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Different Attentional Selection Patterns of Object Information in the Encoding and Maintenance Stages of Visual Working Memory

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Abstract

Whether attentional selection patterns for multi-feature object information are identical across different processing stages (encoding and maintenance) of visual working memory remains controversial. The present study employed a change detection paradigm, introducing pre-cues and post-cues to probe attentional selection patterns during the encoding and maintenance stages of visual working memory, respectively. Results from three experiments demonstrated that in pre-cue trials, participants' detection of changes in task-relevant features was significantly disrupted by changes in task-irrelevant features, manifested as slower response times and lower response criteria in the task-irrelevant feature change condition compared to the unchanged condition; moreover, this interference effect was not modulated by memory load. In contrast, in post-cue trials, interference effects were observed only under low memory load conditions (Experiments 1a/1b), and disappeared when memory load increased (Experiments 2/3). These findings indicate that during the visual working memory encoding stage, both task-relevant and task-irrelevant features of an object are encoded into visual working memory and compete for attentional resources; whereas during the maintenance stage, task-irrelevant features are processed only under low memory load conditions. The results reveal that the attentional selection mode during the encoding stage is object-based, while the attentional selection mode during the maintenance stage is feature-based and modulated by memory load.

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Different Attentional Selection Modes of Object Information in the Encoding and Maintenance Stages of Visual Working Memory

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Abstract

Visual working memory (VWM) and selective attention are two essential topics of investigation in the field of cognitive psychology. Previous studies have suggested that object-based attention selection modes may be present during the VWM encoding stage, and feature-based attention selection modes may be present during the maintenance stage. Nonetheless, these conclusions are based on different research paradigms, object feature dimensions, and response indicators, so it is prudent to exercise caution when inferring the existence of distinct attention selection modes during different stages of VWM processing. The aim of the present study is to evaluate this hypothesis and provide empirical support.

In Experiment 1a, 30 college students were recruited to complete a change-detection task. Participants were instructed to memorize the features of the objects presented in the memory display by means of a pre-cue or retro-cue presented prior to or following the memory display. Specifically, in pre-cue trials, participants were asked to memorize only the cueing task-relevant feature while ignoring the task-irrelevant feature. In retro-cue trials, participants needed to memorize the entire object so that they could select the task-relevant feature according to the retro-cue. The present study examined the “irrelevant-change distracting effect” by comparing memory performance between the condition of task-irrelevant feature changes and no-changes on the memory probe test display. Experiment 1b had a similar procedure, except that the cue types were block designs. Based on the design of Experiment 1b, Experiments 2 and 3 increased the number of memory items to test whether the memory load would modulate the attention selection modes. Twenty-eight participants were recruited for Experiment 1b, Experiment 2, and Experiment 3. All experiments were 2 (cue types: pre-cue, retro-cue) × 2 (task-irrelevant feature change types: change, no-change) within-subjects designs, participants’ response times (RTs) and correct rates were recorded, and the sensitivity and criteria of the participants were calculated by signal detection theory (SDT).

The results of the three experiments showed that the change in task-irrelevant features had an impact on task performance in the pre-cue trials, with longer

RTs and lower criteria in the task-irrelevant feature change condition than in the no-change condition. This distracting effect was not modulated by the memory load. This suggests the existence of robust object-based attentional selection during the encoding stage in VWM. In contrast, in the retro-cue trials, the distracting effect was present only in the low memory load condition (Experiment 1a/1b) and disappeared when the memory load increased (Experiment 2/3). This suggests that during the maintenance stage, task-irrelevant features are processed only under low memory load conditions, and insufficient resources lead to their inability to be processed as the demand for attentional resources for task-relevant features increases.

In summary, the present study provides further evidence for the hypothesis that different modes of attentional selection exist in the encoding and maintenance stages of VWM, specifically that the attention selection mode during the VWM encoding stage is object-based, while the attention selection mode during the maintenance stage is feature-based and regulated by memory load. This study has important implications for resolving the controversy surrounding the attention selection mode of multifeature objects in VWM.

Keywords: visual working memory, encoding stage, maintenance stage, object-based attention, feature-based attention

1 Introduction

Visual working memory (VWM) serves as a temporary storage and processing site for visual information (Baddeley, 2000; Baddeley & Hitch, 1974). Due to limited cognitive resources, VWM cannot simultaneously process all information input from the external environment (Cowan, 2017; Fukuda et al., 2010; Vogel et al., 2001). In this context, the brain can selectively attend to the most task-relevant information for VWM processing according to task demands, thereby alleviating limitations on cognitive resources (Awh et al., 2006; Gazzaley & Nobre, 2012). Objects in daily environments are composed of multiple features (e.g., color, shape, texture). Based on the different types of object information selected by attention, attention can be divided into object-based attention and feature-based attention. Object-based attention refers to the phenomenon where when one feature of a multifeature object is selectively attended, other features of the same object are also selected and influence each other (Luck & Vogel, 1997). Feature-based attention refers to the ability to selectively attend to a single feature without being influenced by other features (Wheeler & Treisman, 2002). However, controversy remains regarding whether the attentional selection mode for multifeature objects in VWM is object-based or feature-based.

Object-based attention theory posits that when one feature of a multifeature object is selected, other features on the same object are automatically activated (Ernst et al., 2013; O'Craven et al., 1999). Previous studies supporting this theory have primarily used the change-detection paradigm, which requires participants to encode memory items into VWM and maintain them for a period before comparing them with probe items, thereby effectively investigating the processing mechanisms of object information in VWM (Lin & Luck, 2012). Luck and Vogel (1997) first provided empirical support for object-based attentional selection of multifeature objects in VWM using the change-detection paradigm. They found no difference in task performance between conditions where participants memorized only a single feature of multifeature objects versus multiple features simultaneously. This indicates that even when the task requires participants to select only one feature for memory, they cannot do so voluntarily and still encode task-irrelevant features into VWM. Subsequently, Shen et al. (2013) further demonstrated that object-based attentional selection in VWM not only exists but is also quite robust. In their study, using a change-detection paradigm, participants were informed before the memory display that they only needed to memorize the color feature and report whether it changed, while ignoring changes in the task-irrelevant shape feature. The results showed that participants' reaction times significantly increased when the task-irrelevant shape feature changed, indicating that the task-irrelevant shape feature was encoded into VWM along with the relevant feature. In subsequent experiments, the same results were observed even after increasing memory load, reducing the probability of task-irrelevant feature changes, and increasing consumption of attentional resources in working memory, suggesting that this object-based attentional selection mode stably exists in VWM encoding.

Although early studies can serve as evidence for the existence of object-based attention mechanisms in VWM, these studies have mostly focused on attentional selection modes occurring during the encoding stage of VWM, where feature-task relevance is informed before the memory display. Existing evidence indicates that attentional selection can occur not only during the encoding stage of memory but also continuously function during the maintenance stage of internal representations (Griffin & Nobre, 2003). However, studies on attentional selection modes during the maintenance stage have yielded different findings (Niklaus et al., 2017; Park et al., 2017; Sasin & Fougnie, 2020; Ye et al., 2016).

Ye et al. (2016) used a memory-report task to investigate whether attentional resources could be successfully concentrated on task-relevant feature dimensions during the maintenance stage of multifeature object representations. They employed retro-cues presented after the memory display to inform participants of feature-task relevance. The experimental conditions were divided into valid cue and neutral cue conditions. In the valid cue condition, the cued feature was the feature to be reported in memory; in the neutral cue condition, the cue pointed to both features, and the memory report was for a randomly selected feature. The results showed that compared to neutral cues, effective retro-cues could increase the likelihood of reporting the target feature, indicating that participants could flexibly allocate internal attentional resources to specific dimensions of internal memory representations using retro-cues. This also suggests that the storage of object features is independent of each other, thereby supporting the feature-based attention hypothesis in VWM. Additionally, Wang et al. (2017) found that under the premise of a fixed number of memory objects, changing the number of feature values in one dimension did not affect memory performance for another feature. They argued that the VWM system has multiple subsystems for storing features, with features of different dimensions stored in independent subsystems, further providing evidence for feature-based attention during the VWM maintenance stage.

In summary, existing studies have provided corresponding evidence supporting both object-based and feature-based attentional selection modes in VWM. The seemingly contradictory conclusions may be due to the fact that these studies investigated different processing stages of VWM. As we know, different processing mechanisms exist in VWM encoding and maintenance stages (Woodman, 2005), so the two attentional selection modes may exist in different processing stages of VWM. For example, after concluding that feature-based storage mechanisms exist in VWM, Ye et al. did not directly refute the existence of object-based attention in VWM. Instead, combining previous research, they further proposed the hypothesis that both object-based and feature-based attention coexist in VWM. They suggested that participants initially encode memory items in an involuntary object-based manner and can then voluntarily store them in VWM in a feature-based manner. However, previous studies have not found empirical support for this hypothesis, and inferences about this hypothesis have been based only on results from different studies that differed in experimental paradigms, report indicators, and feature information selection. For instance, previous studies suggesting object-based attention during the VWM encoding stage mostly used the change-detection paradigm, while studies supporting feature-based attention during the VWM maintenance stage used the recall-report paradigm. Although recall-report paradigms found that participants' reports of task-irrelevant features were at chance level, this does not necessarily mean that task-irrelevant features are absent from VWM. For example, the classic "tip-of-the-tongue" phenomenon in psychology (Brown & McNeill, 1966) demonstrates that temporary retrieval failure does not indicate the absence of relevant memory. Compared to recall-report paradigms, change-detection paradigms only require recognition, which may be more suitable for investigating whether information exists in VWM. Therefore, it is necessary to simultaneously observe attentional selection modes in both VWM encoding and maintenance stages under the same experimental design, report indicators, and feature combinations to provide empirical support for this hypothesis. Based on Shen et al.'s change-detection paradigm, the present study introduced pre-cues and retro-cues to manipulate feature-task relevance at different processing stages of VWM, observing the interfering effect of task-irrelevant feature changes on task-relevant features to effectively understand the attentional selection modes for multifeature object information in VWM.

Furthermore, Xu (2010) found that task-irrelevant shape features of objects could only be encoded into VWM under low memory load conditions, while this process would be weakened or even suppressed under high memory load conditions. Therefore, they argued that processing task-irrelevant information is not mandatory but is influenced by the resource demands of processing task-relevant features. Although subsequent studies demonstrated that memory load does not affect object-based attentional selection modes during the encoding stage (Shen et al., 2013; Yin et al., 2012), it remains unclear whether attentional selection modes during the maintenance stage are affected by memory load. Therefore, the present study further designed three memory load conditions (low, medium, high) to explore whether attentional selection modes in VWM encoding and maintenance stages are regulated by memory load. Based on previous research findings, we hypothesized that: 1) During the encoding stage, object-based attentional selection mode is more likely and is not regulated by memory load, meaning that interfering effects of task-irrelevant features can be stably observed regardless of memory load. Conversely, if the mode is feature-based, no interfering effect would be observed. 2) During the maintenance stage, feature-based attentional selection mode is more likely, meaning no interfering effect would be observed. If regulated by memory load, different interfering effects may be observed under different memory load conditions.

2 Experiment 1: Attentional Selection Modes in VWM Encoding and Maintenance Under Low Memory Load

This experiment used a change-detection paradigm to examine whether changes in task-irrelevant features affect change detection of task-relevant features. The experiment included two trial types: pre-cue trials where cues were presented before the memory display, and retro-cue trials where cues were presented after the memory display. In pre-cue trials, attentional selection occurred during the encoding stage; in retro-cue trials, attentional selection occurred during the maintenance stage. Participants were required to selectively encode or maintain a single feature of multifeature objects according to the cue word. If the attentional modes in both stages are object-based, then interfering effects of task-irrelevant features should exist in both. Conversely, if the attentional selection mode is feature-based, no interfering effect would be observed.

2.1.1 Participants

First, a priori power analysis was conducted using G*Power 3.1 software. With a medium effect size (f = 0.25, Cohen, 2013), α level of 0.05, and statistical power of 0.8, the required sample size was calculated to be 24 participants. To ensure sufficient statistical power, Experiment 1 recruited 30 college students (26 females, 4 males) with a mean age of 19.40 ± 1.10 years. All participants were right-handed, had normal or corrected-to-normal vision, no color blindness or weakness, and no history of mental illness. All participants signed informed consent before the experiment and received compensation afterward.

2.1.2 Apparatus and Materials

All participants were tested individually in a dimly lit room, seated 60 cm from the screen. The selection and creation of experimental materials

followed Shen et al.'s study. All stimuli were presented on an LCD monitor with a resolution of 1024$\times 768 and are fresh rate of 100 Hz, with black (CIE : 0.312/0.329, 1.0 cd/m^{\{2\})as the background color. Stimulus presentation and response recording were controlled by E-Prime 2.0 softw}$
$0.6/0.3, 20cd/m^{\{2\}), blue (CIE: 0.172/0.141, 20cd/m}\{2\}), and pink (CIE: 0.269/0.125, 20cd/m\hat{}\{2\}), and four shapes$
$circle(size : 1.88°\times 1.88°), triangle(size : 1.88°\times 1.8°), square(size : 1.67°\times 1.67°), and pentagram(size : 2.17°\times$2.17°). In both the memory and probe displays, an imaginary circle with a radius of 2.84° visual angle was used to divide six spatial positions on the screen at 60° intervals: lower left, left, upper left, upper right, right, and lower right (as shown in Figure 1 [Figure 1: see original paper] for Experiment 3). Two positions were randomly selected from the six spatial positions to present the figures. A Chinese character cue word ("color" or "shape") was presented before or after the memory display, using Arial font, size 24.

The experiment employed a 2 (cue type: pre-cue, retro-cue) × 2 (task-irrelevant feature change type: no-change, change) within-subjects design. The task-irrelevant feature change type was determined by whether the task-irrelevant feature changed. Since both color and shape could change, there were four possible scenarios: color change/shape change, color change/shape no-change, color no-change/shape change, and color no-change/shape no-change. Due to the nature of the experimental task, in each trial, one feature was designated as task-relevant based on the cue word, while the other served as task-irrelevant. These four scenarios could be categorized into two conditions: task-irrelevant feature no-change (color change/shape no-change, color no-change/shape no-change) and task-irrelevant feature change (color no-change/shape change, color change/shape change). Subsequent analyses primarily compared differences between these two conditions to examine the interfering effect of task-irrelevant features on change detection of task-relevant features.

The experiment consisted of 480 trials, with 120 trials per condition. The experiment was divided into 8 blocks, with participants required to rest with eyes closed for at least 1 minute after each block. The total duration was approximately 50 minutes. Before the formal experiment, each participant completed 30 practice trials and had to achieve accuracy greater than 90% to proceed to the formal experiment. Feedback on correctness was provided after each trial during practice, while during the formal experiment, feedback on RT and accuracy for the current block was provided after completing each block. Participants' RTs and accuracy were recorded throughout the experiment. Additionally, signal detection theory was introduced to evaluate accuracy by calculating two indices: sensitivity score (d) and response criterion (C). Due to the nature of the change-detection paradigm, which requires participants to correctly discriminate differences between old and new stimuli, traditional accuracy indices can only describe the number of correct judgments. These two indices can describe participants' sensitivity in discriminating old and new stimuli and assess their response bias during the task. The calculation formulas are as follows: d = Z[hit rate] - Z[false alarm rate]; C = -0.5(Z[hit rate] + Z[false alarm rate]). Hits refer to successful detection of changes when the task-relevant feature changed, while false alarms refer to reporting a change when the task-relevant feature remained unchanged.

The experimental procedure is shown in Figure 1. Each trial began with a screen requiring any key press. After the participant pressed a key, a fixation point was presented for 200 ms, marking the start of the trial. Trials were divided into pre-cue and retro-cue types, with the main difference being whether the cue word appeared before or after the memory display. In pre-cue trials, the cue word first appeared at the center of the screen for 500 ms. After a random stimulus interval of 500-1000 ms, the memory display was presented for 500 ms, showing two figures composed of different colors and shapes. At this point, participants only needed to memorize the task-relevant feature according to the cue word, while ignoring the task-irrelevant feature. After another delay of 500-1000 ms, a pair of probe stimuli was presented. The spatial positions of the probe stimuli remained unchanged compared to the memory stimuli, but one feature or both features of one figure were changed (e.g., only color changed, or both color and shape changed). All changes occurred only on the same figure. In the experiment, the probability of change for both task-relevant and task-irrelevant features was 50%. The new feature values appearing in the probe were not used in the memory display. The probe stimuli remained on screen until participants responded, with a maximum allowed response time of 2000 ms. Retro-cue trials differed in that when the memory display appeared, participants had to memorize both color and shape features of both figures, and then select one feature to maintain according to the cue word. In the probe display, participants were required to judge whether the task-relevant feature had changed while ignoring changes in the task-irrelevant feature. If the task-relevant feature changed, participants pressed the “F” key with their left hand; otherwise, they pressed the “J” key with their right hand. Key assignment was counterbalanced across participants. Participants were instructed to respond as quickly as possible while maintaining accuracy.

Note: The upper part of the figure shows the pre-cue trial procedure, and the lower part shows the retro-cue trial procedure. The right side shows the number of memory items across different experiments. Figure 1. Experimental procedure diagram.

2.1.3 Results

The mean accuracy rate in Experiment 1 was 95.30%. Before RT analysis, error trials (4.70%) and trials exceeding 3 standard deviations (1.84%) were excluded. Before calculating signal detection theory indices, all no-response trials (0.44%) were excluded. A 2 (cue type: pre-cue, retro-cue) × 2 (task-irrelevant feature change type: no-change, change) repeated measures ANOVA was conducted on the trimmed data. The results are shown in Figure 2 [Figure 2: see original paper].

RT results showed a significant main effect of cue type, $F(1, 29) = 34.48$, $p <$

0.001, $p^2 = 0.54$, with slower RTs in pre-cue trials (M = 701 ms, SE = 20.38) than in retro-cue trials (M = 668 ms, SE = 18.49). The main effect of task-irrelevant feature change type was also significant, F(1, 29) = 30.63, $p < 0.001$, $p^2 = 0.51$, with slower RTs in the change condition (M = 695 ms, SE = 20.01) than in the no-change condition (M = 674 ms, SE = 18.66). The interaction between cue type and task-irrelevant feature change type was significant, F(1, 29) = 5.94, p = 0.021, $p^2 = 0.17$. Further simple effects analysis revealed that in pre-cue trials, RTs were slower in the task-irrelevant feature change condition (716 vs. 687 ms), t(29) = -6.566, $p < 0.001$, Cohen's d = -0.86, 95% CI = [-1.13, -0.59]. In retro-cue trials, RTs were also slower in the task-irrelevant feature change condition (675 ms vs. 661 ms), t(29) = -2.66, p = 0.013, Cohen's d = -0.43, 95% CI = [-0.75, -0.10]. These results indicate that the interfering effect of task-irrelevant features was significantly present in both cue type trials, though the interference was greater in pre-cue trials.

Signal detection theory indices showed that for sensitivity d scores, the main effect of cue type was significant, F(1, 29) = 12.79, p = 0.001, $p^2 = 0.31$, with higher d scores in pre-cue trials (M = 3.83, SE = 0.09) than in retro-cue trials (M = 3.54, SE = 0.10). The main effect of task-irrelevant feature change type was not significant, F(1, 29) = 0.01, p = 0.922, nor was the interaction, F(1, 29) = 2.91, p = 0.099. For response criterion C values, the main effect of cue type was not significant, F(1, 29) = 1.86, p = 0.184. However, the main effect of task-irrelevant feature change type was significant, F(1, 29) = 47.93, $p < 0.001$, $p^2 = 0.62$, with lower C values in the task-irrelevant feature change condition (M = -0.15, SE = 0.04) than in the no-change condition (M = -0.15, SE = 0.03). The interaction between cue type and task-irrelevant feature change type was significant, F(1, 29) = 19.98, $p < 0.001$, $p^2 = 0.41$. Simple effects analysis showed that in pre-cue trials, C values were lower in the task-irrelevant feature change condition (-0.19 vs. 0.25), t(29) = 9.62, $p < 0.001$, Cohen's d = 1.42, 95% CI = [1.12, 1.72]. In retro-cue trials, C values were also lower in the task-irrelevant feature change condition (-0.11 vs. 0.05), t(29) = 2.55, p = 0.016, Cohen's d = 0.50, 95% CI = [0.10, 0.89]. These results are consistent with the RT results, showing that the interfering effect of task-irrelevant features was significantly present in both cue type trials, but was greater in pre-cue trials.

Figure 2. Results of Experiment 1a. Note: Smaller criterion values indicate that participants were more likely to report that the task-relevant feature had changed. Error bars in bar graphs represent standard errors of the mean. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; n.s. $p > 0.05$. The same applies below.

2.2 Experiment 1b

2.2.1 Purpose

The purpose of Experiment 1b was to exclude the interference caused by the random presentation of pre-cues and retro-cues in Experiment 1a. In Experiment 1b, the two cue types were presented in separate blocks to further verify the results of Experiment 1a.

2.2.2 Methods

Twenty-eight college students were recruited for Experiment 1b (22 females, 6 males) with a mean age of 19.04 ± 2.76 years. Experiment 1b made the following changes based on Experiment 1a: 1) To reduce interference between different cue types, pre-cue and retro-cue trials were presented in separate blocks, with block order counterbalanced across participants; 2) To match subsequent memory load experiments, in addition to the four colors and shapes used in Experiment 1a, four additional colors and shapes were added: cyan (CIE: 0.382/0.276, 20 cd/m^2), pink (CIE: 0.502/0.288, 20 cd/m^2), brown (CIE: 0.526/0.388, 20 cd/m^2), olive (CIE: 0.402/0.451, 20 cd/m^2), flag (size: 1.88°$×1.88°), *arrow*(*size* : 1.8°×1.88°), *crescent*(*size* : 1.8°×1.8°), *andcross*(*size* : 1.67°×$1.67°); 3) Experiment 1b had 64 trials per condition, totaling 256 trials, with a total duration of approximately 40 minutes; 4) The random interval of 500-1000 ms in Experiment 1a was fixed at 1000 ms in Experiment 1b. Other aspects remained consistent with Experiment 1a.

2.2.3 Results

The mean accuracy rate in Experiment 1b was 95.31%. Before RT analysis, error trials (4.69%) and trials exceeding 3 standard deviations (1.48%) were excluded. Before calculating signal detection theory indices, all no-response trials (0.52%) were excluded. A 2 (cue type: pre-cue, retro-cue) × 2 (task-irrelevant feature change type: no-change, change) repeated measures ANOVA was conducted on the trimmed data.

RT results showed that the main effect of cue type was not significant, F(1, 27) = 3.39, p = 0.077. The main effect of task-irrelevant feature change type was significant, F(1, 27) = 10.14, p = 0.004, p^2 = 0.27, with slower RTs in the irrelevant feature change condition (M = 739 ms, SE = 26.55) than in the no-change condition (M = 722 ms, SE = 25.74). The interaction was not significant, F(1, 27) = 2.55, p = 0.122. This differs from Experiment 1a results: although the interfering effect of task-irrelevant features existed in both cue type trials, the difference between them was not significant.

Signal detection theory indices showed that for sensitivity d scores, neither main effects nor interaction were significant, Fs < 1.62, ps < 0.214. For response criterion C values, the main effect of cue type was significant, F(1, 27) = 8.76, p = 0.006, p^2 = 0.25, with higher C values in pre-cue trials (M = 0.04, SE = 0.03) than in retro-cue trials (M = -0.08, SE = 0.03). The main effect of task-irrelevant feature change type was significant, F(1, 27) = 27.87, p < 0.001, p^2 = 0.51, with lower C values in the task-irrelevant feature change condition (M = -0.12, SE = 0.03) than in the no-change condition (M = 0.07, SE = 0.03). The interaction was not significant, F(1, 27) = 2.28, p = 0.143. Consistent with

RT results, the interfering effect of task-irrelevant features existed in both cue type trials, but the difference between them was not significant.

Figure 3 [Figure 3: see original paper]. Experimental results. Note: Panels A and B show Experiment 1b results; Panels C and D show Experiment 2 results; Panels E and F show Experiment 3 results.

2.2.4 Discussion

Experiment 1b presented pre-cue and retro-cue trials in separate blocks. The results showed a significant main effect of irrelevant feature change type. Although the interference in the encoding stage still tended to be greater than in the maintenance stage, the interaction between cue type and task-irrelevant feature change type was not significant. This is consistent with Experiment 1a results, indicating that both encoding and maintenance stages exhibit object-based attentional selection modes. However, the purpose of this study was to verify that object-based attentional selection exists in the VWM encoding stage and feature-based attentional selection exists in the maintenance stage. The results of Experiment 1 did not support our hypothesis. We proposed two possible explanations: First, the maintenance stage may indeed be object-based, where participants can only select integrated objects and cannot select features within objects. Second, the maintenance stage may be feature-based, but color and shape features are stored in the same VWM subsystem and compete for resources. Although retro-cues can reallocate resources (Souza et al., 2014; Rerko & Oberauer, 2013), due to the low memory load in the current task (2 items), maintaining task-relevant features may not consume all attentional resources, leaving residual resources for task-irrelevant features. This speculation is similar to Lavie's (2005) load theory, which posits that under high-load conditions, increased resource demands for task-relevant features lead to insufficient resources for task-irrelevant features, preventing their processing. Furthermore, previous studies have found that memory load does not affect object-based attentional selection modes during the encoding stage (Shen et al., 2013; Yin et al., 2012). Therefore, the present study increased memory load in subsequent experiments to explore changes in attentional selection modes during the maintenance stage. We hypothesized that if the maintenance stage is object-based, increasing load would not eliminate the interfering effect. Conversely, if it is feature-based, the interfering effect should be weakened until it disappears.

3 Experiment 2: Medium Memory Load Condition

3.1 Methods

Experiment 2 recruited 28 college students (21 females, 7 males) with a mean age of 21.11 ± 2.08 years. Experiment 2 increased the number of items in the memory and probe displays to 4, randomly selecting 4 positions from the 6 positions to present figures with different colors and shapes. Participants' task remained the same: to judge whether the task-relevant feature changed according to the cue word while ignoring the task-irrelevant feature. The materials and procedure of Experiment 2 were consistent with Experiment 1b. Before the formal experiment, participants completed 30 practice trials to familiarize themselves with the procedure.

3.2 Results

3.2.1 Data Trimming The mean accuracy rate in Experiment 2 was 75.59%, significantly lower than in Experiment 1 (95.31%), $t(84) = -24.57$, $p < 0.001$, Cohen's d = -5.65, 95% CI = [-6.11, -5.20]. This is understandable as the task became more difficult with increased memory load, and participants' performance decreased, demonstrating the effectiveness of the memory load manipulation. Before RT analysis, error trials (24.41%) and trials exceeding 3 standard deviations (0.64%) were excluded. Before calculating signal detection theory indices, all no-response trials (1.17%) were excluded. A 2 (cue type: pre-cue, retro-cue) × 2 (task-irrelevant feature change type: no-change, change) repeated measures ANOVA was conducted on the trimmed data. Additionally, to verify the regulatory role of memory load, a mixed ANOVA across experiments was performed.

3.2.2 Reaction Time Results RT results showed a significant main effect of cue type, $F(1, 27) = 33.40$, $p < 0.001$, $p^2 = 0.55$, with faster RTs in pre-cue trials ($M = 887$ ms, $SE = 28.50$) than in retro-cue trials ($M = 991$ ms, $SE = 29.76$). The main effect of task-irrelevant feature change type was significant, $F(1, 27) = 18.18$, $p < 0.001$, $p^2 = 0.40$, with slower RTs in the irrelevant feature change condition ($M = 956$ ms, $SE = 28.19$) than in the no-change condition ($M = 921$ ms, $SE = 27.88$). The interaction was significant, $F(1, 27) = 8.29$, $p = 0.008$, $p^2 = 0.24$. Simple effects analysis showed that in pre-cue trials, RTs were slower in the task-irrelevant feature change condition (915 vs. 860 ms), $t(27) = -6.07$, $p < 0.001$, Cohen's d = -0.61, 95% CI = [-0.82, -0.40]. However, in retro-cue trials, the difference between change and no-change conditions was not significant (998 vs. 983 ms), $t(27) = -1.24$, $p = 0.227$, Cohen's d = -0.17, 95% CI = [-0.45, 0.11]. This indicates that when memory load increased, the interfering effect of task-irrelevant features disappeared in retro-cue trials.

Since the interfering effect of task-irrelevant features in pre-cue trials was robustly present in both Experiment 1b and Experiment 2, the main difference appeared in retro-cue trials. To examine the effect of memory load on retro-cue trials, we combined the retro-cue trials from Experiment 1b and Experiment 2 and conducted a 2 (memory load: low, medium) × 2 (task-irrelevant feature change type: no-change, change) mixed ANOVA, with memory load as a between-subjects variable and task-irrelevant feature change type as a within-subjects variable. The results showed a significant main effect of memory load, $F(1, 54) = 36.42$, $p < 0.001$, $p^2 = 0.40$, with significantly faster RTs under low memory load ($M = 747$, $SE = 28.53$) than under medium memory load ($M = 991$, $SE = 28.53$). The main effect of task-irrelevant feature change type was not significant, $F(1, 54) = 2.94$, $p = 0.092$, nor was the interaction, $F(1, 54) =$

0.17, $p = 0.682$.

3.2.3 Signal Detection Theory Results Signal detection theory indices showed that for sensitivity d scores, the main effect of cue type was significant, $F(1, 27) = 47.27$, $p < 0.001$, $p^2 = 0.64$, with higher d scores in pre-cue trials ($M = 1.92$, $SE = 0.09$) than in retro-cue trials ($M = 1.30$, $SE = 0.05$). The main effect of task-irrelevant feature change type was not significant, $F(1, 27) = 0.60$, $p = 0.446$, nor was the interaction, $F(1, 27) = 2.38$, $p = 0.135$. For response criterion C values, the main effect of cue type was not significant, $F(1, 27) = 1.69$, $p = 0.204$. However, the main effect of task-irrelevant feature change type was significant, $F(1, 27) = 16.23$, $p < 0.001$, $p^2 < 0.38$, with lower C values in the task-irrelevant feature change condition ($M = 0.19$, $SE = 0.06$) than in the no-change condition ($M = 0.33$, $SE = 0.05$). The interaction between cue type and task-irrelevant feature change type was significant, $F(1, 27) = 14.10$, $p < 0.001$, $p^2 = 0.34$. Further simple effects analysis showed that in pre-cue trials, C values were lower in the task-irrelevant feature change condition (0.16 vs. 0.42), $t(27) = 5.23$, $p < 0.001$, Cohen's $d = 0.95$, 95% CI = [0.58, 1.32]. However, in retro-cue trials, the difference between irrelevant feature change and no-change conditions was not significant (0.23 vs. 0.24), $t(27) = 0.24$, $p = 0.816$, Cohen's $d = 0.04$, 95% CI = [-0.30, 0.37]. This is consistent with the RT results, showing that the interfering effect of task-irrelevant features disappeared in retro-cue trials.

Similarly, we combined the response criterion C values from retro-cue trials in Experiment 1b and Experiment 2 and conducted a 2 (memory load: low, medium) × 2 (task-irrelevant feature change type: no-change, change) mixed ANOVA. The results showed a significant main effect of memory load, $F(1, 54) = 20.66$, $p < 0.001$, $p^2 = 0.28$, with lower C values under low memory load ($M = -0.08$, $SE = 0.05$) than under medium memory load ($M = 0.23$, $SE = 0.05$). The main effect of task-irrelevant feature change type was significant, $F(1, 54) = 5.94$, $p = 0.018$, $p^2 = 0.10$, with lower C values in the task-irrelevant feature change condition ($M = 0.04$, $SE = 0.04$) than in the no-change condition ($M = 0.11$, $SE = 0.04$). The interaction was significant, $F(1, 54) = 4.43$, $p = 0.040$, $p^2 = 0.08$. Simple effects analysis showed that under low memory load, the difference between task-irrelevant feature change and no-change conditions was significant (-0.16 vs. -0.01), $t(54) = 3.21$, $p = 0.002$, Cohen's $d = 0.61$, 95% CI = [-0.23, 0.99]. Under medium memory load, the difference between task-irrelevant feature change and no-change conditions was not significant (0.23 vs. 0.24), $t(54) = 0.24$, $p = 0.815$, Cohen's $d = 0.05$, 95% CI = [-0.34, 0.43]. This indicates that memory load manipulation can affect the interfering effect of task-irrelevant features in retro-cue trials.

Figure 4 [Figure 4: see original paper]. Response criterion C values for retro-cue trials under different memory loads.

3.3 Discussion

Unlike Experiment 1 results, when the number of memory items was increased to 4 in Experiment 2, both RT and response criterion C value results showed that the interfering effect of task-irrelevant features was significantly present in pre-cue trials but disappeared in retro-cue trials. Additionally, the cross-experiment interaction in response criterion C values for retro-cue trials was also significant. These results indicate that different attentional selection modes indeed exist in VWM: the encoding stage is object-based, while the attentional selection mode in the maintenance stage is object-based under low memory load conditions but shifts to feature-based when memory load increases. However, the interfering effect in pre-cue trials remained present, possibly because the number of memory items in Experiment 2 was 4, which falls within the VWM capacity limit of 3-4 items (Vogel et al., 2001), allowing participants to still process task-irrelevant features simultaneously. In Experiment 3, the number of memory items was further increased to 6 to examine whether the interfering effect in pre-cue trials would disappear and to verify the reliability of the disappearance of the interfering effect in retro-cue trials observed in Experiment 2.

4 Experiment 3: High Memory Load Condition

4.1 Methods

Experiment 3 increased the number of memory items in the memory display to 6. The experimental materials and procedure remained consistent with Experiments 1b and 2, with 72 trials per condition, totaling 288 trials.

4.2 Results

4.2.1 Data Trimming The mean accuracy rate in Experiment 3 was 65.54%, significantly lower than in Experiment 2 (75.59%), t(54) = -8.07, $p < 0.001$, Cohen's d = -2.16, 95% CI = [-2.69, -1.62], demonstrating the effectiveness of the memory load manipulation. Before RT analysis, error trials (34.46%) and trials exceeding 3 standard deviations (0.6%) were excluded. Before calculating signal detection theory indices, all no-response trials (1.2%) were excluded. A 2 (cue type: pre-cue, retro-cue) × 2 (task-irrelevant feature change type: no-change, change) repeated measures ANOVA was conducted on the trimmed data.

We further combined the RTs and response criterion C values from retro-cue trials in Experiments 1b, 2, and 3 and conducted a 3 (memory load: low, medium, high) × 2 (task-irrelevant feature change type: no-change, change) mixed ANOVA, with memory load as a between-subjects variable and task-irrelevant feature change type as a within-subjects variable.

4.2.2 Reaction Time Results RT results showed a significant main effect of cue type, F(1, 27) = 17.13, $p < 0.001$, $p^2 = 0.39$, with faster RTs in pre-cue trials (M = 962 ms, SE = 29.85) than in retro-cue trials (M = 1091 ms, SE = 23.72). The main effect of task-irrelevant feature change type was significant, F(1, 27) = 11.17, $p = 0.002$, $p^2 = 0.29$, with slower RTs in the irrelevant feature change condition (M = 1044 ms, SE = 20.89) than in the no-change condition (M = 1009 ms, SE = 24.28). The interaction was not significant, F(1, 27) = 1.54, $p = 0.225$, indicating that there was no difference in the interfering effect of task-irrelevant features between the two cue type trials in RT results.

Cross-experiment analysis showed a significant main effect of memory load, F(2, 81) = 42.73, $p < 0.001$, $p^2 = 0.51$, with RTs gradually increasing as memory load increased (747 vs. 991 vs. 1091 ms). The main effect of task-irrelevant feature change type was significant, F(1, 81) = 2.94, $p = 0.021$, $p^2 = 0.06$, with slower RTs in the irrelevant feature change condition (M = 951 ms, SE = 15.82) than in the no-change condition (M = 935 ms, SE = 16.12). The interaction was not significant, F(2, 81) = 0.40, $p = 0.669$.

4.2.3 Signal Detection Theory Results Signal detection theory indices showed that for sensitivity d scores, the main effect of cue type was significant, F(1, 27) = 80.48, $p < 0.001$, $p^2 = 0.75$, with higher d scores in pre-cue trials (M = 1.30, SE = 0.06) than in retro-cue trials (M = 0.68, SE = 0.06). The main effect of task-irrelevant feature change type was not significant, F(1, 27) = 1.27, $p = 0.269$, nor was the interaction, F(1, 27) < 0.01, $p = 0.999$. For response criterion C values, the main effect of cue type was significant, F(1, 27) = 12.04, $p = 0.002$, $p^2 = 0.31$, with higher C values in pre-cue trials (M = 0.44, SE = 0.06) than in retro-cue trials (M = 0.24, SE = 0.06). The main effect of task-irrelevant feature change type was significant, F(1, 27) = 20.05, $p < 0.001$, $p^2 = 0.43$, with lower C values in the task-irrelevant feature change condition (M = 0.27, SE = 0.05) than in the no-change condition (M = 0.41, SE = 0.05). The interaction was significant, F(1, 27) = 16.90, $p < 0.001$, $p^2 = 0.39$. Simple effects analysis showed that in pre-cue trials, C values were lower in the task-irrelevant feature change condition (0.31 vs. 0.56), t(27) = 5.71, $p < 0.001$, Cohen's d = 0.83, 95% CI = [0.53, 1.12]. However, in retro-cue trials, the difference between irrelevant feature change and no-change conditions was not significant (0.23 vs. 0.25), t(27) = 0.38, $p = 0.705$, Cohen's d = 0.05, 95% CI = [-0.21, 0.31]. This indicates that the interfering effect of task-irrelevant features existed only in pre-cue trials.

In the cross-experiment analysis, response criterion C values showed a significant main effect of memory load, F(2, 81) = 13.16, $p < 0.001$, $p^2 = 0.25$, with lower C values under low memory load (M = -0.08, SE = 0.05) than under medium (M = 0.23, SE = 0.05) and high memory load (M = 0.24, SE = 0.05). The main effect of task-irrelevant feature change type was significant, F(1, 81) = 5.17, $p = 0.026$, $p^2 = 0.06$, with lower C values in the task-irrelevant feature change condition (M = 0.10, SE = 0.03) than in the no-change condition (M = 0.16, SE = 0.03). The interaction was marginally significant, F(2, 81) = 3.10, $p = 0.051$, $p^2 = 0.07$. Simple effects analysis showed that under low memory load, the difference between task-irrelevant feature change and no-change conditions was significant (-0.16 vs. -0.01), t(81) = 3.34, $p = 0.001$, Cohen's d = 0.64, 95% CI = [0.26, 1.02]. Under medium memory load, the difference was not significant (0.23 vs. 0.24), t(81) = 0.25, $p = 0.807$, Cohen's d = 0.05, 95% CI = [-0.33, 0.43]. Under high memory load, the difference was also not significant (0.23 vs. 0.25), t(81) = 0.35, $p = 0.728$, Cohen's d = 0.07, 95% CI = [-0.31, 0.45].

4.2.4 Supplementary Analysis Although cross-experiment analyses yielded some conclusions, the interaction of memory load on response criterion C values only reached marginal significance, suggesting that the effect of memory load across experiments was not strong. Therefore, we introduced the VWM capacity index K value, which is used to evaluate the number of representations stored in VWM (Zhang et al., 2012; Rouder et al., 2011; Pashler, 1988). The specific calculation formula is: $K = S\times(H-FA) / (1-FA)$, where S represents the number of memory items, H represents hit rate, and FA represents false alarm rate. If our experimental results are reliable, we would expect that under low memory load, there should be no difference in VWM capacity between pre-cue and retro-cue trials because both task-relevant and irrelevant features are processed. Under higher memory load conditions, because task-irrelevant features cannot be processed in retro-cue trials, VWM capacity in pre-cue trials should be greater than in retro-cue trials.

We conducted a 3 (memory load: low, medium, high) × 2 (cue type: pre-cue, retro-cue) mixed ANOVA on the results from Experiments 1b, 2, and 3. The results showed a significant main effect of memory load, F(2, 81) = 17.28, $p < 0.001$, $p^2 = 0.30$, with lower K values under low memory load (M = 1.91, SE = 0.08) than under medium (M = 2.53, SE = 0.08) and high memory load (M = 2.51, SE = 0.08), with no significant difference between medium and high load conditions. The main effect of cue type was significant, F(1, 81) = 65.94, $p < 0.001$, $p^2 = 0.45$, with higher K values in pre-cue trials (M = 2.56, SE = 0.05) than in retro-cue trials (M = 2.07, SE = 0.06). The interaction was significant, F(2, 81) = 23.34, $p < 0.001$, $p^2 = 0.37$. Simple effects analysis showed that under low memory load, there was no significant difference between pre-cue and retro-cue trials (1.91 vs. 1.92), t(81) = 0.17, $p = 0.869$. Under medium memory load, K values were significantly higher in pre-cue trials than in retro-cue trials (2.77 vs. 2.28), t(81) = 4.73, $p < 0.001$, Cohen's d = 0.91, 95% CI = [0.53, 1.29]. Under high memory load, K values were also significantly higher in pre-cue trials than in retro-cue trials (3.00 vs. 2.02), t(81) = 9.50, $p < 0.001$, Cohen's d = 1.82, 95% CI = [1.44, 2.20].

Figure 5 [Figure 5: see original paper]. K values for pre-cue and retro-cue trials under different memory loads.

4.3 Discussion

The results of Experiment 3 were similar to those of Experiment 2. Compared to RT results, response criterion C values were more stable. Both within-experiment and cross-experiment analyses showed that when memory load increased, the interfering effect of task-irrelevant features disappeared in retro-cue trials. This is consistent with our initial hypothesis: when the attentional resources required for task-relevant features increase, task-irrelevant features are excluded from VWM due to insufficient resources. Moreover, the analysis of VWM capacity indices further verified our previous results. When the number of memory items increased to 4, differences in VWM storage between the two cue types began to emerge, with lower overall storage in retro-cue trials due to the lack of processing of task-irrelevant features. The interaction across experiments also demonstrates the moderating role of memory load.

5 General Discussion

The purpose of this study was to test whether different attentional selection modes (object-based and feature-based) exist in different processing stages (encoding, maintenance) of VWM. Based on the change-detection paradigm, we introduced pre-cues and retro-cues to investigate attentional selection modes in VWM at different stages. Consistent with previous findings, we found that object-based attentional selection mode exists in the VWM encoding stage and is robust enough not to be affected by memory load level. At the same time, we observed feature-based attentional selection mode in the VWM maintenance stage, but only under higher memory load conditions. In summary, after unifying research paradigm, report indicators, and feature combinations, this study provides direct evidence for object-based encoding and feature-based storage in VWM.

5.1 The Encoding Stage of Visual Working Memory Involves Object-Based Attentional Selection

The robust interfering effect of task-irrelevant features during the VWM encoding stage indicates that all features of an object are encoded into VWM regardless of memory load, supporting the object-based attention theory. Numerous studies using change-detection paradigms with task-irrelevant feature changes have obtained consistent results with the present study (Gao et al., 2011; Jiang et al., 2000; Shen et al., 2013; Yin et al., 2012). Additionally, this study used the whole-report method of the change-detection paradigm, which might lead participants to adopt a memory strategy of associating feature information with spatial location information. Once this spatial location information is activated, it may automatically activate other information that appeared at that location. However, Yin et al. used the partial-report method in the same paradigm and set up two presentation methods: presenting a single probe stimulus at the center of the screen and at the original location. They still found significant interfering effects of task-irrelevant features under both presentation methods. Moreover, to exclude the possibility that these results were due to strategic processing caused by the specificity of the experimental paradigm itself, researchers further verified this object-based encoding effect in visual search paradigms (Foerster & Schneider, 2018; Gao et al., 2016). However, a few studies using event-related potentials (ERP) and functional magnetic resonance imaging (fMRI) techniques have not found evidence of task-irrelevant feature activation, arguing that task-irrelevant features are not selected into VWM (Serences et al., 2009; Woodman & Vogel, 2008). A possible explanation is that when task-relevant features are activated, task-irrelevant features are simultaneously activated, but because they are irrelevant to the current cognitive processing task and remain unchanged between the memory and probe displays throughout the experiment, they transform into a "silent state" of subthreshold neural activation (Bocincova & Johnson, 2019; Mongillo et al., 2008; Stokes, 2015; Stokes et al., 2013). However, numerous behavioral studies have consistently found interfering effects of task-irrelevant features, suggesting that these neural measures may not be suitable for investigating task-irrelevant features. In conclusion, this study replicates previous findings and provides further evidence that object-based attentional selection mode exists in the VWM encoding stage.

5.2 The Attentional Selection Mode in Visual Working Memory Maintenance Stage Is Regulated by Memory Load

In retro-cue trials, we found that under higher memory load conditions (Experiments 2/3), participants could successfully select a single feature from multi-feature objects for maintenance according to task requirements, consistent with previous research findings. Retro-cues can reallocate more attentional resources to task-relevant features to achieve feature-based attention, and also support the hypothesis that object features are stored separately during the VWM maintenance stage (Heathcote et al., 1994; Isenberg et al., 1990; Stefurak & Boynton, 1986; Wheeler & Treisman, 2002; Wolfs et al., 1994). However, the unexpected result was that feature-based attention in the maintenance stage was regulated by memory load. Under low memory load conditions, the interfering effect of task-irrelevant features remained significant (Experiments 1a/b). There are two possible explanations for this. First, cross-experiment results found that memory load had a regulatory effect on the interfering effect of task-irrelevant features. When there were only 2 memory items, the interfering effect was significant, but when the number of memory items increased to 4 and 6, the interfering effect disappeared. Moreover, analysis of memory capacity also showed that differences between the two cue types emerged after memory load increased. These results seem to indicate that the greater the memory load, the more successfully participants can select task-relevant features (Gilchrist et al., 2016; Kuo et al., 2012; Nobre et al., 2008; Souza et al., 2014; van Moorselaar et al., 2015). Previous studies commonly used 3-4 memory items, which is exactly the boundary of VWM capacity (Vogel et al., 2001). At this point, task-irrelevant features may already be unable to be processed due to insufficient resources. Second, in studies supporting feature-based attention in VWM, object information was mostly a combination of color and orientation features. Some studies have proven that attentional resources for these two features are independent (Markov et al., 2019; Wang et al., 2017), with orientation features considered more as spatial information, and spatial and object information stored in different VWM subsystems (Ungerleider & Haxby, 1994; Ventre-Dominey et al., 2005; Vicari et al., 2006; Shen et al., 2007). Therefore, it may not be surprising to find results of separate storage. However, the object information in this study consisted of two basic features: color and shape. Because both are stored in the same VWM subsystem, they compete for the same attentional resources. Although retro-cues can reduce resource competition from task-irrelevant features, maintaining only 2 task-relevant features may not consume all attentional resources, leaving residual resources for task-irrelevant features. However, once the resources required to maintain task-relevant features increase, task-irrelevant features are excluded from VWM due to insufficient resources. This can explain why in Experiments 2 and 3 of this study, the interfering effect of irrelevant features disappeared when memory load increased.

5.3 The Storage Mechanism of Object Feature Information in Visual Working Memory

In previous research, when object-based attentional selection modes were found in the VWM encoding stage, researchers concluded that object feature information is stored in the form of integrated objects (Ernst, 2013; Luria & Vogel, 2011; Vogel, Woodman, & Luck, 2001; O'Craven et al., 1999; Luck & Vogel, 1997), referred to as the object-based storage hypothesis. Conversely, when feature-based attentional selection modes were found in the VWM maintenance stage, researchers concluded that object feature information is stored in the form of independent features (Sasin & Fougnie, 2020; Markov et al., 2019; Niklaus et al., 2017; Wang et al., 2017; Ye et al., 2016), referred to as the feature-based storage hypothesis. This has led to a contradiction between these two perspectives in explaining the storage mechanism of object feature information in VWM. However, the results of this study provide some insights for resolving this contradiction.

First, after balancing the differences between previous studies, this study provides empirical support for the hypothesis that object-based attentional selection mode exists in the VWM encoding stage and feature-based attentional selection mode exists in the maintenance stage. Since feature-based selection can be achieved in the maintenance stage, we should reject the object-based storage hypothesis. According to object-based attention theory, selecting one feature automatically activates another feature in the object (Ernst et al., 2013; O'Craven et al., 1999), but this study found that task-irrelevant features cannot be processed under higher memory load levels. Second, if the feature-based storage hypothesis were correct, all information in an object should be stored in different VWM subsystems, independently and without interference. However, this study found that the interfering effect of task-irrelevant feature changes remained under low memory load conditions and only disappeared under higher memory load levels. This indicates that the storage of object feature information is not completely independent but involves competition for attentional resources. Previous studies finding separate feature storage mostly used objects combining color and orientation features. As mentioned above, these two features may be stored in different VWM subsystems with independent attentional resources (Markov et al., 2019; Wang et al., 2017). However, for basic features like color and shape, they are more likely stored in the same VWM subsystem, competing for the same attentional resources. Moreover, internal attentional resources in VWM are inherently limited, and it would be uneconomical to set up a separate memory system for each feature in an object. Finally, the results of this study support the feature-based storage hypothesis, but emphasize that some simple basic feature information is stored in the same VWM subsystem and competes for resources among themselves.

5.4 Limitations and Future Directions

There are still some limitations in the experimental design of this study. First, the manipulation of memory load as a between-subjects variable may lead to different degrees of data variation across experiments, and the task difficulty also differs across memory load levels, further increasing data variation and reducing the reliability of cross-experiment analysis results. Future studies need to address this issue and further examine the effect of memory load on attentional selection modes in the maintenance stage. Second, to balance the time from feature selection stage to response decision stage, this study matched the time from memory display to probe display in pre-cue trials with the time from cue display to probe display in retro-cue trials. However, this setting inevitably leads to different durations between memory display and probe display in the two cue type trials. Although some studies have found that after balancing the time from feature selection stage to response decision stage, the two cue types have the same selective attention mechanism (Sahan et al., 2016), these results are limited to the selection of spatial information, and whether they apply to non-spatial information selection requires further experimental verification. Finally, although this study found differences in participants' response criteria using signal detection theory, this index is derived from specific formulas and is less direct than some physiological measures. Some studies using eye-tracking technology in visual search paradigms have found that even when participants are informed that task-irrelevant features of memory objects will interfere with searching for task-relevant features, task-irrelevant features always capture participants' first fixation point and prolong the time to successfully find the target when they appear in search items. This provides further evidence that VWM stores task-irrelevant feature information of objects (Foerster & Schneider, 2018). However, this study only investigated attentional selection modes in the VWM encoding stage under low memory load. Future research could combine the experimental design of this study with eye-tracking technology to further verify attentional selection modes in the VWM maintenance stage under different memory load levels.

6 Conclusion

This study used pre-cues and retro-cues to investigate attentional selection modes in VWM encoding and maintenance stages. The results of three experiments indicate that the attentional selection mode in the VWM encoding stage is object-based, while the attentional selection mode in the maintenance stage is feature-based and regulated by memory load. This study is important for resolving the controversy regarding attentional selection modes for multifeature objects in VWM.

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