or 200 ms) were randomly interspersed, each occurring 320 times. After each block, the average accuracy for that set of trials was displayed. At least 32 practice trials were performed prior to recording the test performance. To prevent fatigue, the participants were given a break after each block, and they continued the experiment upon feeling rested.

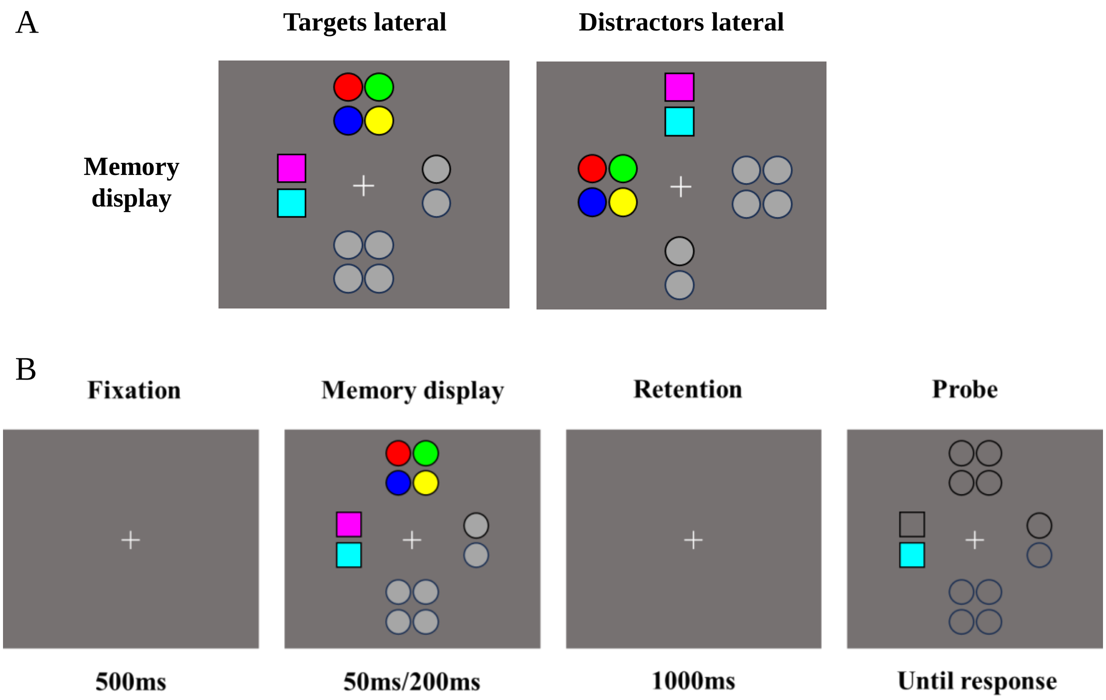

Figure 1. (A) Memory displays utilized in the WM filtering task. The left image demonstrates memory displays where targets are displayed laterally, and distractors are presented on the

vertical midline. These trials enabled the separation of target-related processing and the extraction of target-elicited lateralized ERP components (N2pc, CDA). The right image illustrates memory displays in which distractors are displayed laterally, and targets are presented on the vertical midline. These trials enabled the isolation of distractor-related processing and the extraction of distractor-evoked lateralized ERP components (early PD and PD). (B) Display of a trial sequence. Each trial commenced with a fixation cross, followed by the memory display. Subsequently, a blank screen (containing only a fixation cross) was presented before a probe emerged at one of the previous target locations. Participants were required to determine whether the probe exhibited the same color as the target previously displayed at the same location.

2.4 EEG Data Recording

The ERP recording system from Brain Products (Munich, Germany) was employed, with the EEG recorded utilizing a 64-channel electrode cap based on the international standard 10–20 system. The REF served as the online reference electrode, while the GND was the ground electrode. Horizontal electrooculography (EOG) was collected through the electrode site (IO) located 1 cm from the participant's right eye corner, while the vertical EOG was recorded through the electrode site FCz. The sampling frequency was set at 500 Hz, with an impedance between the electrodes and the scalp of less than 10 kΩ and an impedance of less than 5 kΩ for the electrode sites used in the analysis.

Continuous EEG data were analyzed offline using the MATLAB (2018b), EEGLAB (2023.0), and ERPLAB (v10.0) toolboxes. The average values of TP9 and TP10 (bilateral mastoids) were used for re-referencing, and low-pass filtering (30 Hz, 24 dB/octave) was applied. The average amplitude 200 ms before the memory array appeared was used for baseline correction, and the analysis time window was set to 1000 ms after the memory array presentation.

2.5 Data Analysis

2.5.1 Behavioral Data

We conducted planned pairwise comparisons using two-tailed paired t-tests to assess the differences in response time (RT) and accuracy (ACC) between the 50 ms and 200 ms presentation duration conditions.

2.5.2 EEG Data

Our EEG data analysis methodology was aligned with the approach of Feldmann-Wustefeld and Vogel (2019). In the main task, the EEG data were averaged offline over a 1200 ms epoch, which included a 200 ms prestimulus baseline, with the epochs time-locked to the onset of the memory array. Trials involving incorrect responses, blinks, or saccades between 0 ms and 800 ms were excluded from the analysis.

Blinks were identified when the absolute amplitude of the vertical EOG exceeded 100 μV, whereas saccades were defined by a horizontal EOG amplitude difference of more than 32 μV in a 200 ms window relative to the subsequent 100 ms window (step criterion). Individual channel segments with an absolute voltage exceeding 100 μV were excluded. Data from five participants were discarded because those participants had fewer than 100 trials per condition due to insufficient trials post artifact removal or incorrect responses. The remaining 30 participants had an average of 7.28% unusable trials (SD = 3.41%).

The mean contralateral and ipsilateral ERP activity for each participant was calculated at electrode sites P7/P8, P5/P6, and PO7/PO8. This was done separately for each presentation duration (50 ms vs. 200 ms), for the laterality condition (contralateral vs. ipsilateral), and for sites contralateral and ipsilateral to the targets/distractors (target lateral condition/distractor lateral condition).

We determined the epochs for statistical analyses of different ERP components by calculating the lateralized ERP (contralateral minus ipsilateral) for both the target lateral and distractor lateral conditions, resulting in four distinct waveforms (two for the 50 ms presentation duration conditions and two for the 200 ms presentation duration conditions) that were indicative of lateralized activity due to targets and distractors. The target-early PD and distractor-early PD epochs were determined as ± 50 ms around the most positive peak between 100 ms and 200 ms in the lateral-distractor waveform. The target-N2pc and distractor-N2pc epochs were identified as ± 50 ms around the most negative peak between 200 ms and 300 ms in the lateral-targets waveform. The distractor-PD epoch was established as ± 50 ms around the most positive peak between 250 ms and 350 ms in the lateral-distractor waveform. The mean amplitude for those time windows was calculated separately for laterality (contralateral vs. ipsilateral), for each presentation duration (50 ms vs. 200 ms), and for each participant, resulting in four values for each ERP component per participant. A 2-way repeated measures ANOVA with within-subjects factors of laterality (contralateral or ipsilateral) and presentation duration (50 ms, 200 ms) was conducted for each ERP component.

As anticipated, visual inspection revealed that the CDA in the target lateral condition lacked a clear peak. Thus, we selected a time window of 350–750 ms for the CDA analysis, as used by Feldmann-Wustefeld and Vogel (2019). The mean amplitude within this window for each presentation duration (50 ms vs. 200 ms) was calculated and forwarded to a 2-way ANOVA with the same within-subjects factors. Partial eta squared (η^2) is reported as the measure of effect size for ANOVAs. We applied the Greenhouse–Geisser correction, where appropriate. Planned pairwise comparisons using two-tailed paired t-tests were conducted to compare the differences between the 50 ms and 200 ms presentation duration conditions for each ERP component result, with Cohen's d serving as the estimator of effect size. Bayes factor analysis was also employed to mitigate the incidence of chance-based null results, as suggested by Rouder et al. (2009). The Bayes factor (BF_{10}) provides an odds ratio for the alternative/null hypotheses (values < 1 favor the null hypothesis and values > 1 favor the alternative hypothesis). For instance, a BF_{10} of 0.2 indicates that the null hypothesis is five times more likely than the alternative hypothesis to be true.

3 Results

3.1 Behavioral Results

No significant difference was evident in response times (RT) between the 50 ms and 200 ms stimulus presentation duration conditions, $t\,(29) = 1.006$, $P = 0.323$, *Cohen's* $d = 0.317$, $BF_{10} = 0.308$. However, a significant difference in accuracy (ACC) was noted between the 50 ms and 200 ms stimulus presentation durations, $t\,(29) = 6.813$, $P < 0.001$, *Cohen's* $d = 4.66$, $BF_{10} > 1000$.

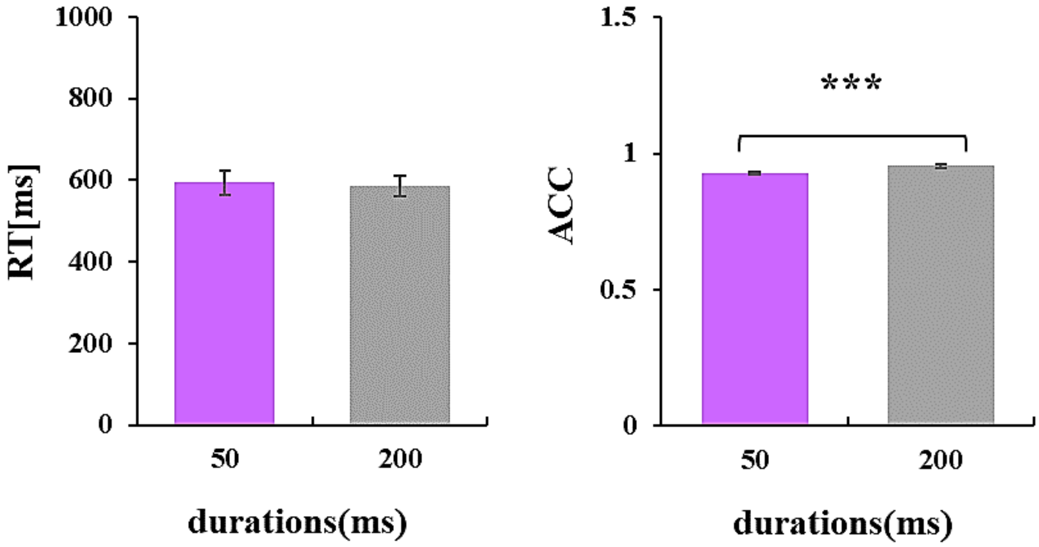

Figure 2. Behavioral results. The left panel presents the results of response times across different duration conditions, while the right panel depicts the accuracy results under different duration conditions. The error bars represent the standard errors of the mean values.

3.2 ERP Results

3.2.1 Target Lateral Condition

3.2.1.1 Early PD (111–171ms)

The appearance of targets elicited an early PD, which refers to a more positive deflection in the ERP at electrodes contralateral to (M = -1.06 μV) than ipsilateral to the targets (-1.36 μV). This indicates a main effect of laterality, $F\ (1,29) = 7.878,\ p = 0.009,\ \eta_p^2 = 0.214$. However, no main effect was determined for the duration of stimulus presentation, $F\ (1,29) = 0.559,\ p = 0.461,\ \eta_p^2 = 0.019$. Moreover, no significant interaction was detected between laterality and the duration of stimulus presentation, $F\ (1,29) = 1.125,\ p = 0.298,\ \eta_p^2 = 0.037$.

The results of planned pairwise comparisons indicated that when the stimulus presentation duration was 200 ms, a significant early PD was elicited, $t\ (29) = 2.656,\ p = 0.013$, *Cohen's* $d = 0.977,\ BF_{10} = 3.679$; however, when the stimulus presentation duration was 50 ms, no significant early PD was elicited, $t\ (29) = 1.981,\ p = 0.057$, *Cohen's* $d = 0.652,\ BF_{10} = 1.076$. No significant difference was evident in the amplitude of the early PD elicited by a stimulus presentation duration of 200 ms compared to 50 ms, $t\ (29) = 1.062,\ p = 0.297$, *Cohen's* $d = 1.171,\ BF_{10} = 0.325$.

3.2.1.2 N2pc(228–288ms)

The targets elicited an N2pc; that is, a more negative deflection in the ERP at electrodes contralateral to (M = 0.27 μV) than ipsilateral to targets (M = 0.58 μV), indicating a main effect of laterality, $F(1,29) = 7.534$, $p = 0.010$, $\eta_p^2 = 0.206$. The mean amplitude was more positive for 200 ms (M = 1.38 μV) than for 50 ms (M = - 0.67 μV), with a main effect of duration of stimulus presentation, $F(1,29) = 68.695$, $p < 0.001$, $\eta_p^2 = 0.703$. No interaction was noted between laterality and the duration of stimulus presentation, $F(1,29) = 0.141$, $p = 0.710$, $\eta_p^2 = 0.005$.

The results of planned pairwise comparisons indicated the elicitation of a significant N2pc whenever the stimulus presentation durations were 200 ms, *t (29) = 2.349, p=0.026, Cohen's d = 0.939*, $BF_{10} = 2.041$, or 50ms , *t (29) =2.596, p=0.015, Cohen's d = 0.841*, $BF_{10} = 3.262$. The amplitude of the N2pc elicited by a stimulus presentation was the same for a duration of 200 ms or 50 ms, *t (29) =1.062, p=0.708, Cohen's d = 0.346*, $BF_{10} = 0.208$.

3.2.1.3 CDA (350–750ms)

Targets elicited a CDA; that is, a more negative deflection in the ERP at electrodes contralateral to (M = - 0.94 μV) than ipsilateral to targets (M = 0.24 μV), indicating a main effect of laterality, F(1,29) = 44.621，p < 0.001，$\eta_p^2 = 0.606$. However, no main effect was detected for the duration of stimulus presentation, F(1,29) = 1.624, p = 0.213, $\eta_p^2 = 0.053$. The laterality and duration of stimulus presentation also showed no interaction, F(1,29) = 0.472，p = 0.497，$\eta_p^2 = 0.016$.

The results of planned pairwise comparisons indicated the elicitation of a significant CDA whenever the stimulus presentation durations were 200 ms, *t (29) = 6.516, p < 0.001, Cohen's d = 3.72*, $BF_{10} > 1000$, or 50 ms , *t (29) = 5.930, p < 0.001, Cohen's d = 4.42*, $BF_{10} > 1000$. The amplitude of the CDA did not differ significantly, whether elicited by a stimulus presentation duration of 200 ms or 50 ms, *t (29) = 0.687, p = 0.498, Cohen's d = 0.526*, $BF_{10} = 0.242$.

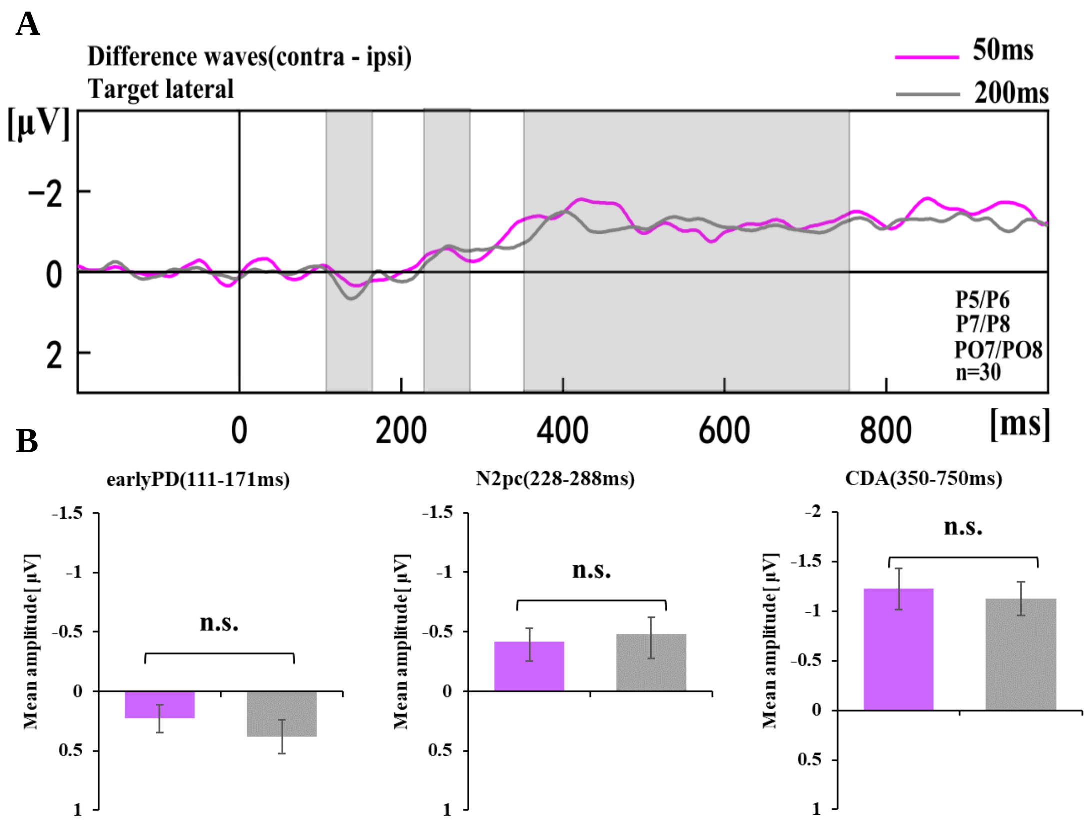

Figure 3. (A) The target laterality difference wave was recorded at the P5/P6, P7/P8, and PO7/PO8 electrode sites, and the average amplitude of the waves was analyzed. The purple and gray lines represent conditions with stimulation presentation durations of 50 ms and 200 ms, respectively. The gray bar chart represents the time windows corresponding to the early PD, N2pc, and CDA of the target laterality. (B) The results of the difference test under the two conditions (stimulation presentation duration of 50 ms or 200 ms) are shown. The purple bar chart represents the condition with a stimulation presentation duration of 50 ms, while the gray bar chart represents the condition with a stimulation presentation duration of 200 ms. Error bars indicate the standard errors of the mean values.

3.2.2 Distractor lateral condition

3.2.2.1 Early PD (111–171 ms)

The appearance of distractors elicited an early PD, reflecting a more positive deflection in the ERP at electrodes contralateral to (M = -1.18 μV) than ipsilateral to targets (-1.69 μV). This indicates a main effect of laterality, $F\ (1,29) = 31.380,\ p < 0.001,\ \eta_p^2 = 0.520$. The mean amplitude was more negative for 200 ms (M = -2.53 μV) than for 50 ms (M = -1.61 μV), indicating a main effect of the duration of stimulus presentation, $F\ (1,29) = 6.813,\ p = 0.014,\ \eta_p^2 = 0.190$. No significant interaction was noted between laterality and the duration of stimulus presentation, $F(1,29) = 1.040, p = 0.316, \eta_p^2 = 0.035$.

The results of planned pairwise comparisons indicated the elicitation of a significant early PD whenever the stimulus presentation durations were 200 ms, $t(29) = 5.446, p < 0.001$, *Cohen's* $d = 1.601, BF_{10} > 1000$ *ms*, or 50 ms , $t(29)=4.189$，$p < 0.001$, *Cohen's* $d = 1.327$, BF_{10} = 118.434. No significant difference was apparent in the amplitude of the early PD elicited by a stimulus presentation duration of 200 ms compared to 50 ms, $t(29) = 0.252, p=0.803$, *Cohen's* $d = 0.302, BF_{10} = 0.200$.

3.2.2.2 N2pc (204–264 ms)

No main effect was evident for laterality, $F(1,29) = 0.027$，$p = 0.870$，$\eta_p^2 = 0.001$. However, the mean amplitude was more positive for 200 ms (M = 0.86 μV) than for 50 ms (M = -1.53 μV), indicating a main effect of the duration of stimulus presentation, $F(1,29) = 86.350, p < 0.001, \eta_p^2 = 0.749$. An interaction was detected between laterality and the duration of stimulus presentation, $F(1,29) = 6.419$，$p = 0.017$，$\eta_p^2 = 0.181$.

The results of planned pairwise comparisons indicated that no significant N2pc was elicited whenever the stimulus presentation durations were 200 ms, $t(29) = 1.360, p = 0.184$, *Cohen's* $d = 0.331$，$BF_{10} = 0.447$, or 50 ms , $t(29)= 1.729$，$p = 0.095$, *Cohen's* $d = 0.490, BF_{10} =0.729$.

3.2.2.3 PD (288–348 ms)

The appearance of distractors elicited a PD, which refers to a more positive deflection in the ERP at electrodes contralateral to (M =1.13 μV) than ipsilateral to targets (M= 0.58 μV). This indicates a main effect of laterality, $F(1,29) = 12.421, p = 0.001, \eta_p^2 = 0.300$. The mean amplitude was more positive for 200 ms (M = 1.58 μV) than for 50 ms (M = 0.14 μV), indicating a main effect of the duration of the stimulus presentation, $F(1,29) = 31.662, p < 0.001, \eta_p^2=0.522$. A significant interaction was evident between laterality and the duration of stimulus presentation, F $(1,29) = 5.643, p = 0.024, \eta_p^2 = 0.163$.

The results of planned pairwise comparisons indicated the elicitation of significant PDs whenever the stimulus presentation durations were 200 ms, $t(29) = 4.119, p < 0.001$, *Cohen's* $d = 1.197$，$BF_{10} = 121.3$, or 50 ms, $t(29) = 2.225$，$p = 0.034$, *Cohen's* $d = 0.721$，$BF_{10} = 1.630$. A significant difference was noted in the amplitude of the PD elicited by a stimulus presentation duration of 200 ms compared to 50 ms, t $(29) = 2.376, p = 0.024$, *Cohen's* $d = 1.9625$，$BF_{10} = 2.145$.

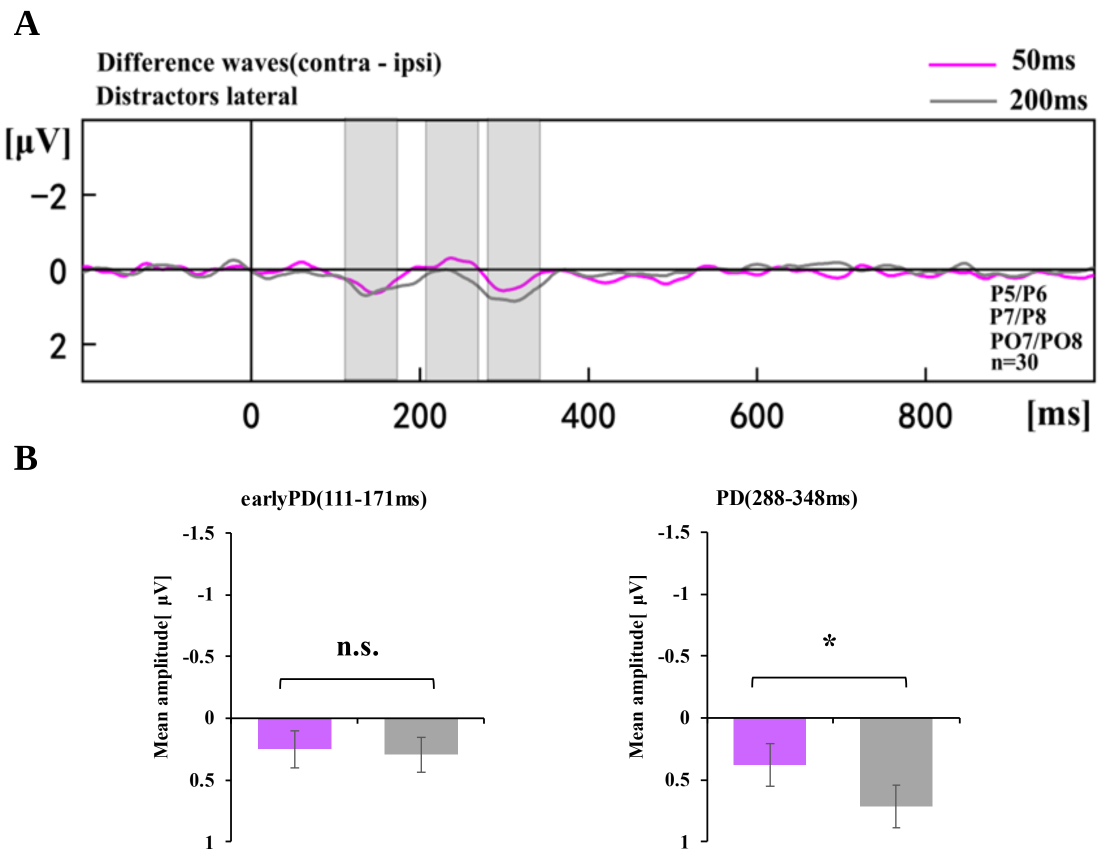

Figure 4. (A) Distractor laterality difference waves were recorded at the P5/P6, P7/P8, and PO7/PO8 electrode sites, with the average amplitude of the waves analyzed. The purple and gray lines represent conditions with stimulation presentation durations of 50 ms and 200 ms, respectively. The gray bar chart represents the condition with a stimulation presentation duration of 200 ms. The time windows correspond to the early PD, N2pc, and CDA of the target laterality. (B) The different test results under the two conditions (stimulation presentation duration of 50 ms or 200 ms) are shown. The purple bar chart represents the condition with a stimulation presentation duration of 50 ms, while the gray bar chart represents the condition with a stimulation presentation duration of 200 ms. Error bars indicate the standard errors of the mean values.

4 Discussion

The results of our study revealed that when the number of target items was two, no significant difference was observed in the CDA amplitude elicited by the target items, regardless of the stimulus presentation duration (50 ms or 200 ms). However, extension of the stimulus presentation duration resulted in a significant improvement in the individuals' VWM accuracy. When distractors were presented with a contralateral bias, a significant PD component was elicited at both 50 ms and 200 ms durations, but the PD amplitude elicited by distractors was larger under the 200 ms presentation duration condition than under the 50 ms presentation duration condition. Thus, our current findings suggest that consolidation time is an important factor influencing the suppression effects of distractors.

Feldmann-Wustefeld and Vogel (2019) found that increasing the number of distractors resulted in increases in the PD amplitude, leading them to suggest that the PD amplitude reflects the strength of "gating" in the gating theory. This theory posits that as the interference effect of distractors increases, a larger voluntary effort is required to close the "gate" to prevent distractors from entering VWM. In our study, the two target items had already been fully consolidated into VWM by 50 ms; therefore, when the stimulus presentation duration was 200 ms, this left more time for the late consolidation phase. At that point, individuals could further allocate their unused VWM resources for processing visual stimuli. However, this condition also inadvertently creates an opportunity for distractors to enter VWM and disrupt the VWM performance. To prevent this, individuals need to exert a larger voluntary effort to tightly close the "gate" and suppress the entry of distractors. In the current experiment, the longer stimulus presentation duration meant that distractors appeared on the visual field for a longer duration, thereby increasing the likelihood of their entry into the VWM system. Thus, reducing the exposure time of distractors in the memory array (i.e., decreasing the stimulus presentation duration) effectively reduced the distraction effects of distractors.

Our results with two target items also demonstrated that the CDA amplitude was not significantly different between the two stimulus presentation durations (50 ms and 200 ms). This finding was consistent with previous research and supported the notion of bandwidth-limited consolidation (i.e., parallel consolidation for two colors; see Hao et al., 2018; Mance et al., 2012). While no significant difference was found in the CDA amplitude, the average accuracy was significantly higher with the 200 ms stimulus presentation than with a 50 ms presentation. This finding validated the slot-resource model (Awh et al., 2007; Barton et al., 2009; Fougnie et al., 2010), which suggests that while the VWM resources have a finite total capacity, the precision of VWM representations depends on resource allocation under different task conditions. Moreover, according to our previously proposed two-phase resource allocation model (Ye et al., 2017, 2019), the VWM consolidation process includes two distinct resource allocation phases. When the stimulus presentation duration is relatively limited, individuals automatically allocate resources to each memory stimulus as efficiently as possible, resulting in a relatively low memory precision for stimuli. If the stimuli continue to be presented until the early VWM consolidation phase is completed, then resource allocation enters a late consolidation phase, allowing individuals to further allocate unused VWM resources to memory representations, thereby enhancing the precision of the representations. Therefore, in the current experiment, participants only needed to remember two target items, so they were left with sufficient resources to allocate to each memory item. However, when the stimulus presentation duration was only 50 ms, even though individuals could allocate more resources to remember target items, they could not achieve the same level of consolidation as was possible with a longer stimulus presentation duration of 200 ms.

One point worth noting is that we initially expected that we would not observe a significant PD component in the 50 ms presentation duration condition. However, in reality, we saw that a significant PD amplitude was already elicited in the 50 ms presentation duration condition. Moreover, neither condition elicited a CDA component, suggesting that distractors in both conditions required suppression and were successfully suppressed (Hakim et al., 2021). We propose two possible explanations for this phenomenon: (1) The first explanation is that the consolidation speed for target items may be faster than we initially assumed. Previous research has indicated that consolidating a color item takes approximately 50 ms (Vogel et al., 2006) and that two color items can be consolidated in parallel into VWM. Therefore, we hypothesize that 50 ms may be a sufficient duration for consolidating two color items into VWM. However, the observation of a significant PD component in the 50 ms presentation duration condition may indicate that the time required to consolidate two target items into VWM is less than 50 ms, suggesting a faster actual consolidation speed than we had assumed. (2) The second explanation is that the consolidation of target items and the suppression of distractors may not be a sequential process, but rather a parallel one. In other words, individuals may start suppressing distractors while consolidating target items; consequently, even with a very brief stimulus presentation duration, a PD component may still be observed. Future research could further investigate these two possibilities.

5 Conclusions

This study manipulated the duration of stimulus presentation and explored the influence of time factors on individual suppression control of distractors. The results indicated that the suppression of distractors in VWM is regulated by the duration of the stimulus presentation, so that a longer presentation duration will result in a larger distraction effect and a stronger suppression effect on distractors.

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