Effects of Visual Working Memory Load Type on Attentional Selection

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Abstract

By manipulating the presentation position of the Flanker task relative to the visual working memory task, we investigated the effects of precision load and capacity load on attentional selection during the encoding and maintenance phases of visual working memory. Behavioral results revealed that both the presentation position of the Flanker task and the type of visual working memory load influenced attentional selection. ERP results demonstrated that during the maintenance phase, when the search target and distractor were incongruent, the load type affected the N2 component. The study indicates that during the encoding phase, visual working memory load primarily reduces interference effects by occupying more perceptual resources, thereby supporting perceptual load theory. In contrast, during the maintenance phase, when the Flanker task was located within the memory items, the differential neural activities of the two load types during working memory representation led to variations in cognitive control resources allocated to attentional selection, which may constitute the mechanism through which the two load types influence attentional selection during the maintenance phase.

Full Text

The Effects of Visual Working Memory Load Type on Attentional Selection

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Abstract

By manipulating the presentation position of a Flanker task relative to a visual working memory task, this study investigated how precision load and capacity load affect attentional selection during the encoding and maintenance phases of visual working memory. Behavioral results revealed that both the presentation position of the Flanker task and the type of visual working memory load influenced attentional selection. ERP results showed that during the maintenance phase, load type affected the N2 component when the search target and distractor were incongruent. The findings indicate that during the encoding phase, visual working memory load reduces interference effects primarily by occupying more perceptual resources, supporting perceptual load theory. However, during the maintenance phase, when the Flanker task appears within memory items, different neural activities associated with the two load types during working memory representation lead to differential allocation of cognitive control resources to attentional selection, which may explain how the two load types affect attentional selection during the maintenance phase.

Keywords: visual working memory; attentional selection; precision load; capacity load; N2

1 Introduction

The human perceptual system constantly receives vast amounts of information, including both relevant and irrelevant information. Selective attention helps people focus on task-relevant information while ignoring or inhibiting irrelevant information. However, attentional selection is not always effective, and the presence of irrelevant information can interfere with the processing of task-relevant information. Perceptual load theory posits that the level of perceptual load in the current task determines resource allocation during selective attention. If perceptual load increases in the current task, fewer perceptual resources remain available for processing irrelevant information, thereby reducing interference effects and facilitating attentional selection. Conversely, if cognitive control load increases in the current task, fewer resources remain available for inhibiting irrelevant information processing, which instead increases interference effects and hinders attentional selection (De Fockert, Rees, Frith, & Lavie, 2001; Lavie, 1995, 2005; Lavie & De Fockert, 2005; Lavie & Tsal, 1994).

As a storage buffer, visual working memory constitutes an important component of working memory, temporarily maintaining and manipulating visual information (Luck & Vogel, 2013). It possesses both storage and cognitive control functions, playing a crucial role in visual perception and cognitive processes (Baddeley, 2012; Ma, Husain, & Bays, 2014; Repovš & Baddeley, 2006; Suchow, Fougnie, Brady, & Alvarez, 2014). Recently, the impact of visual working memory load on attentional selection has become a focal point for researchers. Some studies have inserted Flanker tasks into visual working memory tasks and found that increased visual working memory load reduces interference from irrelevant information. Roper and Vecera (2014) presented a Flanker task during the maintenance phase of visual working memory and found that interference effects were smaller under high visual working memory load than under low load. Konstantinou, Beal, King, and Lavie (2014) presented Flanker tasks during both the encoding and maintenance phases of visual working memory, finding that high visual working memory load reduced interference effects regardless of whether memory items and attentional selection tasks were presented simultaneously or sequentially. This suggests that high visual working memory load reduces interference effects during both the maintenance and encoding phases. Completing a Flanker task requires judging visual information about attentional targets, which consumes visual resources that may overlap with those consumed by the visual working memory task. Therefore, increasing visual working memory load consumes more visual resources, leaving fewer resources available for processing distractors and thus reducing interference effects. However, other studies have inserted Stroop tasks into visual working memory tasks and found that increased visual working memory load actually increases interference from irrelevant information. Stins, Vosse, Boomsma, and de Geus (2004) required participants to first complete a visual working memory task and then perform a Stroop task that involved judging word meaning while ignoring ink color, finding that increased visual working memory load enhanced Stroop interference effects. Gil-Gómez de Liaño, Stablum, and Umiltà (2016) required participants to first perform a visual working memory task and then complete a Stroop task involving judging word meaning direction while ignoring arrow direction, finding that Stroop interference effects were greater when a visual working memory task was performed compared to when it was not. Completing a Stroop task requires participants to convert visual processing to verbal processing, a transformation that consumes cognitive control resources that overlap with those consumed by visual working memory. Therefore, increasing visual working memory load reduces the cognitive control resources available for completing the Stroop task, thereby increasing interference effects. These findings suggest that the overlap in resource consumption between visual working memory tasks and attentional selection tasks may account for the different effects of visual working memory load on attentional selection.

Recently, researchers (Zhang & Luck, 2015) have distinguished between visual working memory capacity load and precision load, examining how these two load types affect attentional selection. Capacity load refers to the number of items to be remembered, while precision load refers to the degree of change between memory items and probe items. The results showed that Flanker interference effects were greater under high capacity load than under low capacity load, whereas interference effects were smaller under high precision load than under low precision load. High visual working memory capacity load may broaden the attentional scope, thereby increasing interference effects. In contrast, under high visual working memory precision load conditions, participants must engage in more detailed perceptual processing of memory items to detect subtle changes between memory and probe items, focusing attention on a smaller attentional scope that ultimately narrows attentional breadth and reduces interference effects. These findings contradict previous studies using Flanker tasks (Konstantinou et al., 2014; Roper & Vecera, 2014). The discrepancy may arise from differences in the presentation position of the attentional selection task, which leads to varying degrees of resource overlap between the visual working memory task and the attentional selection task. In Konstantinou et al. (2014) and Roper and Vecera (2014), Flanker distractors were located in the periphery of visual working memory items, likely outside the focus of attention. Since both distractor processing and the visual working memory task consume perceptual resources, distractors may not receive sufficient processing resources, reducing interference effects. In contrast, in Zhang and Luck (2015), Flanker distractors were located within memory items, easily falling within the attentional focus and potentially entering perceptual processing automatically (Gronau, Cohen, Gershon, & Ben-shakhar, 2003). Completing the Flanker task requires consuming cognitive control resources to inhibit distractor processing, which overlaps with the cognitive control resources consumed by the visual working memory task. Consequently, distractors do not receive sufficient inhibitory resources, increasing interference effects.

What mechanisms underlie the effects of different types of visual working memory load on attentional selection? Does visual working memory load affect attentional selection differently when Flanker distractors are presented at different positions? The present study aimed to address these questions by varying the presentation position of the attentional selection task relative to the visual working memory task and manipulating the type of visual working memory load. Four experiments were designed. Experiment 1 examined how different types of visual working memory load affect attentional selection when memory items and the Flanker task are presented simultaneously. When memory items and the Flanker task appear together in the same visual field, both capacity load and precision load increase perceptual load, consuming more visual resources and potentially leaving fewer resources available for processing distractors, thereby reducing interference effects. Therefore, Hypothesis 1 states that regardless of whether the Flanker task appears within or in the periphery of memory items, both visual working memory precision load and capacity load will reduce interference effects. Experiment 2 examined how different load types affect attentional selection when memory items and the Flanker task are presented sequentially. When the Flanker task appears in the periphery of memory items, distractors fall outside the attentional focus, and their processing consumes perceptual resources. When either working memory precision load or capacity load increases, both consume more perceptual resources, leaving insufficient resources for distractor processing and reducing interference effects. When the Flanker task appears within memory items, distractors fall within the attentional focus and automatically enter perceptual processing. Visual working memory capacity load broadens attentional scope (Ahmed & De Fockert, 2012), and completing the Flanker task requires consuming cognitive control resources to inhibit distractor processing, which overlaps with the cognitive control resources consumed by the high-capacity working memory task, increasing interference effects. However, visual working memory precision load may narrow attentional scope (Zhang & Luck, 2015), allowing sufficient resources to inhibit distractor processing during the Flanker task and reducing interference effects. Therefore, Hypothesis 2 states that when the Flanker task appears in the periphery of memory items, both high precision load and high capacity load will reduce interference effects; when the Flanker task appears within memory items, high capacity load will increase interference effects while high precision load will reduce interference effects. To further test this hypothesis, Experiment 3 employed a Navon task to manipulate attentional scope (Navon, 1977), examining whether changes in attentional scope under different loads during the maintenance phase cause visual working memory load to affect attentional selection differently. Hypothesis 3 states that under high precision load, interference effects will be smaller when attending to local features than when attending to global features; under high capacity load, interference effects will be larger when attending to local features than when attending to global features. Building on the behavioral studies, Experiment 4 used event-related potential (ERP) technology, with the N2 component reflecting cognitive control resource investment (Heil, Osman, Wiegelmann, Rolke, & Hennighausen, 2000; Kopp, Rist, & Mattler, 1996), to examine cognitive control resource consumption during Flanker task completion under different visual working memory loads. Hypothesis 4 states that because visual working memory capacity load consumes more cognitive control resources, fewer resources remain available for completing the Flanker task, resulting in smaller N2 amplitudes than the baseline condition. In contrast, because visual working memory precision load narrows attentional scope, more cognitive control resources remain available for completing the Flanker task, resulting in larger N2 amplitudes than the baseline condition.

2 Experiment 1: Effects of Visual Working Memory Load Type and Attentional Selection Task Position on Attentional Selection When Memory Items and Attentional Selection Tasks Are Presented Simultaneously

Based on previous research (Zhang & Luck, 2015), Experiment 1 presented memory items and the Flanker task simultaneously while varying the presentation position of the attentional selection task relative to memory items, to examine how visual working memory capacity load and precision load affect attentional selection.

2.1.1 Participants

Thirty-six university students (16 male, mean age = 20.80 ± 1.50 years) participated in the experiment. All participants had normal or corrected-to-normal vision, no color blindness or color weakness, no history of mental illness, and had not participated in similar experiments previously. Participants received compensation after the experiment. Based on Zhang and Luck (2015), with an effect size of $p^2 = 0.22$, G*Power 3.1 software was used to calculate the required sample size as 14 per group (power = 95%, $\alpha = 0.05$). In this experiment, participants were divided into two groups of 18 each.

2.1.2 Apparatus and Materials

The experiment was programmed using E-Prime 1.1 and conducted on a computer with a screen resolution of 1024 × 768 and a refresh rate of 60 Hz.

Visual working memory task materials consisted of colored squares. Colors were randomly selected from a perceptually homogeneous CIELAB color space (Zhang & Luck, 2008), which contains a color ring composed of 180 evenly distributed hues (see [Figure 1: see original paper]). Memory items comprised either 2 or 4 colored squares measuring 2° × 2°, presented at positions $±$6° from the central fixation point. The color difference between any two squares in a memory array was at least 48° in color space.

Flanker task materials came in two types: one presented in the periphery of memory items, where target letters (X or N, 1.4° × 0.8°) appeared randomly on a large circle (radius = 8°) composed of black dots, and distractor letters (N or X, 1.8° × 0.8°) appeared 10° to the left or right of the fixation point; the other presented within memory items, where target letters (X or N, 1.4° × 0.8°) appeared randomly on a small circle (radius = 2°) composed of black dots, and distractor letters (N or X, 1.8° × 0.8°) appeared 3° to the left or right of the fixation point.

2.1.3 Experimental Design

The experiment employed a 3 (visual working memory load type: baseline, high-precision load, high-capacity load) × 2 (attentional selection task position: periphery of memory items, within memory items) mixed design. The attentional selection task position was a between-subjects factor with two conditions: Flanker task presented in the periphery of visual working memory items or within visual working memory items. Visual working memory load type was a within-subjects factor with three conditions: in the baseline condition, memory items consisted of 2 colored squares with a large color change between detection and memory items (96° difference in color space); in the high-precision load condition, memory items consisted of 2 colored squares with a small color change between detection and memory items (24° difference in color space); in the high-capacity load condition, memory items consisted of 4 colored squares with a large color change between detection and memory items (96° difference in color space). Response times for the Flanker task and accuracy for the visual working memory task were recorded.

2.1.4 Procedure

Participants sat approximately 57 cm from the computer screen. The experimental procedure is illustrated in [Figure 2: see original paper]. A fixation cross

"+" appeared for 1000 ms to signal the start of the trial, followed by simultaneous presentation of visual working memory items and the Flanker task for 200 ms. The Flanker task appeared either in the periphery or within memory items. Participants were instructed to remember the colors of the squares and search for the target letter on the circle composed of black dots. A "?" then appeared for 2000 ms, prompting participants to identify the target letter on the circle: press "0" for "X" and "2" for "N". This was followed by a fixation cross "+" for 1850 ms, and finally the visual working memory probe item. The probe consisted of a single colored square presented randomly at one of the memory item positions. In 50% of trials, the probe color remained unchanged; in the other 50%, it changed. Participants pressed "A" if the probe matched the memory item in both color and position, and "S" otherwise. The experiment consisted of 3 blocks (baseline, high-precision load, high-capacity load), with block order counterbalanced using a Latin square. Each block included 12 practice trials and 72 experimental trials. Participants rested for 5 minutes after each block, and the entire experiment lasted approximately 60 minutes.

2.2.1 Accuracy of the Visual Working Memory Task

Accuracy rates for the visual working memory task under different conditions are shown in . A two-way ANOVA with Flanker task position and load type as factors (repeated measures on the latter) revealed a significant main effect of visual working memory load type, $F(2, 68) = 93.17$, $p < 0.001$, $\mathrm{p}^2 = 0.73 > 0.14$ (the larger p^2, the greater the effect of the independent variable on the dependent variable. According to Cohen's (1992) standards: $0.01 < \mathrm{p}^2 < 0.06$ indicates a small effect; $0.06 < \mathrm{p}^2 < 0.14$ indicates a medium effect; $\mathrm{p}^2 > 0.14$ indicates a large effect). Accuracy in the baseline condition ($M = 0.86$, 95% CI [0.83, 0.89]) was higher than in both the high-precision condition ($M = 0.71$, 95% CI [0.68, 0.74]) and high-capacity condition ($M = 0.68$, 95% CI [0.65, 0.71]), $ps < 0.001$. Accuracy in the high-precision condition was higher than in the high-capacity condition, $p = 0.034$. No other effects were significant.

2.2.2 Response Times for the Flanker Task

Only data from trials with correct responses on both the visual working memory task and Flanker task were analyzed. Response times for the Flanker task under different conditions are shown in . A three-way ANOVA with Flanker task position, congruency, and visual working memory load type as factors (repeated measures on the latter two) revealed a significant interaction between congruency and visual working memory load type, $F(2, 68) = 4.77$, $p = 0.012$, $\mathrm{p}^2 = 0.12$, $0.06 < \mathrm{p}^2 < 0.14$. No other effects were significant.

To further analyze the effect of working memory load type on the attentional selection task, we examined Flanker interference effects, calculated as the difference in response times to target letters between incongruent and congruent distractor conditions (Konstantinou et al., 2014; Zhang & Luck, 2015). Interference effects under different conditions are shown in . Post-hoc comparisons revealed that interference effects in the baseline condition (M = 191.83, 95% CI [155.44, 228.23]) were greater than in both the high-precision condition (M = 144.72, 95% CI [101.65, 187.80]) and high-capacity condition (M = 144.89, 95% CI [101.52, 188.26]), $p_1 = 0.015$, $p_2 = 0.007$. Interference effects did not differ between the high-precision and high-capacity conditions, $p = 0.99$.

2.3 Discussion

Visual working memory accuracy results showed that accuracy was lower under both high-precision and high-capacity load conditions compared to baseline, indicating that our manipulation of visual working memory load type was effective. Both high-precision and high-capacity loads consumed more cognitive resources than the baseline condition, impairing visual working memory maintenance.

Flanker interference effects revealed that when visual working memory items and the Flanker task were presented simultaneously, interference effects under both high-precision and high-capacity loads were smaller than in the baseline condition, regardless of whether the Flanker task appeared within or in the periphery of memory items. This aligns with Konstantinou et al.'s (2014) findings on visual working memory capacity load. When visual working memory items and the Flanker task are presented simultaneously, both tasks are primarily in the encoding stage. Regardless of load type (precision vs. capacity) or presentation position, increasing visual working memory load reduces interference effects. This suggests that when memory items and attentional selection tasks are presented simultaneously, the effect of visual working memory load on attentional selection is not influenced by changes in the attentional selection task position. Both high-precision and high-capacity loads increase perceptual load, thereby reducing interference effects. The question then arises: when memory items and attentional selection tasks are presented sequentially, does the effect of visual working memory load on attentional selection depend on the presentation position of the attentional selection task? Experiment 2 addresses this question.

3 Experiment 2: Effects of Visual Working Memory Load Type and Attentional Selection Task Position on Attentional Selection When Memory Items and Attentional Selection Tasks Are Presented Sequentially

Building on Experiment 1, Experiment 2 presented memory items and the Flanker task sequentially while varying the presentation position of the attentional selection task relative to memory items, to examine how visual working memory capacity load and precision load affect attentional selection.

3.1.1 Participants

Thirty-six university students (18 male, mean age = 19.40 ± 2.10 years) participated in the experiment. All participants had normal or corrected-to-normal vision, no color blindness or color weakness, no history of mental illness, and had not participated in similar experiments previously. Participants received compensation after the experiment.

3.1.2 Apparatus and Materials

The apparatus and materials were identical to those used in Experiment 1.

3.1.4 Procedure

In Experiment 2, memory items and the Flanker task were presented sequentially. Specifically, memory items appeared for 200 ms, followed by a fixation cross "+" for 1850 ms, and then the Flanker task for 150 ms. Other procedures remained the same as in Experiment 1. The trial procedure is illustrated in [Figure 3: see original paper].

3.2.1 Accuracy of the Visual Working Memory Task

Accuracy rates for the visual working memory task under different conditions are shown in . A two-way ANOVA with Flanker task position and load type as factors (repeated measures on the latter) revealed a significant main effect of visual working memory load type, $F(2,\ 68) = 63.19$, $p < 0.001$, $\text{p}^2 = 0.81 > 0.14$. Accuracy in the baseline condition ($M = 0.87$, 95% CI [0.84, 0.90]) was higher than in both the high-precision condition ($M = 0.70$, 95% CI [0.68, 0.73]) and high-capacity condition ($M = 0.70$, 95% CI [0.66, 0.74]), $ps < 0.001$. Accuracy did not differ between the high-precision and high-capacity conditions, $p = 0.90$. No other effects were significant.

3.2.2 Response Times for the Flanker Task

Only data from trials with correct responses on both the visual working memory task and Flanker task were analyzed. Response times for the Flanker task under different conditions are shown in . A three-way ANOVA with Flanker task position, congruency, and visual working memory load type as factors (repeated measures on the latter two) revealed a significant main effect of congruency, $F(1,\ 34) = 42.82$, $p < 0.001$, $\text{p}^2 = 0.56 > 0.14$. Response times were longer when target and distractor were incongruent ($M = 894.25$, 95% CI [827.23, 961.27]) than when they were congruent ($M = 707.32$, 95% CI [653.04, 761.60]). The interaction between congruency and visual working memory load type was significant, $F(2,\ 68) = 4.98$, $p = 0.01$, $\text{p}^2 = 0.13$, $0.06 < \text{p}^2 < 0.14$. The three-way interaction between Flanker task position, congruency, and visual working memory load type was also significant, $F(2,\ 68) = 5.07$, $p = 0.009$, $\text{p}^2 = 0.13$, $0.06 < \text{p}^2 < 0.14$. No other effects were significant.

To further analyze the effect of working memory load type on the attentional selection task, we calculated Flanker interference effects. Interference effects under different conditions are shown in [Figure 4: see original paper]. Further analysis revealed that when the Flanker task was presented within memory items, interference effects differed significantly across load types, $F(2,\ 68) = 6.78$, $p = 0.002$. Interference effects in the baseline condition were greater than in the high-precision condition, $p = 0.023$, while interference effects in the high-capacity condition were greater than in both the baseline condition ($p = 0.045$) and high-precision condition ($p = 0.002$). When the Flanker task was presented in the periphery of memory items, interference effects also differed significantly across load types, $F(2, 68) = 3.27$, $p = 0.044$. Interference effects in the baseline condition were significantly greater than in both the high-precision and high-capacity conditions ($p_1 = 0.06$, $p_2 = 0.046$), with no difference between the high-precision and high-capacity conditions, $p = 0.82$.

3.3 Discussion

Visual working memory accuracy results showed that accuracy under both high-precision and high-capacity loads was lower than in the baseline condition, consistent with Experiment 1. Flanker interference effects showed that when the Flanker task was presented after visual working memory items, both high-precision and high-capacity loads reduced interference compared to baseline when the Flanker task appeared in the periphery of the visual working memory task. This aligns with Konstantinou et al.'s (2014) findings on visual working memory capacity load. However, when the Flanker task appeared within the visual working memory task, visual working memory precision load and capacity load had different effects on attentional selection during the maintenance phase: high-precision load reduced interference compared to baseline, while high-capacity load increased interference compared to baseline. Why does visual working memory load type affect attentional selection differently during the maintenance phase when the attentional selection task appears within the visual working memory task? This may be related to changes in attentional scope under different load types during the maintenance phase. Therefore, we designed Experiment 3, which used a Navon task to manipulate attentional scope, placing the attentional selection task within visual working memory items to examine how visual working memory load type and attentional scope changes affect attentional selection during the maintenance phase.

4 Experiment 3: Effects of Visual Working Memory Load Type and Attentional Scope Changes on Attentional Selection When Memory Items and Attentional Selection Tasks Are Presented Sequentially

Based on Experiment 2, Experiment 3 presented a Navon task within memory items to investigate how visual working memory load type affects attentional selection under varying attentional scope conditions.

4.1.1 Participants

Thirty-six university students (15 male, mean age = 19.70 ± 1.70 years) participated in the experiment. All participants had normal or corrected-to-normal vision, no color blindness or color weakness, no history of mental illness, and had not participated in similar experiments previously. Participants received compensation after the experiment.

4.1.2 Apparatus and Materials

The apparatus and visual working memory task materials were identical to those used in Experiment 1.

Navon task materials consisted of composite large letters ($5° \times 2.5°$) composed of small letters ($0.7° \times 0.6°$). The large letters were either S or H, and the small letters were also either S or H. There were two combination types: congruent (both large and small letters were S or both were H) and incongruent (large letter S with small letter H, or large letter H with small letter S). Navon stimuli were presented within visual working memory items, specifically within a circle of radius 6° centered on the fixation point.

4.1.3 Experimental Design

The experiment employed a 3 (visual working memory load type: baseline, high-precision load, high-capacity load) × 2 (Navon task attentional focus: global, local) mixed design. The Navon task attentional focus was a between-subjects factor with two conditions: attending to global features required identifying the large letter in the Navon task, with a 4:1 ratio of trials requiring responses to large letters versus small letters; attending to local features required identifying the small letter, with a 4:1 ratio of trials requiring responses to small letters versus large letters (Ahmed & De Fockert, 2012). Visual working memory load types were identical to those in Experiment 1. Accuracy for the visual working memory task and response times for the Navon task were recorded.

The procedure is illustrated in [Figure 5: see original paper]. A fixation cross "+" appeared for 1000 ms, followed by memory items for 200 ms. A fixation cross "+" then appeared for 350 ms, followed by a text cue ("large letter" or "small letter") for 1500 ms, instructing participants which letter level to attend to. After another fixation cross "+" for 350 ms, the Navon stimulus appeared for 1850 ms. Participants identified the letter according to the text cue and pressed the corresponding key: "S" for letter S and "H" for letter H. Finally, the visual working memory probe item appeared. The probe consisted of a single colored square presented randomly at one of the memory item positions. In 50% of trials, the probe color remained unchanged; in the other 50%, it changed. Participants pressed "A" if the probe matched the memory item in both color and position, and "S" otherwise. The experiment consisted of 3 blocks (baseline, high-precision load, high-capacity load), with block order counterbalanced using a Latin square. Each block included 12 practice trials and 72 experimental trials.

Participants rested for 5 minutes after each block, and the entire experiment lasted approximately 60 minutes.

4.2.1 Accuracy of the Visual Working Memory Task

Accuracy rates for the visual working memory task under different conditions are shown in . A two-way ANOVA with Navon task attentional focus and visual working memory load type as factors (repeated measures on the latter) revealed a significant main effect of visual working memory load type, $F(2, 68) = 142.81$, $p < 0.001$, $\mathrm{p}^2 = 0.81 > 0.14$. Accuracy in the baseline condition ($M = 0.87$, 95% CI [0.84, 0.88]) was higher than in both the high-precision load ($M = 0.69$, 95% CI [0.66, 0.71]) and high-capacity load ($M = 0.66$, 95% CI [0.63, 0.69]) conditions, $ps < 0.001$. The difference between high-precision and high-capacity load conditions was marginally significant, $p = 0.08$. No other effects were significant.

4.2.2 Response Times for the Navon Task

Only data from trials with correct responses on both the visual working memory task and Navon task were analyzed. Response times for the Navon task under different conditions are shown in . A three-way ANOVA with Navon task attentional focus, congruency, and visual working memory load type as factors (repeated measures on the latter two) revealed a significant main effect of congruency, $F(1, 34) = 52.09$, $p < 0.001$, $\mathrm{p}^2 = 0.61 > 0.14$. Response times were longer when target and distractor were incongruent ($M = 944.47$, 95% CI [892.22, 996.73]) than when they were congruent ($M = 871.64$, 95% CI [824.40, 918.87]). The interaction between Navon task attentional focus and visual working memory load type was significant, $F(2, 68) = 10.36$, $p < 0.001$, $\mathrm{p}^2 = 0.23 > 0.14$. The three-way interaction between Navon task attentional focus, congruency, and visual working memory load type was also significant, $F(2, 68) = 19.72$, $p < 0.001$, $\mathrm{p}^2 = 0.37 > 0.14$. No other effects were significant.

To further analyze the effect of working memory load type on the attentional selection task, we examined Navon interference effects, calculated as the difference in response times to target letters between incongruent and congruent large-small letter conditions (see [Figure 6: see original paper]). This reflects the degree of interference from distractor letters on target letters (Ahmed & De Fockert, 2012). Further analysis revealed that in the baseline condition, Navon interference effects did not differ significantly between local and global attention conditions, $F(1, 34) < 1$, $p = 0.93$. In the high-precision load condition, Navon interference effects were smaller when attending to local features than when attending to global features, $F(1, 34) = 10.89$, $p = 0.002$. In the high-capacity load condition, Navon interference effects were larger when attending to local features than when attending to global features, $F(1, 34) = 9.11$, $p = 0.005$.

4.3 Discussion

Visual working memory accuracy results showed that accuracy under both high-precision and high-capacity loads was lower than in the baseline condition, consistent with Experiments 1 and 2. Navon interference effects indicated that under high visual working memory precision load, interference effects were larger when attending to global features than when attending to local features. Conversely, under high visual working memory capacity load, interference effects were larger when attending to local features than when attending to global features. This may be because high visual working memory precision load narrows attentional scope, which aligns with the attentional focus required for local Navon task processing but conflicts with global Navon task processing. In contrast, high visual working memory capacity load broadens attentional scope, which aligns with global Navon task processing but conflicts with local Navon task processing. Consequently, different types of visual working memory load produce different effects on Navon attentional selection tasks. Changes in attentional scope may cause distractors to enter perceptual processing to different degrees, resulting in varying overlap in cognitive control resource consumption between the Flanker task and the visual working memory task. When the Flanker task is presented within memory items, completing it requires participants to deploy cognitive control resources to inhibit distractors and accomplish the target task. Could differences in cognitive control resource consumption under different visual working memory loads account for the different effects of visual working memory load types on attentional selection during the maintenance phase? Experiment 4 used ERP technology to further investigate this question.

5 Experiment 4: ERP Study on How Visual Working Memory Load Type Affects Attentional Selection When Memory Items and Attentional Selection Tasks Are Presented Sequentially

Using ERP technology and the N2 component as an index of cognitive control resource investment under conflict resolution conditions (Heil et al., 2000; Kopp et al., 1996), Experiment 4 presented the Flanker task within memory items after memory items to explore the mechanisms by which visual working memory precision load and capacity load affect attentional selection.

5.1.1 Participants

Eighteen university students participated in the experiment. All had normal or corrected-to-normal vision, no color blindness or color weakness, were right-handed, had no brain damage or history of mental illness, and had not participated in similar experiments previously. Participants received compensation after the experiment. Four participants were excluded from analysis due to incomplete data or excessive blinking, leaving a final sample of 14 participants

(6 male, mean age = 20.85 ± 1.80 years). Based on Qi et al. (2014), with an effect size of Cohen's $d = 1.11$ for N2 interference effects under high versus low capacity load, G*Power 3.1 software was used to calculate the required sample size as 11 (power = 95%, $\alpha = 0.05$).

5.1.2 Apparatus and Materials

The apparatus and visual working memory task materials were identical to those used in Experiment 2.

5.1.3 Experimental Design

The experiment employed a single-factor within-subjects design with three levels of visual working memory load type (baseline, high-precision load, high-capacity load). Response times for the Flanker task, accuracy for the visual working memory task, and EEG data were recorded.

The experiment was conducted in a soundproof, electromagnetically shielded dark room. The procedure is illustrated in [Figure 7: see original paper]. A fixation cross "+" appeared for 500 ms to signal the start of the trial, followed by a blank screen for 600–700 ms. Memory items were then presented for 200 ms, and participants were instructed to remember the colors of the squares. After a blank screen for 1850 ms, the Flanker task appeared for 500 ms, followed by a "?" for 1500 ms. Participants identified the target letter on the circle: press "0" for "X" and "2" for "N". Finally, the visual working memory probe item appeared. Participants judged whether the color at that position matched the color of the memory item at that position: press "A" for same, "S" for different. The experiment consisted of 3 blocks (baseline, high-precision load, high-capacity load), with block order counterbalanced using a Latin square. Each block included 12 practice trials and 144 experimental trials. Participants rested for 5 minutes after every 72 trials, and the entire experiment lasted approximately 120 minutes.

5.2 ERP Data Acquisition and Analysis

EEG data were collected using a 64-channel CURRY7 system from NeuroScan with an extended international 10-20 system electrode cap. Vertical electrooculogram (VEOG) was recorded from electrodes above and below the left orbit, and horizontal electrooculogram (HEOG) from electrodes 1.5 cm lateral to each eye. During recording, all electrodes were referenced to the left mastoid, with the right mastoid electrode also recorded. Offline analysis used the average of both mastoids as reference. Impedance for all electrodes was maintained below 5 kΩ. The low-pass filter was set at 100 Hz, with no high-pass filter, using DC sampling at 500 Hz. Offline data analysis was performed using the CURRY7 system. Data were DC-corrected, and blink and eye movement artifacts were corrected using the artifact correction correlation method. A low-pass filter of

30 Hz was applied. The 200 ms period before the onset of visual working memory items served as the baseline for correction. Trials with amplitudes exceeding $±$75 V were excluded. The N2 component was analyzed in a time window of 2300–2550 ms after memory item onset (250–500 ms after Flanker task onset), defined as $±$20 ms around the peak of the negative component for each participant under each load condition. Based on previous research (Forster, Carter, Cohen, & Cho, 2011; Qi et al., 2014), analysis focused on fronto-central electrode sites (Fz, FCz, Cz).

5.3.1 Accuracy of the Visual Working Memory Task

A repeated-measures ANOVA on visual working memory task accuracy revealed a significant main effect of visual working memory load type, $F(2, 26) = 96.00$, $p < 0.001$, $\mathrm{p}^2 = 0.88 > 0.14$. Accuracy in the baseline condition ($M = 0.90$, 95% CI [0.87, 0.94]) was higher than in both the high-precision load ($M = 0.70$, 95% CI [0.66, 0.74]) and high-capacity load ($M = 0.73$, 95% CI [0.68, 0.78]) conditions, $ps < 0.001$. The difference between high-precision and high-capacity load conditions was marginally significant, $p = 0.08$.

5.3.2 Response Times for the Flanker Task

Only data from trials with correct responses on both the visual working memory task and Flanker task were analyzed. Response times for the Flanker task under different conditions are shown in . A two-way ANOVA with Flanker task congruency and visual working memory load type as factors (repeated measures) revealed a significant main effect of congruency, $F(1, 13) = 53.37$, $p < 0.001$, $\mathrm{p}^2 = 0.80 > 0.14$. Response times were longer when target and distractor were incongruent ($M = 712.14$, 95% CI [594.17, 830.10]) than when they were congruent ($M = 487.13$, 95% CI [410.99, 563.27]). The interaction between congruency and visual working memory load type was significant, $F(2, 26) = 14.37$, $p < 0.001$, $\mathrm{p}^2 = 0.53 > 0.14$. Post-hoc tests on Flanker interference effects showed that interference effects were significantly greater in the high-capacity load condition than in the baseline condition, $p = 0.028$, and significantly smaller in the high-precision load condition than in the baseline condition, $p = 0.014$.

5.3.3 ERP Results

Grand-averaged waveforms at electrodes Fz, FCz, and Cz are shown in [Figure 8: see original paper], and average N2 amplitudes under different conditions are shown in [Figure 9: see original paper]. A two-way ANOVA on mean amplitudes in the 2300–2550 ms time window with visual working memory load type and Flanker task congruency as factors (repeated measures) revealed a significant main effect of visual working memory load type, $F(2, 26) = 7.71$, $p = 0.002$, $\mathrm{p}^2 = 0.37 > 0.14$. N2 amplitude in the capacity condition ($M = 1.68$, 95% CI [-2.164, 5.2]) was smaller than in the baseline condition ($M = -0.142$, 95% CI [-3.84, 3.55]), $p = 0.073$, and smaller than in the precision condition ($M = -2.68$, 95% CI [-7.08, 1.71]), $p = 0.008$. N2 amplitude in the baseline condition was smaller than in the precision condition, $p = 0.021$. The two-way interaction was significant, $F(2,\ 26) = 3.62$, $p = 0.041$, $\mathrm{p}^2 = 0.22 > 0.14$. Simple effects analysis revealed no differences in N2 amplitude across load types under congruent conditions, $F(2,\ 26) = 2.51$, $p = 0.12$. However, under incongruent conditions, N2 amplitudes differed significantly across load types, $F(2,\ 26) = 10.06$, $p = 0.001$. N2 amplitude in the precision condition was significantly larger than in the baseline condition, $p = 0.036$, while N2 amplitude in the capacity condition was significantly smaller than in the baseline condition, $p = 0.039$.

5.4 Discussion

Behavioral results showed that visual working memory task accuracy was higher in the baseline condition than under high-precision and high-capacity loads, consistent with Experiments 1, 2, and 3. Flanker interference effects were significantly greater under high-capacity load than baseline, and significantly smaller under high-precision load than baseline, consistent with Experiment 2. ERP results showed that under incongruent conditions, N2 amplitude was significantly larger under high-precision load and significantly smaller under high-capacity load compared to baseline. Previous research indicates that N2 amplitude reflects the amount of attentional resources invested in conflict detection and resolution (Kanske & Kotz, 2010). This suggests that compared to baseline, more attentional resources were invested in conflict detection and resolution under high visual working memory precision load, while fewer resources were invested under high-capacity load.

6 General Discussion

This study investigated how visual working memory load type affects attentional selection through four experiments. Experiment 1 examined how visual working memory load type and attentional selection task position affect attentional selection when memory items and attentional selection tasks are presented simultaneously. Experiment 2 examined how visual working memory load type and attentional selection task position affect attentional selection when memory items and attentional selection tasks are presented sequentially. Experiment 3 used a Navon task to manipulate attentional scope changes, exploring how visual working memory load type affects attentional selection. Experiment 4 used ERP technology to investigate the mechanisms underlying the effects of visual working memory load type on attentional selection.

The results showed that during the encoding phase of visual working memory, both high-capacity and high-precision loads reduced Flanker interference compared to baseline, regardless of whether the Flanker task appeared within or in the periphery of visual working memory items. During the maintenance phase of visual working memory, when the Flanker task appeared in the periphery of memory items, both high-capacity and high-precision loads reduced Flanker interference compared to baseline. However, when the Flanker task appeared within visual working memory items, the two load types produced opposite effects: high-capacity load increased interference while high-precision load reduced interference compared to baseline. When the Navon task appeared within visual working memory items, interference effects were smaller when attending to local features than when attending to global features under high-precision load, but larger when attending to local features than when attending to global features under high-capacity load. When the Flanker task appeared within visual working memory items, high-precision load elicited larger N2 amplitudes while high-capacity load elicited smaller N2 amplitudes compared to baseline.

6.1 How Visual Working Memory Precision Load and Capacity Load Affect Attentional Selection Tasks When Presented Simultaneously

Why did both high-precision and high-capacity loads reduce interference effects when the visual working memory task and Flanker task were presented simultaneously? When these tasks are presented simultaneously, both are primarily processed during the encoding stage. Visual working memory task completion is accompanied by activation of visual perceptual cortex (Ester, Serences, & Awh, 2009; Harrison & Tong, 2009; Munneke, Heslenfeld, & Theeuwes, 2010; Pasternak & Greenlee, 2005; Serences, Ester, Vogel, & Awh, 2009). Both visual working memory capacity load and precision load increase perceptual load (Lavie, Hirst, De Fockert, & Viding, 2004). High-precision load increases perceptual load by increasing the difficulty of discriminating memory items, while high-capacity load increases perceptual load by increasing the number of memory items. Perceptual load theory (Lavie, 1995; Lavie & Tsal, 1994) posits that perceptual resources are limited. When capacity is not exceeded, both task-relevant and task-irrelevant stimuli are processed. However, when task-relevant stimulus load is sufficiently high, processing task-relevant stimuli consumes limited perceptual resources, leaving insufficient resources for processing distractors and thereby reducing interference effects. In Experiment 1, when visual working memory items and the Flanker attentional selection task were presented simultaneously, participants had to encode memory items while ignoring Flanker distractor letters and perceptually processing target letters. At this stage, visual working memory task processing and Flanker task processing shared perceptual resources. When visual working memory load (precision or capacity) increased, the visual working memory task consumed more perceptual processing resources, leaving fewer resources available for the Flanker task and consequently fewer resources for processing distractors, resulting in reduced interference effects. These findings align with Konstantinou et al. (2014) and support perceptual load theory. Experiment 1 also showed that when visual working memory items and the Flanker task were presented simultaneously, changes in Flanker task position did not alter the effects of visual working memory precision and capacity loads on attentional selection tasks. However, why did changes in Flanker task position modify these effects when visual working memory tasks and attentional selection tasks were presented sequentially?

6.2 How Attentional Scope and Visual Working Memory Load Type Affect Attentional Selection When Tasks Are Presented Sequentially

When visual working memory items and attentional selection tasks are presented sequentially, the Flanker attentional selection task occurs during the maintenance phase of visual working memory. When visual working memory items are presented, participants attend to a specific spatial region and process and represent memory items that fall within this region. After memory items disappear and the maintenance phase begins, because the Flanker task appears in the periphery of memory items, participants must shift attention to the space outside the memory item region and represent the Flanker task that falls within this new region. Completing these two-stage tasks requires participants to successively select different spatial regions for attention, involving spatially based attention and attentional shifts across spatial regions, which consumes attentional resources (Baddeley, 1996; Norman & Shallice, 1986). Therefore, whether visual working memory capacity load or precision load increases, the increased memory load, attentional shifts across space, and processing of attentional selection targets all consume attentional resources compared to baseline, leaving insufficient resources for processing distractors and thus reducing interference effects. These results align with Roper and Vecera (2014) and Konstantinou et al. (2014), supporting perceptual load theory. However, when the Flanker task appears within memory items during the maintenance phase, distractors easily fall within the attentional focus and automatically enter perceptual processing. From the encoding to maintenance phase of visual working memory, precision load and capacity load may redistribute attentional resources across the attended space, affecting distractor processing and producing different effects on interference. Research shows that spatial distribution of attention affects attentional selection: compared to focused attention, when diffuse attention is more demanding, individuals are more susceptible to distractor interference during attentional selection tasks (Belopolsky & Theeuwes, 2010; Belopolsky, Zwaan, Theeuwes, & Kramer, 2007). Compared to baseline, high-precision load requires detailed processing of memory items, focusing attention on a finer spatial scale and thereby narrowing attentional scope. Narrowed attentional resources make attention more focused during the maintenance phase, facilitating conflict resolution in the Flanker task and reducing interference effects. In contrast, high-capacity load requires remembering more items, broadening attentional scope and potentially dispersing attention across a coarser, more extensive space. Broadened attentional resources are more diffuse, making it difficult to effectively resolve Flanker task conflicts that appear within memory items during the maintenance phase, thus increasing interference effects. Our findings provide a good explanation for the inconsistency between Konstantinou et al. (2014) and Zhang and Luck (2015). In Konstantinou et al. (2014), Flanker distractors were located in the periphery of memory items and did not receive sufficient perceptual resources, reducing interference effects. In Zhang and Luck (2015), Flanker distractors were located within memory items. When visual working memory capacity load increased, it consumed more cognitive control resources, reducing inhibition of distractors and increasing interference effects.

Experiment 3 used a Navon task to manipulate attentional scope changes (Navon, 1977). After presenting visual working memory items, a Navon task was presented within memory items to further explore why the two load types produce different effects on attentional selection tasks. The results showed that under high-precision load, interference effects were smaller when attending to local features than when attending to global features. Under high-capacity load, interference effects were larger when attending to local features than when attending to global features. High visual working memory precision load narrows attentional scope, which conflicts with the attentional focus required for global Navon task processing but aligns with local Navon task processing, impairing performance in the former and facilitating performance in the latter. High visual working memory capacity load broadens attentional scope, which aligns with global Navon task processing but conflicts with local Navon task processing. This suggests that when attentional selection tasks appear within visual working memory items during the maintenance phase, the consistency between visual working memory and attentional selection tasks in terms of attentional spatial changes may account for the different effects of visual working memory precision and capacity loads on attentional selection.

What is the mechanism linking attentional scope changes and different visual working memory loads to attentional selection tasks? Experiment 4 used ERP technology to investigate this question. The results showed that under incongruent conditions, high-precision load elicited larger N2 amplitudes and reduced interference effects compared to baseline, while high-capacity load elicited smaller N2 amplitudes and increased interference effects compared to baseline. The N2 component is associated with conflict monitoring and attentional control during cognitive processing, reflecting the amount of cognitive control resources invested in conflict resolution: larger N2 amplitude indicates more control resources invested in conflict resolution (Heil et al., 2000; Kanske & Kotz, 2010; Kopp et al., 1996; van Veen & Carter, 2002). High-precision working memory load narrows attentional scope, and completing a Flanker task presented within memory items also requires narrowing attentional scope. The alignment between these attentional foci provides sufficient resources for inhibiting distractors, resulting in larger N2 amplitudes than baseline. In contrast, high-capacity working memory load broadens attentional scope, while Flanker tasks presented within memory items require narrowing attentional scope. This misalignment leads to insufficient cognitive control resources for inhibiting distractors, resulting in smaller N2 amplitudes than baseline.

Additional research has found that different types of visual working memory load involve distinct neural mechanisms. Storage of visual working memory capacity information is associated with activation in the inferior intraparietal sulcus, whereas storage of visual working memory precision information is associated with activation in the superior intraparietal sulcus and lateral occipital cortex (Bettencourt & Xu, 2016; Weber, Peters, Hahn, Bledowski, & Fiebach, 2016; Xu & Chun, 2006). Unlike capacity information, precision information storage during the maintenance phase continues to occupy visual channels and activate primary visual cortex (Ester, Anderson, Serences, & Awh, 2013). Moreover, precision information storage is associated with functional connectivity between parietal and occipital regions (Weber, Hahn, Hilger, & Fiebach, 2017). Activation in these brain regions and neural connections reflects perceptual or attentional demands of working memory processes (Mitchell & Cusack, 2008), suggesting that precision information processing in visual working memory consumes more perceptual resources that persist into the maintenance phase. Under high-precision load, because precision information storage continues to occupy visual channels and primary visual cortex remains activated during the maintenance phase (Ester et al., 2013), the appearance of the Flanker task facilitates continued investment of more attentional resources in conflict detection and resolution, promoting conflict resolution. Under high-capacity load, because capacity information storage is completed and primary visual cortex is no longer activated during the maintenance phase, the appearance of the Flanker task requires reactivation of primary visual cortex and investment of resources in conflict detection and resolution, leading to reduced cognitive control resource investment and impairing conflict resolution. This indicates that different neural activity patterns associated with visual working memory capacity and precision loads during the maintenance phase lead to differential investment of cognitive control resources in attentional selection tasks, resulting in different efficiencies in completing attentional selection tasks during the maintenance phase.

7 Conclusion

When Flanker tasks are presented during the encoding phase of visual working memory, both visual working memory capacity load and precision load reduce Flanker interference effects. When Flanker tasks are presented in the periphery of memory items during the maintenance phase, both load types reduce Flanker interference effects, supporting perceptual load theory. However, when Flanker tasks are presented within memory items, the two load types produce opposite effects: capacity load increases interference effects while precision load reduces them. The underlying mechanism is that different neural activities associated with the two load types during working memory representation lead to differential investment of cognitive control resources in attentional selection during the maintenance phase.

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