Can Negative Emotional Information from Task-Irrelevant Working Memory Representations Capture Visual Attention? An Eye-Tracking Study

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Abstract

This study investigated the influence of negative emotional information from irrelevant working memory representations on visual attentional selection by analyzing first fixations and behavioral response times in a visual search task. Experiment 1 found that on the first fixation percentage index, which reflects early attentional selection, a significant attentional capture effect occurred regardless of the emotional valence of the working memory representation. Experiment 2 found that when neutral emotional target stimuli were employed, a robust attentional capture effect was still exhibited on the first fixation percentage index. On the first fixation duration index, both Experiment 1 and Experiment 2 found that distractors in the memory-matching condition were significantly shorter than those in the control condition, demonstrating rapid attentional disengagement. In contrast, on the behavioral response time index, the early attentional capture effect disappeared (Experiment 1) and was even reversed into an attentional suppression effect (Experiment 2). These results indicate that during the early attentional selection stage, memory-driven attentional capture effects are not influenced by the emotional valence of working memory representations, but cognitive control facilitates rapid attentional disengagement from memory-matching distractors after early attentional capture, with its effectiveness being modulated by the emotional valence of target stimuli.

Full Text

Can Negative Emotional Information in Task-Irrelevant Working Memory Representations Capture Visual Attention? An Eye-Tracking Study

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Abstract

This study investigated how task-irrelevant negative emotional information in working memory representations influences visual attentional selection by analyzing first fixation points and behavioral reaction times in a visual search task. Experiment 1 found that in the first fixation percentage index, which reflects early attentional selection, a significant attentional capture effect occurred regardless of the emotional valence of the working memory representation. Experiment 2 revealed that when neutral emotional targets were used, the attentional capture effect remained robust in the first fixation percentage index. In terms of first fixation duration, both experiments showed that distractors in the memory-matching condition were significantly shorter than those in the control condition, demonstrating rapid attentional disengagement. However, in the reaction time index, the early attentional capture effect disappeared (Experiment 1) or was even reversed into an attentional suppression effect (Experiment 2). These results indicate that during early attentional selection, memory-driven attentional capture is not modulated by the emotional valence of working memory representations, but cognitive control facilitates rapid disengagement from memory-matching distractors after initial capture, with its effectiveness being modulated by the emotional valence of target stimuli.

Keywords: cognitive control; emotional working memory; attentional capture effect; attentional suppression effect; eye-tracking technique
Classification Number: B842.6

1. Introduction

From an evolutionary perspective, emotional stimuli—especially threatening negative emotional stimuli such as violence, blood, fierce animals, and angry expressions—are closely linked to human survival and thus receive prioritized processing (Baluch & Itti, 2011; Sutherland et al., 2017). Researchers have found that negative emotional stimuli can influence attentional bias, attracting attention more quickly or occupying more attentional resources, a phenomenon known as the negative emotional bias effect (Nummenmaa et al., 2009; Pourtois et al., 2006). Even under subliminal perceptual conditions with reduced visibility (Nasrallah et al., 2009) or in attentional blink tasks with subliminal attentional conditions (McHugo et al., 2013), negative emotional stimuli can still be rapidly identified. Studies have also shown that even when negative emotional stimuli are task-irrelevant, they can still capture attention and impair processing of the current task (Gupta et al., 2016; Padmala et al., 2018). For instance, high-arousal negative distractors (such as mutilation images) produce greater interference effects than neutral distractors in both letter search tasks (Gupta et al., 2016; Okon-Singer et al., 2007) and orientation discrimination tasks (Erthal et al., 2005).

Researchers have proposed three main theoretical explanations for attentional bias toward task-irrelevant emotional stimuli. The first is the automatic processing view, which posits that emotional stimuli are processed automatically and are not influenced by factors such as task relevance or difficulty (Attar & Müller, 2012; Oei et al., 2012). The second is the Biased Competition Model of Attention (Desimone & Duncan, 1995), which argues that task-irrelevant emotional stimuli must compete for attentional resources, and the resources they can obtain decrease as the resources required by the current task increase, thereby reducing their impact on the current task. This view has received support from several studies (Erthal et al., 2005; Huang et al., 2013; Pessoa et al., 2002). The third is the Perceptual Load Theory (Lavie, 1995, 2010), which suggests that the level of perceptual load in the current task determines the allocation of selective attention resources at the perceptual level. Low perceptual load leads to spillover effects of attention to task-irrelevant emotional stimuli, whereas high perceptual load can eliminate interference from such stimuli. For example, Gupta et al. (2016) found that task-irrelevant emotional stimuli interfered with target search in low-perceptual-load search tasks, but this interference decreased in high-perceptual-load search tasks.

The above theoretical explanations and related research have primarily focused on how negative emotional stimuli capture visual attention in a bottom-up manner. Although numerous studies have examined how emotion modulates attentional resources to influence information storage in working memory (Borg et al., 2011; Garrison & Schmeichel, 2019), few have investigated how negative emotional information already stored in working memory influences visual attentional selection in a top-down fashion. In recent years, substantial research has confirmed that information stored in working memory (i.e., working memory representations) can capture visual attention (see reviews: Soto et al., 2008; Pan, 2010; Zhang & Huang, 2013), a phenomenon termed memory-driven attentional capture (Olivers et al., 2006). Unlike stimulus-driven attentional capture elicited by salient physical stimuli (Theeuwes, 2012), in studies of memory-driven attentional capture, all visual search stimuli are perceptually homogeneous in physical features, and the attentional capture advantage of distractors sharing features with working memory representations originates from the top-down activation of those representations (Soto et al., 2008).

Most studies on memory-driven attentional capture have used neutral stimulus materials (such as colored geometric shapes or irregular figures). To date, only two studies have explored how emotion-related working memory representations affect visual attention. Grecucci et al. (2010) used emotional state words (e.g., "fearful," "joyful," "neutral") as memory materials and required participants to perform a visual search task during the memory retention period, specifically judging the location (left or right) of a face of a particular gender (male or female) presented on both sides. They found that whether the emotion expressed by the face matched the memory word had no effect on the visual search task. Another study by Moriya et al. (2014) examined the influence of emotional information in working memory on the anger superiority effect (i.e., detecting angry faces among happy faces is faster than detecting happy faces among angry faces). In their study, participants were required to hold a face or emotional word of different emotional valence (angry or happy) in working memory while completing a visual search task (i.e., judging whether the presented faces included a face of different emotional valence). The results showed that working memory for angry information weakened the anger superiority effect, whereas working memory for happy information did not affect it. Although the latter study indicated that emotional information in working memory can influence visual attentional selection, neither study compared different emotional valences of working memory representations with neutral ones, making it impossible to determine whether the observed attentional capture effects originated from the working memory representation itself or from its emotional attributes. In other words, whether emotional information in working memory can guide visual attention or modulate memory-driven attentional capture remains unknown.

In real life, people often experience intrusive memories that disrupt their inner peace after unpleasant events (van Schie & Anderson, 2017). Intrusive memories are unwanted memories associated with negative emotions and possessing perceptual characteristics (Kvavilashvili, 2014). They represent a common symptom feature and one of the main causes of negative emotional bias in many clinical disorders, such as post-traumatic stress disorder (Catarino et al., 2015), depression (Joormann et al., 2009), rumination (Fawcett et al., 2015), and anxiety (Marzi et al., 2014). Therefore, investigating how emotional information in task-irrelevant working memory representations captures visual attention has important clinical implications for understanding negative emotional attentional bias in individuals with emotional disorders.

Building on the classic dual-task paradigm in memory-driven attentional capture research (Soto et al., 2005), this study used emotional scene pictures as stimuli to explore how task-irrelevant negative emotional information in working memory representations affects visual attentional selection. Previous research has shown that reaction time, as a behavioral output following a series of cognitive processes, is susceptible to cognitive control factors, which can mask or even alter attentional capture effects observed in early stages of visual search. In contrast, first fixation percentage can more sensitively detect attentional capture by working memory representations during early visual search stages (Bahle et al., 2018; Zhang et al., 2018; Zhang et al., 2016). Therefore, this study employed eye-tracking technology and utilized both first fixation and reaction time indices to compare differences in attentional capture effects observed during early attentional selection and response stages of visual search.

Experiment 1 manipulated the emotional valence of working memory task stimuli to compare the effects of task-irrelevant negative versus neutral emotional stimuli in working memory representations on visual attentional capture. Experiment 2 set the target stimuli as neutral emotional stimuli to eliminate the influence of target emotional attributes on the results and further explored the mechanisms through which task-irrelevant negative emotional information in working memory representations affects visual attentional selection. In Experiment 2, distractors in the control condition were negative emotional stimuli that did not match the working memory representation, and their attentional capture occurred at the perceptual level; in the memory-matching condition, distractors matched the working memory representation, and their attentional capture occurred at the working memory level. Therefore, Experiment 2 could also compare differences in attentional capture by negative emotional stimuli at the perceptual versus working memory levels. Based on previous research, this study hypothesized that: (1) At the perceptual level (i.e., stimulus-driven attentional capture), negative emotional stimuli would have stronger attentional capture ability than neutral emotional stimuli, manifested as significantly greater first fixation capture and longer reaction times when distractors were negative versus neutral in the absence of working memory-matching stimuli. (2) At the working memory level (i.e., memory-driven attentional capture), if negative emotional information in working memory representations enhances attentional capture, then memory-matching distractors that are negative would produce significantly greater attentional capture than those that are neutral. (3) Since stimuli matching working memory in this study served only as distractors in the visual search task, based on findings by Woodman and Luck (2007), Han and Kim (2009), and Zhang et al. (2016), cognitive control might strategically divert attention away from memory-matching distractors to improve visual search efficiency, potentially causing the attentional capture effect to disappear or even reverse in the reaction time index, which is more susceptible to cognitive control.

2. Experiment 1

2.1.1 Participants

G*Power 3.1.9.2 (Faul et al., 2007) was used to estimate the planned sample size ($\alpha = 0.05$, $1\text{-}\beta = 0.80$). For detecting an interaction effect in a two-factor repeated-measures design, referencing results from Zhang et al. (2017), when the interaction was significant for both first fixation percentage and reaction time indices, the minimum p^2 was 0.21, requiring only 7 participants. However, considering variability in research variables and result stability, Experiment 1 calculated the planned sample size using a medium effect size (effect size $f = 0.25$, Faul et al., 2007), yielding 24 participants. The actual sample in Experiment 1 consisted of 24 university students (12 males and 12 females, aged 18–21 years, mean age 19.17 $\pm$ 0.87 years). All participants were right-handed, had normal or corrected-to-normal vision, no color blindness or weakness, were in good health with no psychiatric history, and had not participated in similar experiments previously.

Given that this study examined emotion and used emotional scene pictures as stimuli, participants were screened using the State-Trait Anxiety Inventory (STAI) (Wang et al., 1999) and the Beck Depression Inventory-II (BDI-II) (Yang et al., 2012). All participants' standardized scores on state anxiety, trait anxiety, and depression were controlled below 1.96 to exclude individuals with high anxiety or depression. In Experiment 1, participants' standardized scores on the three scales ranged between -0.94 to 1.26, -1.18 to 1.54, and -1.20 to 1.34, respectively. Participants signed informed consent before the experiment and received compensation afterward.

2.1.2 Apparatus

Eye movements were recorded using an EyeLink 1000 Plus desktop eye tracker (SR Research Ltd., Mississauga, Ontario, Canada) with a sampling frequency of 1000 Hz. Stimuli were presented on a 19-inch LCD monitor (resolution 1024$\times$768, refresh rate 75 Hz) with a gray background. During the experiment, participants rested their chin on a chinrest to control head movement, with their eyes approximately 57 cm from the center of the screen. The experimental program was written and run using E-Prime 1.1.

2.1.3 Materials

Negative and neutral emotional scene pictures were selected from the International Affective Picture System (IAPS) (Lang et al., 2008) and the Chinese Affective Picture System (CAPS) (Bai et al., 2005). Negative pictures depicted frightening animals, human aggression, bodily mutilation, or disaster scenes, while neutral pictures depicted neutral scenes of animals or human activities. The picture selection process was as follows: (1) Initial selection: Two teachers initially selected 238 negative and 206 neutral emotional pictures from CAPS and IAPS. All pictures subtended 10.25° $\times$ 8.04° of visual angle. (2) Emotional rating: Eight university students (3 males, 5 females, mean age 19.88 $\pm$ 1.81 years) rated the valence (1: very unpleasant; 9: very pleasant), arousal (1: very calm; 9: very excited), and motivational tendency (1: very want to avoid; 9: very want to approach) of the initially selected pictures using 9-point scales. Mean ratings were calculated for each picture on each dimension. Inter-rater reliability (Kendall' s W) ranged from 0.67 to 0.69, with $^2(443)$ values between 2367.54 and 2455.70, ps $<$ 0.001. (3) Picture classification: To ensure balance across the three emotional dimensions and equal frequency of presentation, 156 negative and 156 neutral emotional pictures were selected for the formal experiment and divided into four categories based on experimental requirements: "memory stimuli" (72 pictures), "distractor stimuli" (24 pictures), "target stimuli" (48 pictures), and "new memory probe stimuli" (12 pictures). Ratings on each emotional dimension were matched across categories (see Table 1 ; Yuan et al., 2014).

Table 1 Emotional dimension ratings (M±SD) and difference tests for each picture category in Experiment 1

Based on the valence of the presented pictures, the experiment included two types of emotional blocks: in neutral emotional blocks, all pictures were neutral; in negative emotional blocks, all pictures were negative. In the memory task and memory probe task, a single picture was presented at the center of the screen each time. Memory pictures were randomly selected from the "memory stimuli" category, and memory probe pictures were either identical to the memory picture from the same trial ("yes" response) or randomly selected from the "new memory probe stimuli" category ("no" response). In the visual search task, two different pictures were presented at 2.2° of visual angle to the left and right of central fixation, each surrounded by a black border (line width 0.1° of visual angle) with openings on both sides. The border openings of target pictures differed in width (0.7° and 0.45° of visual angle), while distractor pictures had identical openings on both sides (0.45°). Target pictures were randomly selected from the "target stimuli" category, while distractor pictures were selected based on the matching type (independent variable): in the memory-matching condition, they were identical to the memory picture, while in the control condition, they were randomly selected from the "distractor stimuli" category.

2.1.4 Procedure

The experimental procedure is illustrated in Figure 1 [Figure 1: see original paper]. At the beginning of each trial, a small dot appeared at the center of the screen for drift correction. Participants were required to fixate on the dot, and when the eye tracker detected that the participant' s fixation coincided with the dot for more than 1000 ms, the experimenter pressed the spacebar to initiate the memory task. After the memory stimulus was presented for 1000 ms, a red fixation cross "+" appeared at the center of the screen for 750 ms, followed by either a visual search task or a memory probe task. When the task was visual search, participants were required to search for the target stimulus within 3000 ms and quickly and accurately press a key to indicate the direction of the larger border opening (left side: "F" key; right side: "J" key; equal numbers of trials for both responses, randomly presented). When the task was memory probe, participants were required to judge whether the picture presented at the center of the screen was identical to the memory stimulus ("yes" response: "F" key; "no" response: "J" key; equal numbers of trials for both responses, randomly presented), with no time limit. The program automatically advanced to the next trial when a response was detected or when the maximum time limit was exceeded.

Figure 1 [Figure 1: see original paper] Experimental flowchart

To prevent participants from strategically biasing their attention toward memory-matching stimuli during visual search, the instructions explicitly stated that "the memory stimulus may appear in the visual search task, but it will never be the search target," reminding participants that attending to memory-matching stimuli would not facilitate visual search efficiency. Additionally, only visual search or memory probe tasks were randomly presented after the memory stimulus, eliminating the possibility that participants might intentionally bias attention toward memory-matching stimuli during visual search to achieve better memory performance (Dowd et al., 2015; Zhang et al., 2017).

Experiment 1 employed a 2 (block type: negative emotional block/neutral emotional block) × 2 (matching type: memory-matching condition/control condition) within-subjects design. In the memory-matching condition, the picture from the memory task reappeared as a distractor in the visual search task; in the control condition, the memory picture did not appear in the visual search task. To avoid potential emotional carryover effects from mixing negative and neutral emotional block trials, the formal experiment consisted of 2 negative emotional blocks and 2 neutral emotional blocks, with block order balanced across participants using an ABBA sequence. Each block comprised 24 trials presenting only memory probe tasks and 48 trials presenting visual search tasks (half memory-matching and half control conditions) randomly intermixed. Participants rested for 5 minutes after each block. Before the formal experiment, 24 practice trials were administered to familiarize participants with the procedure and requirements.

The eye tracker recorded participants' right eye movements during the visual search task. A 9-point matrix calibration was performed at the beginning of the experiment and after each rest period. Before the visual search task, participants were required to maintain their eyes at the red fixation cross "+" (acceptable range: within 1.5° of visual angle from the fixation center).

2.2 Results and Discussion

Data were analyzed using SPSS 23.0. All participants achieved memory probe task accuracy above 92%, with no significant difference between negative and neutral emotional blocks (97.83% vs. 97.74%, $t(23) = 0.15$, $p = 0.88$). Mean accuracy in the visual search task was high across all conditions (> 97.83%), so visual search accuracy was not analyzed further.

In this study, visual search reaction time and first fixation data were analyzed only for trials with correct visual search responses and reaction times within 3 standard deviations of the mean. Differences in reaction time and the percentage of first fixations captured by distractors between memory-matching and control conditions reflected attentional capture effects by memory-matching stimuli at the response stage and early visual search stage, respectively.

Additionally, considering that non-significant results in significance testing cannot serve as evidence supporting the null hypothesis, Bayesian Information Criterion (BIC) analysis was conducted on key null results following Masson (2011). Larger posterior probability values pBIC(H_0|D) provide stronger support for the null hypothesis, whereas larger pBIC(H_1|D) support the alternative hypothesis. According to criteria from Masson (2011) and Raftery (1995), pBIC(Hi|D) values of 0.75–0.95 indicate strong evidence, 0.95–0.99 indicate very strong evidence, and values > 0.99 indicate extremely strong evidence.

2.2.1 Reaction Time Analysis A 2 (block type: negative emotional block/neutral emotional block) × 2 (matching type: memory-matching condition/control condition) repeated-measures ANOVA on mean visual search reaction times revealed (see Figure 2 [Figure 2: see original paper]) that neither the main effects of block type ($F(1, 23) = 0.92$, $p = 0.35$) and matching type ($F(1, 23) = 2.81$, $p = 0.11$) nor their interaction ($F(1, 23) = 1.32$, $p = 0.26$) were significant, indicating no memory-driven attentional capture effect in the reaction time index.

2.2.2 Eye Movement Analysis Since first fixation can precisely reflect stimulus-driven attentional capture during early visual search stages, this study measured working memory representation-driven attentional capture by comparing the percentage and duration of first fixations on distractors between memory-matching and control conditions. First fixation was defined as the location of the first fixation after the initial saccade following visual search stimulus onset. Trials were excluded from first fixation calculations when (Zhang et al., 2018): (1) fixation was not in the central "+" area (a circular region with a diameter of 2° of visual angle centered on the screen) after search stimulus onset; or (2) the first saccade latency was less than 100 ms or greater than 500 ms. First fixation percentage was calculated as the percentage of first fixations falling within the distractor interest area out of the total valid trials for each condition. First fixation duration was defined as the duration from when the first fixation entered the interest area until it left that area.

(1) First Fixation Percentage on Distractors

A 2 (block type) × 2 (matching type) repeated-measures ANOVA on first fixation percentage falling within distractor interest areas revealed (see Figure 2) that the main effect of block type was not significant, $F(1, 23) = 1.16$, $p = 0.29$; the main effect of matching type was significant, $F(1, 23) = 21.96$, $p < 0.001$, $p^2 = 0.49$, 95% CI: [5.70%, 14.71%]; and the interaction was significant, $F(1, 23) = 6.75$, $p = 0.02$, $p^2 = 0.23$.

Simple effects tests on the interaction revealed that in both block types, first fixation percentage in the memory-matching condition was significantly greater than in the control condition (negative emotional block: 38.98% vs. 25.28%, $t(23) = 6.26$, $p < 0.001$, Cohen' s $d = 1.16$, large effect size, 95% CI: [9.18%, 18.23%]; neutral emotional block: 36.82% vs. 30.10%, $t(23) = 2.33$, $p = 0.03$, Cohen's d = 0.49, small effect size, 95% CI: [0.74%, 12.68%]), demonstrating significant attentional capture effects. A paired-samples t-test on the magnitude of attentional capture effects revealed that the effect was significantly larger in the negative emotional block than in the neutral emotional block (13.70% vs. 6.71%, $t(23) = 2.60$, $p = 0.02$, Cohen' s d = 0.55, medium effect size, 95% CI: [1.42%, 12.56%]). Additionally, paired-samples t-tests showed that in the control condition, distractors in the negative emotional block captured significantly fewer first fixations than those in the neutral emotional block (25.28% vs. 30.10%, $t(23) = -3.52$, $p = 0.002$, Cohen' s d = 0.47, small effect size, 95% CI: [-7.66%, -1.99%]), but there was no significant difference between blocks in the memory-matching condition (38.98% vs. 36.82%, $t(23) = 0.99$, $p = 0.33$, Cohen' s d = 0.41, $pBIC(H_0|D) = 0.75$). These results indicate that although the negative emotional block showed a larger attentional capture effect than the neutral emotional block, this difference primarily originated from the control condition: when stimuli did not match the memory representation, neutral emotional distractors captured more first fixations than negative emotional distractors; however, when stimuli matched the memory representation, there was no significant difference between negative and neutral emotional distractors in first fixation capture.

(2) First Fixation Duration on Distractors

A 2 × 2 ANOVA on first fixation duration within distractor interest areas revealed that the main effect of block type was marginally significant, $F(1, 23) = 4.15$, $p = 0.05$, $p^2 = 0.15$, 95% CI: [-0.22, 29.31], with longer first fixation durations in the negative emotional block than in the neutral emotional block (262 ms vs. 247 ms). The main effect of matching type was significant, $F(1, 23) = 4.66$, $p = 0.04$, $p^2 = 0.17$, 95% CI: [-52.24, -1.10], with significantly shorter first fixation durations in the memory-matching condition than in the control condition (241 ms vs. 268 ms). The interaction was not significant, $F(1, 23) = 0.26$, $p = 0.62$. These results indicate that after attention was captured by memory-matching stimuli, it disengaged more quickly from them.

Figure 2 [Figure 2: see original paper] Reaction times and first fixation percentages captured by distractors in Experiment 1 visual search task (Note: Bar graphs show first fixation percentages, line graphs show reaction times, and error bars represent standard errors. The same applies below.)

Experiment 1 results showed that although no memory-driven attentional capture effect was found at the reaction time level, eye movement measures revealed that distractors matching memory representations captured more first fixations, demonstrating attentional capture during early visual search. Interestingly, further analysis revealed that when distractors did not match working memory, negative emotional distractors captured significantly less attention than neutral emotional distractors, whereas when they matched working memory representations, their attentional capture was not affected by emotional valence. Two possible explanations may account for this difference: (1) Working memory representation-driven attentional capture is not modulated by emotional valence;

(2) Attentional capture by distractors is subject to competition from simultaneously presented task-relevant target stimuli. Since negative stimuli receive prioritized processing (Vuilleumier & Huang, 2009), in Experiment 1, the negative target stimulus in the negative emotional block may have exerted greater influence on negative distractors than the neutral target on neutral distractors in the neutral emotional block, resulting in negative emotional distractors capturing fewer first fixations in the control condition. Similarly, competition from negative emotional target stimuli may have weakened the attentional capture ability of negative emotional distractors in the memory-matching condition. To test these possibilities, Experiment 2, building on Experiment 1, set the target stimuli as neutral emotional stimuli to hold constant the target' s emotional type influence on distractors. More importantly, because target stimuli were always neutral, when distractors were memory-matching stimuli, they reflected attentional capture by negative emotional stimuli at the working memory level; when distractors were non-matching stimuli, they reflected attentional capture by negative emotional stimuli at the perceptual level. Thus, Experiment 2 could compare attentional capture effects by negative emotional stimuli at these two different levels.

3. Experiment 2

3.1 Method

3.1.1 Participants Nineteen university students were initially recruited for Experiment 2. One female participant was excluded due to high trait anxiety and depression scores, leaving a final sample of 18 participants (10 males, aged 16–19 years, mean age 17.44 ± 0.71 years). Given that the p^2 for the interaction in Experiment 1 was 0.23, this sample size was sufficient to detect the expected effect. Participants' standardized scores on state anxiety, trait anxiety, and depression ranged between -1.06 to 1.78, -1.17 to 1.70, and -1.23 to 1.29, respectively. All participants were right-handed, in good health with no psychiatric history, had normal or corrected-to-normal vision, no color blindness or weakness, and had not participated in similar experiments previously. Participants signed informed consent before the experiment and received compensation afterward.

3.1.2 Apparatus and Materials The apparatus and materials were identical to those in Experiment 1. The procedure was similar to Experiment 1, with the only difference being that visual search targets in both block types were neutral stimuli. That is, in the negative emotional block, search targets were also randomly selected from the neutral "target stimuli" category (compared to Experiment 1, neutral target stimuli were presented twice as many times in Experiment 2).

3.1.3 Procedure The procedure was identical to Experiment 1.

3.2 Results and Discussion

Mean accuracy in the memory probe task was 97.80% for negative emotional stimuli and 98.38% for neutral emotional stimuli, with no significant difference between them ($t(17) = -0.79$, $p = 0.44$). Mean accuracy in the visual search task was high across all conditions ($\geq 97.34\%$, $M = 98.47\%$), so visual search accuracy was not analyzed further.

3.2.1 Reaction Time Analysis ANOVA results for reaction times revealed (see Figure 3 [Figure 3: see original paper]) a significant main effect of matching type, $F(1, 17) = 10.38$, $p = 0.005$, $p^2 = 0.38$, 95% CI: [-113.42, -23.65], with significantly shorter reaction times in the memory-matching condition than in the control condition (1005 ms vs. 1073 ms), demonstrating an attentional suppression effect opposite to attentional capture (69 ms). Neither the main effect of block type ($F(1, 17) = 0.06$, $p = 0.81$) nor the interaction ($F(1, 17) = 0.93$, $p = 0.35$) was significant.

3.2.2 Eye Movement Analysis (1) First Fixation Percentage on Distractors

ANOVA on first fixation percentage falling within distractor interest areas revealed (see Figure 3) significant main effects of block type ($F(1, 17) = 8.38$, $p = 0.01$, $p^2 = 0.33$, 95% CI: [1.28%, 8.14%]) and matching type ($F(1, 17) = 25.96$, $p < 0.001$, $p^2 = 0.60$, 95% CI: [8.33%, 20.11%]), and a significant interaction between them ($F(1, 17) = 4.69$, $p = 0.04$, $p^2 = 0.22$).

Simple effects tests on the interaction revealed that in both block types, first fixation percentage in the memory-matching condition was significantly greater than in the control condition (negative emotional block: 50.50% vs. 40.27%, $t(17) = 3.17$, $p = 0.006$, Cohen' s $d = 0.90$, large effect size, 95% CI: [3.41%, 17.04%]; neutral emotional block: 49.78% vs. 31.57%, $t(17) = 5.27$, $p < 0.001$, Cohen' s $d = 1.44$, large effect size, 95% CI: [10.92%, 25.50%]), both showing significant attentional capture effects. Moreover, the attentional capture effect was significantly smaller in the negative emotional block than in the neutral block (10.23% vs. 18.21%), $t(17) = 2.17$, $p = 0.04$, Cohen' s $d = 0.56$, medium effect size, 95% CI: [-15.76%, -0.21%].

Additionally, results showed that in the control condition, negative emotional distractors captured significantly more first fixations than neutral emotional distractors (40.27% vs. 31.57%, $t(17) = 3.57$, $p = 0.002$, Cohen' s $d = 0.94$, large effect size, 95% CI: [3.55%, 13.85%]), while there was no significant difference between them in the memory-matching condition (50.50% vs. 49.78%, $t(17) = 0.29$, $p = 0.78$, Cohen' s $d = 0.14$, $pBIC(H_0|D) = 0.82$). These results indicate that although the neutral emotional block showed a larger attentional capture effect than the negative emotional block, this difference primarily originated from the control condition rather than the memory-matching condition. That is, when stimuli did not match the memory representation, negative emotional distractors captured more first fixations than neutral emotional distractors (i.e., perceptual-level attentional bias toward negative emotional stimuli), but when stimuli matched the memory representation, there was no significant difference between the two emotional block types in first fixation capture.

(2) First Fixation Duration on Distractors

ANOVA on first fixation duration within distractor interest areas revealed a significant main effect of matching type, $F(1, 17) = 31.50$, $p < 0.001$, $p^2 = 0.65$, 95% CI: [-97.77, -42.54], with significantly shorter first fixation durations in the memory-matching condition than in the control condition (200 ms vs. 269 ms), indicating that participants rapidly disengaged attention from memory-matching distractors. Neither the main effect of block type ($F(1, 17) = 0.007$, $p = 0.94$) nor the interaction ($F(1, 17) = 0.74$, $p = 0.40$) was significant.

Combined reaction time and first fixation results showed that during early visual search stages, both neutral and negative emotional stimuli exhibited significant memory-driven attentional capture effects, consistent with Experiment 1. However, at the response stage, this attentional capture effect was reversed into attentional suppression, indicating that when working memory representations served only as distractors, they still automatically captured visual attention, but cognitive control subsequently prompted rapid disengagement from these distractors, potentially leading to attentional suppression effects in the reaction time index. Additionally, after eliminating the influence of target emotional valence in Experiment 2, results further demonstrated that emotional valence only modulated attentional capture by distractors that did not match memory representations (i.e., perceptual-level attentional bias), consistent with classic findings that negative emotional stimuli capture visual attention more strongly. However, at the working memory level, no modulatory effect of emotional valence on memory-driven attentional capture was found ($pBIC(H_0|D)$ values > 0.75, providing strong evidence for accepting the null hypothesis (Masson, 2011)).

Experiment 2 found that in the control condition, negative distractors captured significantly more first fixations than neutral distractors, opposite to the pattern in Experiment 1. This difference confirmed the influence of target emotional valence on distractors: when target stimuli were neutral (Experiment 2), the processing priority of negative emotional stimuli caused negative distractors to show stronger attentional capture than neutral distractors; when targets were negative (Experiment 1), target stimuli weakened the attentional capture ability of competing negative distractors. Furthermore, although the neutral emotional block procedure was identical to Experiment 1, its attentional capture effect was significantly larger in Experiment 2 (18.21% vs. 6.71%, $t(40) = 2.57$, $p = 0.01$, Cohen' s $d = 0.80$). Further analysis revealed that the first fixation percentage in the matching condition was significantly greater in Experiment 2 than in Experiment 1 (49.78% vs. 36.82%, $t(40) = 2.77$, $p = 0.009$, Cohen' s $d = 0.88$), while there was no significant difference in the control condition (30.10% vs. 31.57%, $t(40) = 0.45$, $p = 0.66$). This result will be discussed in the General

Discussion.

4. General Discussion

This study primarily investigated how task-irrelevant negative emotional information in working memory representations affects visual attentional capture. The findings indicate that: (1) When visual search distractors do not match working memory representations, consistent with previous research (Nummenmaa et al., 2009; Pourtois et al., 2006), negative emotional distractors have stronger attentional capture ability than neutral emotional distractors; (2) When distractors match working memory representations, they produce stronger attentional capture than non-matching distractors, demonstrating classic memory-driven attentional capture; (3) Memory-driven attentional capture is not affected by the emotional valence of working memory representations, with no significant difference in capture effects between negative and neutral emotional stimuli in working memory; and (4) After distractors matching working memory representations capture the first fixation, cognitive control prompts attention to disengage more quickly from these distractors, causing the attentional capture effect to disappear or even reverse in the reaction time index.

First, contrary to the expectation that negative emotion would enhance memory-driven attentional capture, the results showed that this effect was not influenced by the emotional valence of working memory representations. In contrast, negative emotional distractors in the control condition captured more first fixations than neutral distractors. These results suggest that the negative emotional information of physical stimuli can enhance their attentional capture ability at the perceptual level in a bottom-up manner, whereas the emotional information of working memory representations does not affect their ability to capture visual attention. As mentioned in the introduction, although Grecucci et al. (2010) also examined how emotional information in working memory representations affects visual attentional selection, they did not compare whether attentional capture differs across emotional valences. Based on the current findings, the attentional capture by emotional information in working memory observed by Grecucci et al. (2010) likely originated primarily from the working memory representation itself rather than its emotional attributes. Consistent with this conclusion, a comparison of brain imaging findings from Grecucci et al. (2010) and Soto et al. (2007) revealed that despite using different memory materials (emotional words vs. neutral colored geometric shapes), both studies identified the same neural network associated with attentional capture by working memory representations (the fronto-pulvinar network), suggesting that emotional valence of working memory representations does not affect the neural pathways underlying their interaction with visual attention.

As discussed in the introduction, researchers have used automatic emotional processing theory, attentional biased competition theory, and perceptual load theory to explain emotional attention caused by negative emotional stimuli at the perceptual level. Clearly, these theories cannot be simply applied to how emotional information at the working memory level affects visual attention. Although researchers (e.g., Soto et al., 2008) have used attentional biased competition theory to explain memory-driven attentional capture—arguing that top-down neural activation of working memory representations gives matching stimuli a competitive advantage—the current findings suggest that emotional information in working memory representations does not strengthen this top-down neural pathway for matching perceptual stimuli. Why does the negative emotional bias effect observed at the perceptual level not appear at the working memory level? In recent years, many researchers using the breaking continuous flash suppression (b-CFS) task have found that unconscious negative emotional information, such as angry faces and body postures (Gray et al., 2013; Zhan et al., 2015), threatening information (Gayet et al., 2016), and disgusting stimuli (Zhang et al., 2018), can break through suppression and enter awareness faster than neutral stimuli. Gayet et al. (2016) proposed that negative emotional information enters awareness faster because negative emotion enhances stimulus salience, which is why negative emotional stimuli can quickly capture attention in visual search tasks. Working memory, as the content of current conscious processing, means that emotional information in working memory representations already exists at the conscious level and cannot leverage the advantage of rapid conscious access to strengthen its attentional capture ability. This may be the primary reason why emotional valence did not affect memory-driven attentional capture in this study.

Second, the results showed a dissociation between first fixation percentage and reaction time measures: stable attentional capture effects were observed in first fixations, but these early-stage effects disappeared (Experiment 1) or were reversed into attentional suppression effects (Experiment 2) at the response stage. This pattern aligns with recent eye-tracking studies (Bahle et al., 2018; Zhang et al., 2016), reflecting that when memory-matching stimuli serve only as distractors, cognitive control operates after they capture attention, prompting attention to deviate from these stimuli. Analyses of first fixation duration on distractors in both experiments support this interpretation: first fixation duration on memory-matching distractors was significantly shorter than on control distractors, showing rapid attentional disengagement. This result is consistent with Moher and Egeth' s (2012) "search and destroy" inhibition theory and the signal suppression theory (Gaspelin & Luck, 2018; Sawaki & Luck, 2011). The former proposes a two-stage inhibition process: attention is first guided bottom-up to stimuli that "should be ignored," followed by top-down cognitive control to inhibit these stimuli. The latter suggests that attentional capture is prevented by top-down suppression mechanisms, and attention is only captured by memory-matching distractors when suppression fails. Therefore, attentional capture or suppression effects can be viewed as the result of a trade-off between failed and successful suppression. Both theories emphasize cognitive control over memory-matching distractors, but the former focuses on a two-stage process of capture followed by inhibition (see also Theeuwes, 2010' s two-stage model of visual attentional selection), while the latter emphasizes that suppression is formed before visual search initiation. The eye movement results from this study—showing rapid disengagement after attention was captured by memory-matching stimuli—are more consistent with the "search and destroy" inhibition theory. However, this does not rule out the possibility that participants formed suppression of working memory representations before visual search initiation, with trials showing first fixation capture representing instances of suppression failure. What is clear is that even when suppression failed and memory-matching distractors captured attention, the inhibition mechanism still operated, prompting rapid attentional disengagement.

Finally, the reaction time results also indicate that the process of cognitive control inhibiting memory-matching distractors is modulated by the emotional attributes of the current primary task (i.e., target stimuli). Specifically, in the negative emotional block where visual search targets were negative emotional stimuli, the attentional capture effect observed in early visual search stages was eliminated at the response stage. However, when the visual search targets were changed to neutral emotional stimuli in Experiment 2, the early attentional capture effect was reversed into attentional suppression at the response stage. This may be because changing the targets to neutral emotional stimuli in Experiment 2 strengthened participants' motivation to inhibit negative emotional distractors. For example, Vogt et al. (2017) investigated attentional bias toward threat signals and instrumental safety signals (signals that help avoid threat through reinforcement) and found that when both signals were presented simultaneously, participants' attention tended to bias toward instrumental safety signals in both dot-probe and Go-Nogo tasks. Vogt et al. (2017) proposed that the motivation to achieve safety guides attention allocation when facing threats. Therefore, when Experiment 2' s targets were safe neutral emotional stimuli, this may have enhanced participants' motivation to inhibit negative distractors or induced a relatively safe emotional atmosphere that helped maintain an inhibitory state toward negative emotional stimuli. The modulation of motivation level on memory-driven attentional capture has been supported by some studies. For instance, Carlisle and Woodman (2011a, 2011b) and Hu et al. (2013) manipulated the proportion of memory-matching distractors to modulate motivation to inhibit them, finding that higher proportions led to greater attentional deviation from these distractors. Additionally, interestingly, the study found that even though the neutral emotional block procedure was identical to Experiment 1, memory-matching stimuli in Experiment 2 captured significantly more attention than in Experiment 1, while there was no difference in the control condition. This suggests that although the ABBA method was used to control for emotional interactions between neutral and negative emotional blocks, such interactions still existed: the emotional atmosphere induced by target stimuli' s emotional attributes also affected memory-driven attentional capture in the neutral emotional block. Typically, working memory stores information relevant to the current task, such as visual search templates, so attention prioritizes information consistent with working memory content to optimize visual search efficiency. Soto et al. (2008) proposed that this reflects an automatic "benefit" pattern from working memory, which still drives attention toward memory-matching stimuli even when they serve as distractors. It is possible that in a relatively safe emotional atmosphere with safe neutral content in working memory, participants' attention was more inclined to "benefit" from working memory, resulting in stronger attentional capture effects. Future research should further test this speculation.

Although this study approached the issue from the perspective of intrusive memory to investigate visual attentional capture by negative emotional working memory representations, it did not find an effect of emotional valence on memory-driven attentional capture. However, given that this study used a healthy participant sample, its conclusions cannot be directly generalized to populations with trait emotional disorders (e.g., individuals with depression, PTSD, or anxiety). Future research should examine these populations.

In summary, this study found that: (1) During early attentional selection, memory-driven attentional capture is not affected by the emotional valence of task-irrelevant working memory representations; and (2) After early attentional capture, cognitive control prompts attention to quickly disengage from distractors matching working memory representations, with its effect being modulated by the emotional valence of target stimuli.

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Note: Figure translations are in progress. See original paper for figures.