Attention-operated working memory representations determine visual selective attention

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Abstract

It has been demonstrated that visual attention is guided by information actively maintained in working memory (WM). However, it remains unknown whether other operations (e.g. inhibition) on WM contents influence selective attention. This issue was investigated in a visual search task where WM contents with either operation (maintenance or inhibition) appeared as distractors in the search display. Behavioral results showed that search performance was slowed down for presenting the maintained contents, but speeded up for the inhibited contents. These results suggested an operation-directed selection of WM contents that visual attention was distinctively influenced by contents with different operation. These observations were further confirmed by the indexes of event-related potentials (ERPs). The inhibited WM contents were suppressed at sensory gating stage (i.e., suppressed P1 amplitude), while the maintained WM contents guided visual attention (i.e., enhanced N2pc amplitude). It seems that results from ERPs and behavior are integrated. The maintained contents guided visual attention that hindered performance of searching a target, while the inhibited contents screened attention that facilitated target searching in the other space. Besides, P3 component indexing updating of WM, which revealed comparable latency both for the maintained and the inhibited WM contents, but with longer latency than the neutral contents. These results suggested that the WM contents with distinct operations were expelled from the focus of executive attention after the onset of the search task, which might be necessary for the WM contents influencing selective attention. The current study reveals that operations of WM contents distinctively affect early selective attention to the matching contents, which sheds some light on the interaction between WM and visual attention.

Full Text

Preamble

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Attention-operated working memory representations determine visual selective attention

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Abstract: Previous research has demonstrated that visual attention is guided by information actively maintained in working memory (WM). However, it remains unclear whether other operations (e.g., inhibition) performed on WM contents also influence selective attention. This issue was investigated using a visual search task in which WM contents undergoing either maintenance or inhibition appeared as distractors in the search display. Behavioral results showed that search performance was slowed when maintained contents were present, but speeded when inhibited contents were present. These findings suggest an operation-directed selection mechanism whereby visual attention is differentially influenced by contents undergoing different operations. This pattern was further confirmed by event-related potential (ERP) indices. Inhibited WM contents were suppressed at the sensory gating stage (i.e., suppressed P1 amplitude), whereas maintained WM contents guided visual attention (i.e., enhanced N2pc amplitude). The ERP and behavioral results converge: maintained contents guided visual attention, hindering target search performance, while inhibited contents filtered attention, facilitating search in other locations. Additionally, the P3 component, which indexes WM updating, revealed comparable latency for both maintained and inhibited WM contents, though longer than for neutral contents. These results suggest that WM contents with distinct operations were expelled from the focus of executive attention after search task onset, which may be necessary for WM contents to influence selective attention. The current study reveals that operations on WM contents distinctively affect early selective attention to matching contents, shedding light on the interaction between WM and visual attention.

Keywords: selective attention; working memory (WM); event-related potentials (ERPs); attentional operation; inhibition

1 Introduction

Working memory (WM) and attention are closely related. Information maintained in WM has been shown to influence selective attention, though some studies have failed to find such effects. Thus, further investigation is needed to resolve this controversy and understand its underlying mechanisms.

The finding that visual attention in a search task is biased toward content maintained in a concurrent WM task suggests a guidance effect driven by memory content. This guidance effect is automatic and robust, even in the presence of a salient search target. However, other studies have found no guidance effect of maintained WM contents when the selective attention task requires active representation. Given that the number of items that can be processed by executive attention is limited, WM contents and search targets would compete for attentional focus in dual-task paradigms. When the target is actively represented and occupies attentional focus, WM contents that are merely stored but not under executive attention produce diminished or absent guidance effects. Thus, there appear to be two different states of WM: contents under executive attention influence visual attention, while merely stored contents do not.

It seems that ongoing processing of WM contents with executive attention may be critical for influencing visual attention. Executive function involves two distinct operations: maintenance and inhibition. While previous studies have focused on how maintained WM contents influence attention, little is known about how inhibitory operations affect selective attention. Inhibition excludes irrelevant information and suppresses distractors, a process emphasized in numerous studies. Top-down suppression of irrelevant information is essential and continuously engaged to optimize performance. As a crucial executive function, inhibition is indispensable for revealing the mechanisms underlying the interaction between selective attention and WM contents. Investigating whether inhibited WM contents influence attention can directly test the view that WM contents under executive attention affect selective attention. Comparing the effects of inhibited versus maintained contents on selective attention will illuminate the relationship between attention and WM contents undergoing different operations.

As noted above, executive attention operating on WM contents likely influences selective attention to matching information. However, it remains unclear whether it is the contents under executive attention per se or the specific operation performed on them that affects selective attention. We propose two alternative hypotheses to resolve this question: attention-directed guidance and operation-directed selection. Since operations on WM contents (maintenance and inhibition) both involve executive attention, these contents are processed within the attentional focus and can readily gain control of visual attention.

Based on this view, attention-directed guidance suggests that matching contents under executive attention will be more accessible and attract visual attention in the other task. Therefore, attention-directed guidance predicts that both maintained and inhibited WM contents will capture visual attention, showing similar patterns of selective attention. In contrast, operation-directed selection acknowledges the accessibility of contents under executive attention but further posits that the specific operation (maintenance or inhibition) performed on executive attention determines the selective attention allocated to perceptually matching contents. In other words, maintained content is attended while inhibited content is suppressed when they appear in the visual field. This view predicts that maintained and inhibited contents will produce distinct patterns of selective attention.

In the current experiment, we used a dual-task paradigm combining a WM task and a visual search task, modified from Olivers et al. (2006). In the WM task, participants first memorized two colors, then received a cue indicating which color to maintain and which to inhibit. Stimuli were presented in bilateral visual fields in the search array, enabling examination of lateralized processing indicative of selective attention. Additionally, cued or uncued WM contents could appear in the visual field opposite the search target. A baseline (neutral condition) was established when no memory item appeared in the search array. Using a moderate interval between the WM task and search task, the cued and uncued WM contents were presumed to undergo different operations (maintenance and inhibition, respectively) under executive attention. If attention-directed guidance determines how WM contents influence attention, both maintained (cued) and inhibited (uncued) WM contents should guide attention and impair search performance. Alternatively, operation-directed selection predicts adverse effects for maintained WM contents and beneficial effects for inhibited WM contents in the search task.

In addition to behavioral measures, we employed electrophysiological methods to reveal the neural mechanisms underlying selective attention influenced by WM operations. Electroencephalogram (EEG) data were recorded while participants performed the dual-task. Early ERP components (e.g., P1 and N1) were used to index selective attention at the sensory gating stage. The attentional guidance effect was assessed via the N2pc component, which is sensitive to spatially selective attention. Additionally, the P3 component was examined as a later attentional index.

2.1 Participants

Twenty-four right-handed college students (11 females, aged 18-25 years) from Southwest University participated for monetary compensation. All reported normal or corrected-to-normal visual acuity and normal color vision. Informed consent was obtained from all participants. The study was approved by the Review Board of Southwest University (Chongqing, China) for Human Participant Research.

2.2 Apparatus, stimuli and procedure

E-Prime software (version 1.1, Psychology Software Tools Inc., Pittsburgh, USA) controlled stimulus presentation and response collection. Stimuli were displayed on a 17-inch monitor with 1,024 × 768 pixel resolution and 85 Hz refresh rate. Viewing distance was approximately 70 cm.

Stimuli appeared on a gray background (RGB: 128, 128, 128). Color patches subtended 1.6° × 1.6° visual angle. Ten colors were selected from the Munsell color system, comprising five principal hues (red, yellow, green, blue, and purple) with specific values listed in Table 1 . Hue and value were kept nearly constant while chroma varied between 8 and 12. Note that these colors were only approximations of Munsell’ s original colors due to monitor limitations. Vertical lines subtended 0.8° × 0.1° visual angle, with targets tilted 15°. In the search array, four lines were presented, each centered on a color patch.

The trial sequence is shown in Figure 1 [Figure 1: see original paper]. Each trial began with a 500 ms black fixation cross, followed by a 1500 ms memory array containing two colors to be remembered. Color patches appeared on the horizontal meridian, 1.5° above and below fixation. A 500 ms mask array containing two Mondrian patches then appeared at the same locations. During the final 200 ms of the mask array, an arrow at fixation cued distinct attentional operations (maintenance vs. inhibition) on the memory colors. The arrow pointed to the color to be tested and maintained, while the uncued color was irrelevant and to be inhibited. The inter-stimulus interval between mask and search arrays varied randomly between 1000-1200 ms. The search array contained four objects in separate quadrants of an imaginary clock face with 6.5° radius.

Colors differed between left and right visual fields but were identical within each field. Participants responded to target location (left vs. right visual field). After 500 ms, a test array with two different color patches appeared horizontally, requiring a response about cued color presence. Both search and test arrays remained visible until response or 3000 ms. The inter-trial interval was 500 ms.

2.3 Assignment of stimuli

Stimulus locations were counterbalanced. In the mask array, upward and downward arrows appeared equally often. In the search array, targets appeared equally often in all four quadrants. Cued and uncued colors appeared in left and right visual fields with equal probability. Cue direction relative to target location and left/right correspondence between search target and cued color in the test were counterbalanced.

Colors in each array were controlled for specific purposes. In the memory array, colors were selected from adjacent hues (red, yellow, green, blue, and purple) to ensure visual similarity, promoting visual representation of memory colors.

In the search array, when one memory color appeared, the other color was the most dissimilar to it. Otherwise, two colors dissimilar to both memory colors were displayed. Luminance contrast and color distance in the search array were approximately equated to avoid physical attribute differences. In the memory test, two similar colors were chosen to ensure visual representation of memory colors.

2.4 Design

Our primary focus was the interaction between operations on visual WM content and visual attention. We manipulated the relationship between WM contents with distinct operations (maintained vs. inhibited) and the search target. Specifically, one memory color appeared in the search array on half of trials, with cued (cued condition) and uncued (uncued condition) colors presented opposite the target equally often. On the remaining trials, other colors appeared in the search array as a neutral condition. Thus, we established three Search conditions (cued, uncued, and neutral) in a 1:1:2 ratio to avoid bias toward memory items.

For the memory test, cued and uncued colors were presented equally often and independently, generating four combinations of Cued color (presence, absence) × Uncued color (presence, absence).

Participants completed 24 practice trials with memory test feedback. The main experiment consisted of 24 blocks of 24 trials each, with pseudo-random trial assignment. Each block lasted 2-3 minutes, with self-paced rest periods. The entire experiment required 60-70 minutes. Practice data were excluded from analysis.

2.5 EEG recordings and pre-processing

EEG data were recorded using a Brain Products system (band pass: 0.01-100 Hz, sampling rate: 500 Hz, notch filter off) from 60 scalp Ag-AgCl electrodes positioned according to the international 10-20 system. All inter-electrode impedances were maintained below 5 kΩ, with FCz as reference and AFz as ground. Electro-oculograms (EOGs) were simultaneously recorded from four surface electrodes placed above and below the left eye and at the outer canthi of both eyes to monitor eye movements and blinks. EEG and EOG signals were amplified using DC voltage.

EEG data were pre-processed using EEGLAB 11.0 (Delorme & Makeig, 2004). Continuous recordings were band-pass filtered between 1-40 Hz. EEG epochs were segmented into 1200 ms windows (200 ms pre-stimulus to 1000 ms post-stimulus) for the search task and baseline-corrected using the pre-stimulus interval. Epochs were visually inspected, and trials with substantial movement artifacts were removed. Trials contaminated by eye blinks and other movements were corrected using independent component analysis (ICA) (Delorme & Makeig, 2004; Delorme, Sejnowski, & Makeig, 2007). In all datasets, independent components showing large EOG channel contributions and frontal scalp distributions were clearly identifiable as eye movements and were removed. After ICA and additional baseline correction, EEG trials (minimum 110 trials per condition) were re-referenced to bilateral mastoid electrodes.

2.6 Data analysis

Behavioral data analyses. In search task analyses, data from one participant were excluded due to excessive errors (exceeding three standard deviations). Trials with incorrect responses or RTs exceeding 1200 ms were removed (approximately 4% of trials) from mean RT analyses. One-way repeated-measures ANOVA was performed on mean RTs and accuracies for Search condition. Memory test data were analyzed using a 2 (Cued color: presence, absence) × 2 (Uncued color: presence, absence) repeated-measures ANOVA.

ERP data analyses. Statistics were based on 23 participants with normal error rates. Single-participant averaged waveforms in each condition were combined to create grand-averaged waveforms for group-level scalp topographies. P1, N1, N2pc, and P3 components were analyzed for the search task.

The P1 showed maximal activation around 100 ms at lateral parietal-occipital scalp sites. At electrodes P1/2, P3/4, PO3/4, and PO7/8, P1 peak amplitudes were identified as the maximum positive deflection in the 60-130 ms window. A 4 (Electrode: P1, P3, PO3, PO7) × 2 (Hemisphere: left, right) × 3 (Search condition: cued, uncued, neutral) repeated-measures ANOVA was performed on peak amplitudes and latencies.

N1 peak amplitudes were identified at occipital electrodes (Oz, O1/2, POz, PO3/4) as negative deflections within the 160-200 ms window. A 6 (Electrode: Oz, O1/2, POz, PO3/4) × 3 (Search condition: cued, uncued, neutral) repeated-measures ANOVA was performed on N1 peak amplitudes and latencies.

The N2pc component was measured at pooled occipital electrodes (PO7/PO8) by subtracting ipsilateral from contralateral waveforms relative to the target. For statistical analysis, N2pc waveforms were computed with a 100-ms pre-stimulus to 400-ms post-stimulus interval using the pre-stimulus period as baseline (Figure 4 [Figure 4: see original paper]). Mean area amplitudes across 170-250 ms were compared between contralateral and ipsilateral electrodes using paired-sample t-tests for each condition. N2pc amplitudes across Search conditions were obtained by averaging area amplitudes across 170-250 ms and analyzed with one-way ANOVA.

P3 peak amplitudes were identified at four posterior midline electrodes (CPz, Pz, POz, Oz) in the 280-400 ms range. A two-way (Electrode × Search condition) repeated-measures ANOVA was performed.

All statistical analyses were conducted using Statistical Product and Service Solutions (version 13.0, SPSS Inc.). Greenhouse-Geisser correction for degrees of freedom was applied when sphericity assumptions were violated ($p < .05$). For multiple comparisons, p-values were adjusted using Bonferroni correction.

3.1.1 Search task

Figure 2 [Figure 2: see original paper] shows mean RTs and error rates in the search task. Mauchly’ s test of sphericity on RTs was significant (^{2}(2) = 12.68, p = .002) for Search condition, so corrected degrees of freedom were used. There was a significant main effect of Search condition (F(2,44) = 35.00, $p < .001$, p 2 = 0.61) on RTs. Pairwise comparisons indicated that RTs in the cued condition were 39 ms slower than in the neutral condition (t(22) = 5.37, $p < .001$, d = 1.12) and 49 ms slower than in the uncued condition (t(22) = 7.02, $p < .001$, d = 1.46).

Interestingly, performance in the uncued condition was significantly better (10 ms faster) than in the neutral condition (t(22) = 2.60, p = .048, d = 0.54). These results indicate that cued colors opposite the target hindered selection, while uncued colors opposite the target facilitated visual search. Accuracies showed equal variances (^{2} = 2.28, p = .32), and no main effect was observed due to high accuracy (>99%) across all conditions (F(2,44) = 1.70, p = .19).

3.1.2 Memory test

Overall mean accuracy in the memory task was 84.5%, with mean reaction time of 831 ms. Accuracy analyses showed main effects of Cued color (F(1,23) = 29.97, $p < .001$, p 2 = 0.57), with better performance when the cued color was present (t(23) = 5.47, $p < .001$, d = 1.12), and of Uncued color (F(1,23) = 17.58, $p < .001$, p 2 = 0.43), with worse performance when the uncued color was present (t(23) = -4.19, p = .001, d = -0.86).

Moreover, the interaction between Cued color and Uncued color was significant (F(1,23) = 7.49, p = .012, p 2 = 0.25). Follow-up tests revealed a simple effect of Uncued color when the cued color was absent (F(1,23) = 15.82, p = .001, p 2 = 0.41), but no simple effect when the cued color was present (F(1,23) = 2.75, p = .11). These results suggest that the uncued color may have been mistaken for the cued color when the latter was absent.

Correct responses were entered into mean RT analyses. A main effect of Cued color emerged (F(1,23) = 16.02, p = .001, p 2 = 0.41), with faster responses when the cued color was present (t(23) = -4.00, p = .001, d = -0.82). A main effect of Uncued color also emerged (F(1,23) = 4.29, p = .05, p 2 = 0.16), with slower RTs when the uncued color was present (t(23) = 2.07, p = .05, d = 0.42). The interaction between Cued and Uncued colors was also significant (F(1,23) = 18.92, p < .001, p 2 = 0.45). Follow-up tests revealed significant simple contrasts of Uncued color, reversed for cued color presence (t(23) = -2.50, p = .02, d = -0.51) and absence (t(23) = 4.51, p < .001, d = -0.92). Accuracy and RT results were consistent, indicating that uncued color presence influenced cued color detection, even though the two colors were clearly distinguishable.

3.2.1 P1

For P1 peak amplitude analysis, Mauchly' s test of sphericity was significant for Electrodes and all interactions (p < .05), so reported values used corrected degrees of freedom. Results showed main effects of Electrodes (F(3,66) = 7.64, p = .001, p 2 = 0.26) and Search condition (F(2,44) = 8.29, p = .001, p 2 = 0.27). Pairwise comparisons of Search condition (Figure 3 [Figure 3: see original paper]) showed smaller P1 peak amplitudes in the uncued condition relative to cued (t(22) = -4.72, p < .001, d = 0.98) and neutral conditions (t(22) = -2.76, p = .034, d = -0.58), but no difference between cued and neutral conditions (t(22) = 1.05, p = .67). The Electrode × Search condition interaction was also significant (F(6,132) = 3.32, p = .016, p 2 = 0.13). Follow-up tests on separate electrodes revealed significant simple effects of Search condition at P1/2 (F(2,44) = 7.86, p = .003, p 2 = 0.43), P3/4 (F(2,44) = 7.09, p = .004, p 2 = 0.40), and PO3/4 (F(2,44) = 11.29, p < .001, p 2 = 0.52), but not at PO7/8 (F(2,44) = 2.15, p = .14). No other main effects or interactions were observed (p > .05).

For P1 peak latency analysis, Mauchly' s test of sphericity was significant for the Electrode × Search condition interaction and three-way interaction (p < .05). However, neither main effects nor interactions were found (F < 1.5, p > .1).

3.2.2 N1

Mauchly' s test of sphericity was significant for Electrode and the Electrode × Search condition interaction (p < .05). No main effect of Search condition was observed for peak amplitudes (F(2,44) = 0.50, p = .61) or latencies (F(2,44) = 0.725, p = .49).

3.2.3 N2pc

Mauchly' s test of sphericity was not significant for Search condition (p > .05). N2pc area amplitude showed a significant main effect of Search condition (F(2,44) = 10.76, p = .003, p 2 = 0.33). Pairwise comparisons revealed more negative mean amplitudes in the cued condition than in uncued (t(22) = -3.94, p = .002, d = -0.82) and neutral conditions (t(22) = -3.62, p = .005, d = -0.75), with no difference between uncued and neutral conditions (t(22) =

1.19, p = .75). Additionally, paired-sample t-tests of area amplitude between contralateral and ipsilateral electrodes were significant for all Search conditions (t(22) = -4.94, $p < .001$ for cued; t(22) = -3.46, p = .002 for uncued; t(22) = -2.64, p = .015 for neutral).

3.2.4 P3

Mauchly' s test of sphericity for peak amplitude was significant for Electrode and the Electrode × Search condition interaction ($p < .05$), and for peak latency was significant for the Electrode × Search condition interaction ($p < .05$). The 4 × 3 repeated-measures ANOVA on peak amplitude showed significant main effects of Electrode (F(3,66) = 4.19, p = .019, p 2 = 0.16) and Search condition (F(2,44) = 7.13, p = .002, p 2 = 0.25).

Pairwise comparisons on Search condition indicated smaller P3 peak amplitude in the neutral condition than in cued (t(22) = 3.64, p = .003, d = 0.758) and uncued conditions (t(22) = 3.58, p = .007, d = 0.75), with no difference between cued and uncued conditions (t(22) = 0.51, p = .91). No significant interaction was observed (F(6,132) = 1.38, p = .26). The same analysis on P3 peak latencies showed no significant main effects of Electrode (F(3,66) = 1.54, p = .21) or Search condition (F(2,44) = 2.05, p = .14), and no significant interaction (F(6,132) = 0.91, p = .50).

4 Discussion

The current study examined how WM contents undergoing distinct operations influence selective attention. Participants memorized two colors, then received a cue to maintain one and inhibit the other. These different operations on WM contents differentially modulated behavioral and ERP indices of selective attention in a concurrent visual search task. Specifically, search task responses were slowed when distractors were maintained (cued) WM contents but speeded when they were inhibited (uncued) WM contents, relative to neutral conditions. Consistently, ERP results reflecting early selective attention showed an inhibitory process marked by reduced P1 amplitude for inhibited WM contents, while enhanced N2pc amplitude indicated attentional guidance by maintained WM contents. Together, behavioral and ERP results demonstrate that selective attention was influenced by both maintained and inhibited WM contents, but these influences differed according to their operations during WM processing. Thus, operation-directed selection is supported: perceptually matching content is selected based on its operation under executive attention.

Interestingly, selective attention reflected in the P3 component as late attentional updating was equally modulated by maintained and inhibited WM contents.

Behavioral performance showed that selective attention was differentially modulated by maintained versus inhibited WM contents due to their distinct operations. Notably, both WM contents were initially memorized but then cued for different operations. Thus, it was the operation performed on the contents that placed them under executive attention and made them accessible, which in turn influenced attentional selection. Moreover, the influences differed: maintained contents produced adverse effects while inhibited contents produced beneficial effects. These distinct attentional patterns align with operation-directed selection rather than attention-directed guidance. We propose that contents under executive attention affect visual attention according to their ongoing operations. The present study extends previous views by demonstrating that distinct operations on information separately determine selective attention to matching content.

ERP results further elucidated the mechanisms underlying operation-directed selection. The P1 component reflected inhibitory processes at the sensory gating stage. Previous studies have suggested an inhibitory mechanism for filtering interference, with smaller P1 amplitude for targets in suppressed locations. In the current experiment, reduced amplitude was observed in search arrays containing inhibited WM contents compared to maintained or neutral contents. This suppressed P1 component indicates that inhibited WM contents were filtered from visual attention, narrowing the search scope and facilitating performance. Thus, electrophysiological modulation of inhibited WM contents was consistent with the behavioral benefit. Furthermore, inhibitory filtering of specific content has been observed during WM representation and in template-for-rejection tasks, processes similar to transferring inhibitory WM operations to perceptually matching contents. Therefore, P1 modulation suggests that inhibited WM contents were suppressed similarly to operations during WM maintenance.

Notably, attentional guidance by maintained WM contents was indicated by enhanced N2pc amplitude, as demonstrated in previous studies. Here, N2pc amplitude was larger in search arrays with maintained content than with inhibited or neutral content, with no difference between inhibited and neutral arrays. Thus, guidance effects were observed for maintained but not inhibited WM contents. This guidance implies that maintained WM contents captured visual attention, replicating Kumar et al. (2009). Consequently, maintained WM contents increased distraction, hindering target search at opposite locations and producing behavioral costs. According to Desimone (1996), search templates are also maintained in WM, so attentional guidance by maintained WM contents may resemble selection by an active search template. However, in the current dual-task, WM content guidance differed from search template guidance because it was detrimental to search performance. Thus, there may have been competition for selective attention after guidance, as Duncan and colleagues have shown. It is worth noting that preliminary inhibition of memory-relevant contents is inappropriate in dual tasks. Therefore, the larger N2pc amplitude elicited by maintained contents likely reflects competition for selective attention between search target and maintained WM content, revealing attentional re-deployment to the search target after initial guidance, as shown in neuroimaging studies. Meanwhile, the absence of attentional guidance for inhibited WM contents was reasonable, as they were suppressed at the sensory gate (P1 component). Together, behavioral performance aligns with early ERP evidence, illustrating that WM content operations determine selective attention to matching contents. We suggest that operation-directed selection likely results from transferring internal operations to perceptual selection of the same contents.

Moreover, P3 amplitude findings provided convincing evidence that both maintained and inhibited WM contents were under executive attention. The P3 component is thought to reflect revision of mental representations induced by prior exposures. Results showed equal P3 amplitudes for maintained and inhibited WM contents, both larger than for neutral contents. This larger P3 amplitude indicates that visual scenes containing WM contents were updated, regardless of whether contents were maintained or inhibited. This attentional updating may reflect a requirement to shift attentional focus that had previously been occupied by WM contents.

Thus, we conclude that both maintained and inhibited WM contents were under executive attention, and their different influences on selective attention resulted from distinct operations. Notably, attentional shifting from refreshing the visual context helped focus on the current search task.

However, our operation-directed selection conclusion seems to contradict a similar experiment by Olivers et al. (2006), who found attentional guidance by maintained WM items but no influence from inhibited WM items. This discrepancy may stem from differences in WM task difficulty. Olivers et al. (2006) used highly similar WM stimuli requiring precise visual representation and increased cognitive load. High cognitive load can lead to loss of cognitive control, hindering appropriate suppression of task-irrelevant information. Thus, insufficient inhibitory operation of uncued contents might explain their null effect on visual attention.

Nevertheless, the current study used a relatively easy task that ensured proper maintenance and inhibition operations on WM contents, revealing distinct patterns of influence on selective attention and supporting operation-directed visual selection.

The operation-directed visual selection view has two aspects. First, attentional allocation is influenced by contents under executive attention, even for retrieved memories. In other words, previously maintained contents or priming items cannot influence visual attention unless they are under executive attention at that moment. However, executive attention is not always obvious in dual tasks due to capacity limitations and goal competition, typically allowing only the immediate goal to occupy attentional focus. Thus, when facing an immediate search task, this influence occurs only when attentional focus is dominated by WM contents; otherwise, it is absent. Second, we extend this view by proposing that the direction of attentional influence (attend vs. suppress) is determined by the operation performed on WM contents under executive attention.

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