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Article

Visualizer Cognitive Style Modulates the Role of Object-based Attention in Retaining Bindings in Visual Working Memory

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Abstract: The role of object-based attention in retaining bindings in visual working memory (VWM) has received persistent focus. However, the underlying mechanism remains unclear. By using the Chinese revised version of the Object-Spatial Imagery Questionnaire, participants were divided into object visualizers (OVs) and spatial visualizers (SVs). We explored whether the visualizer cognitive style modulates the role of object-based attention in bindings VWM through three experiments. The results showed that, compared with SVs, OVs had an advantage in maintaining bindings and had larger cost of the object-based attention. Event-related potentials results showed that for OVs, the P2 during binding VWM encoding was reduced and the late positive component (LPC) during the secondary task performing was enhanced when the object-based attention was consumed, while the P2 and the LPC were not affected for SVs. These findings suggest that the object-based attentional investment in holding bindings in VWM is modulated by the visualizer cognitive style, with OVs having a larger investment compared with SVs. The mechanism underlying this modulation is based on the allocation of on-demand resources to meet the task requirements. The theory of object-based attention in retaining bindings in VWM is further elucidated as an on-demand resources when allocating such attention.

Keywords: visualizer cognitive style; visual working memory; binding; object-based attention; P2; late positive component

1. Introduction

Visual information contains multiple features, such as colors, shapes, and directions. Visual attention can bind multiple features into a unified object during perception, which is referred to as the binding process (Treisman and Gelade 1980, Treisman 1998). Binding representations can store in visual working memory (VWM) (Luck and Vogel 1997, Wheeler and Treisman 2002), a limited-capacity system for temporarily storing and processing visual information (Baddeley 2012, Baddeley et al. 2021). However, the mechanisms of the role of visual attention in holding bindings in VWM has not been determined.

The dual-task paradigm is commonly used to study the attentional demand in VWM (Allen et al. 2006). This paradigm introduces a secondary task that competes for visual attention in the VWM maintenance stage. Studies have examined whether holding bindings in VWM is more affected by a secondary task than holding features (Hollingworth and Maxcey-Richard 2013, Johnson et al. 2008, Shen et al. 2015). Visual attention is classified as space-based attention and object-based attention. Space-based attention refers to the system by which perceptual processing resources are devoted to a specific location and enhances the processing of all features at a specific location of the visual field (Hollingworth and Maxcey-Richard 2013), while object-based attention enhances the features at the

locations that define the selected object, and can be allocated rapidly throughout the object (Cavanagh et al. 2023, Itti and Koch 2001).

A series of studies were found that spatial-based attention plays no special role in maintaining bindings in VWM, whereas object-based attention plays a crucial role in such process (Gao et al. 2017, Hollingworth and Maxcey-Richard 2013, Johnson et al. 2008, Shen et al. 2015). For instance, when a secondary task that competed the object-based attention was inserted in the VWM maintenance stage, bindings were selectively more impaired by the secondary task than features, which indicated that retaining bindings requires more object-based attention than retaining features (Shen et al. 2015). Furthermore, this role of object-based attention is robust across binding types, VWM activation states, and number of features within the bindings, suggesting that object-based attention underline a broad range of binding forms, and bound more features does not require extra object-based attention (Gao et al. 2017, He et al. 2020, Lu et al. 2019, Zhou et al. 2021). Researchers proposed that the reentrant process may be the underlying mechanism by which binding representing in VWM requires more object-based attention than features.

Furthermore, the property of binding representations modulates the degree of object-based attention requirement for bindings. In contrast to bindings of dissimilar features, holding bindings composed of similar features do not require increased object-based attention than features (Che et al. 2019). Moreover, compared to the separate bindings (e.g., color-shape bindings), the integral bindings, characterized by tightly bound perceptual characteristics that cannot be processed independently (e.g., width and height of an object), do not require more object-based attention than features (Wan et al. 2020). The reason may be that the stability of the binding representation modulates the degree of involvement of object-based attention.

The visualizer cognitive style, a typical cognitive style, characterizes two contrasting imagery abilities individuals use to acquire and process visual information (Kozhevnikov et al. 2005). Using the Object-Spatial Imagery Questionnaire (OSIQ), researchers distinct two type of visualizers: object visualizers (OVs) and spatial visualizers (SVs) (Blajenkova et al. 2006). OVs have advantages in processing images holistically, integrate them as a single perceptual unit, leading them excel in constructing pictorial objects and outperform SVs in tasks requiring the generation of high-resolution images (e.g., recognizing degraded objects). In contrast, SVs have advantages in processing images analytically, part by part, using spatial relations to arrange and analyze the components. SVs outperform OVs in representing dynamic spatial relations and transformations (e.g., mental rotation) (Kozhevnikov et al. 2005, Kozhevnikov et al. 2010). Such differences unlike strategies, is a trade-off between object and spatial visualization abilities within a limited capacity in visual attention (Kozhevnikov et al. 2010). A functional magnetic resonance imaging study showed greater neural efficiency for OVs than SVs during object imagery task (Motes et al. 2008). Moreover, due to this neural efficiency OVs are demonstrated superior performance in object VWM (Li et al. 2011).

Given that bindings in VWM are a form of object maintenance, OVs might outperform SVs in holding multi-feature bindings VWM, and OVs should invest more object-based attention than SVs. Although previous research has ascribed object-based attention a crucial role in holding bindings, the exact mechanism of how object-based attention works is not known. In the present study, we addressed this gap in knowledge by examining the role of visualizer cognitive style therein.

In Experiment 1, we investigated whether OVs outperform SVs in holding bindings in VWM. The modified delayed matching task with a long or short delay interval was used. The hypothesis is that OVs and SVs perform comparable under the short delay condition, while OVs perform better than SVs under the long delay condition. In Experiment 2, we adopted a dual-task paradigm to investigate whether visualizer cognitive style modulates the requirement of object-based attention in retaining features and bindings. The hypothesis is that compared to SVs, OVs who excel in binding maintenance within VWM would exhibit larger impairment in binding retention when object-based attention is consumed by a secondary task. In Experiment 3, we used the event-related potential (ERP) technique to investigate how the visualizer cognitive style modulates object-based attention while holding bindings and performing the secondary task in VWM. P2 and late positive component (LPC) were used as ERP

indicator during VWM encoding and the secondary task performing, respectively. P2 reflects the recruitment of attentional resources in VWM encoding (Smith 1993, Wolach and Pratt 2001). The hypothesis is that OV's would elicit lower P2 during VWM encoding under the task-present condition than the task-absent condition, compared to SVs. LPC has been linked to the effort requirement in VWM maintenance (Gunseli et al. 2014a, Gunseli et al. 2014b). The hypothesis is that OV's would invest more effort in holding bindings when the secondary task competes object-based attention, resulting in larger LPC amplitude, compared to SVs.

2. Experiment 1: Holding bindings in VWM for object and spatial visualizers

2.1. Method

2.1.1. Revised Version of Object-Spatial Image Questionnaire

We employed the Chinese revised version of the Object-Spatial Imagery Questionnaire (OSIQ-R) by Li et al. (2011) to classify the participants as either OV's or SV's. It consists of 15 items in the object imagery scale (e.g., "When I read a novel, I can usually form a detailed and vivid image of the scene based on the description") and 15 items in the spatial imagery scale (e.g., "I can easily imagine and mentally rotate 3-dimensional geometric figures"). Participants were instructed to rate each statement on a 5-point scale ranging from 1 (total disagreement) to 5 (total agreement). Object and spatial imagery scores were computed separately by summing the ratings of the 15 items for each scale. For the present study, the Cronbach's α coefficients for the object and spatial scales were 0.78 and 0.73, indicating acceptable reliability.

2.1.2. Participants

A total of 1290 college students were tested with the OSIQR. OV's were defined as participants scoring in the top 30% on the object imagery scale and in the bottom 30% on the spatial imagery scale. Conversely, SV's were defined as participants scoring in the bottom 30% on the object imagery scale and in the top 30% on the spatial imagery scale. Based on the OSIQR scores, 123 students ($M_{\text{object-scores}} = 3.90$, 95%CI [3.85, 3.96]; $M_{\text{spatial-score}} = 2.35$, 95%CI [2.30, 2.39]) were classified as OV's and 83 students ($M_{\text{object-scores}} = 2.86$, 95%CI [2.80, 2.93]; $M_{\text{spatial-score}} = 3.42$, 95%CI [3.36, 3.48]) were classified as SV's. These participants were then included in the object or spatial visualizer pools, from which subjects for the three experiments were randomly selected.

The sample size for the current experiment was calculated using the G*Power (Version 3.1.9; Faul et al. 2007). Based on the previous study (Li et al. 2011, Shen et al. 2015), we predicted a large effect size ($f = 0.40$), the alpha level (α) = 0.05, and the statistical power ($1 - \beta$) = 0.80, leading to the minimal required sample size of 16.

Twenty OV's (13 females, 18-22 years old; $M_{\text{object-scores}} = 3.95$, 95%CI [3.81, 4.10], $M_{\text{spatial-score}} = 2.76$, 95%CI [2.62, 2.90]) and 20 SV's (12 females, 18-20 years old; $M_{\text{object-scores}} = 2.40$, 95%CI [2.31, 2.49]; $M_{\text{spatial-score}} = 3.30$, 95%CI [3.21, 3.39]) were randomly selected from the OV's and SV's pools in this experiment. The difference in gender was not significant between the two groups ($\chi^2 = 1.07$, $p = 0.744$). All participants had normal or corrected-to-normal vision and normal color vision. Each participant was naive regarding the purpose of the study. All the participants were right-handed and had no history of neurological problems. The present study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of the School of Psychology at Shandong Normal University.

2.1.3. Materials and apparatus

The stimuli in the present study are shown in Figure 1. They consisted of 6 shapes ($1.5^\circ \times 1.5^\circ$) and 6 colors (red: 255, 0, 0; green: 0, 255, 0; blue: 0, 0, 255; yellow: 255, 255, 0; purple: 255, 0, 255; white: 255, 255, 255). In the feature probe condition, visual shapes and color blobs were used as the stimuli. The visual shapes were filled in black (RGB: 0, 0, 0; see Figure 1, top row). The color blobs were vague,

irregular and noncanonically shaped circles (Shen et al. 2015; see Figure 1, middle row). In the binding probe condition, the items were objects with a random combination of shapes and colors (see Figure 1, bottom row). The memory array contained 3 items distributed horizontally in the center of the screen, with an inter-circle distance of no less than 2.5° . The probe was located 2.5° below the center of the screen.

The stimuli were displayed with E-prime 2.0 (Psychology Software Tools, Inc., Sharpsburg, Pennsylvania, USA) in gray (RGB: 125, 125, 125) background on an LCD monitor with a resolution of 1024×768 pixels at a 60Hz refresh rate.

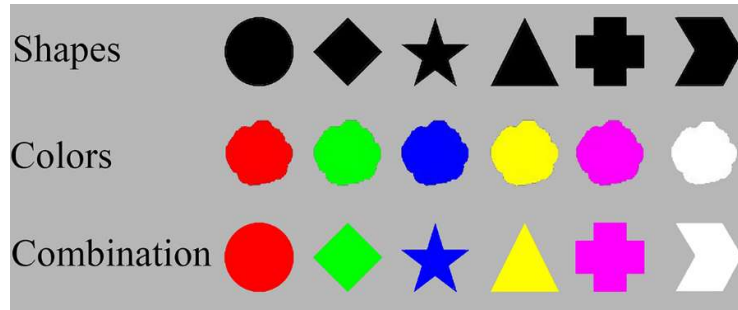


Figure 1. The shapes and colors used in the current study. In the feature condition, the stimuli were the shapes in black (top row), or colored noncanonical “blobs,” as shown in the middle row. In the binding condition, the stimuli were color-shape combinations, as shown in the bottom row.

2.1.4. Design and procedure

A 2 (cognitive style: *OVs* vs. *SVs*) $\times$ 2 (delay: *short* vs. *long*) mixed experimental design was utilized, in which cognitive style served as a between-subjects factor, the delay served as a within-subjects factor. The delay is the time of interval between the disappearance of the memory array and the presentation of the test probe: the short delay condition is 1000ms, the long delay condition is 3000ms. There were two blocks: binding probe with short delay and a binding probe with long delay.

During the experiment, participants were seated in a quiet room, approximately 57cm from the screen. As shown in Figure 2, each trial started with the presentation of two black digits for 1000ms. Participants were instructed to repeatedly articulate these two digits aloud throughout the entire trial to prevent verbal coding of the stimuli. After a 500-ms fixation on a cross in the center of the screen, the memory array was presented for 500ms. Next, a retention interval of 1000 or 3000ms (short or long delay) was presented. A probe was then presented for 2000ms in the center of the lower screen, during which the participants determined whether the color and shape combination of the probe was identical to the items presented in the memory array by pressing a response key (pressing “F” for a “yes” response or “J” for a “no” response). In 50% of the trials, the probe was one of the memory array. While in the remaining trials the probe was different from the items in the memory array, which were formed by combining two features from two randomly selected items in the memory array. Each block had 48 trials, resulting in a total of 96 trials. Participants complete 20 practice trials before each block. The order of two blocks was counterbalanced between participants. A 5 mins break was taken between blocks. The task lasted approximately 30 mins.

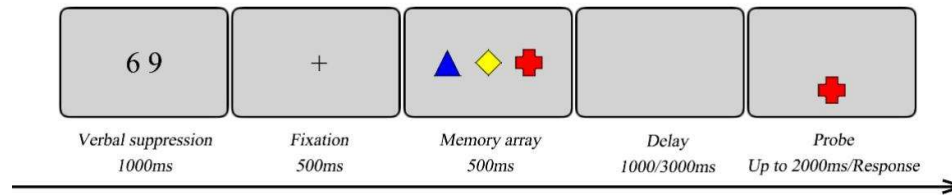


Figure 2. A schematic illustration of a trial in Experiment 1. Here a trial is presented with the probe present in the memory array.

2.1.5. Analysis

The statistical analysis was computed with SPSS 26.0 (IBM SPSS Statistics, Armonk, NY: IBM Corp.). Accuracy was analyzed in using a two-way mixed, repeated measures analysis of variance (ANOVA).

2.2. Results

A 2 cognitive style $\times$ 2 delay two-way mixed, repeated measures ANOVA on the accuracy showed that the main effect of the cognitive style was significant, $F(1, 38) = 4.94$, $p = 0.032$, $\eta_p^2 = 0.12$. OV_s ($M = 0.82$, 95%CI [0.80, 0.85]) performed better than SV_s ($M = 0.78$, 95%CI [0.76, 0.81]). The main effect of the delay was significant, $F(1, 38) = 38.45$, $p < 0.001$, $\eta_p^2 = 0.50$. The accuracy under the short delay condition ($M = 0.84$, 95%CI [0.81, 0.86]) was better than that under the long delay condition ($M = 0.77$, 95%CI [0.75, 0.79]). The interaction was significant, $F(1, 38) = 13.91$, $p < 0.001$, $\eta_p^2 = 0.27$. A simple effect analysis showed that the accuracy for OV_s was better than SV_s under the long delay condition, $F(1, 38) = 16.82$, $p < 0.001$, $\eta_p^2 = 0.31$. However, there was no significant difference in accuracy between OV_s and SV_s under the short delay condition, $F(1, 38) = 0.023$, $p = 0.880$, $\eta_p^2 = 0.001$ (see Figure 3).

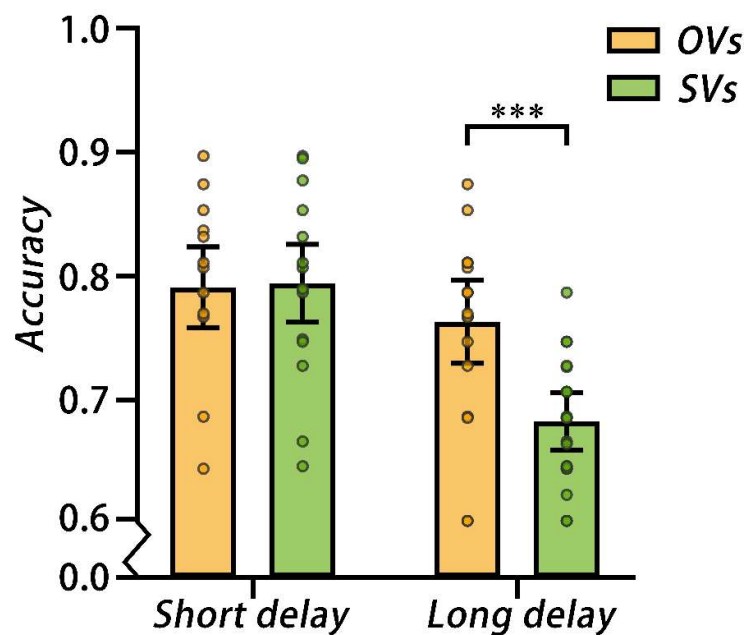


Figure 3. The mean accuracy for Experiment 1, error bars represent the 95% CIs, each dot corresponds to the data of an individual participant. OV_s = object visualizers; SV_s = spatial visualizers; *** $p < 0.001$.

2.3. Discussion

In Experiment 1, we investigated the color-shape binding VWM performances of OV and SV by manipulating varying the delays between the memory array and the probe. The results showed that OV and SV performed comparable under the short delay condition, whereas OV performed better than SV in holding bindings in VWM under the long delay condition. Which suggests that OV has more advantages in long-term holding bindings VWM than SV, consistent with our hypothesis. Studies have revealed that holding bindings in VWM requires more object-based attention than holding features (Gao et al. 2017, Shen et al. 2015, Zhou et al. 2021). Object-based attention plays a crucial role in holding bindings in VWM. Does OV invest more object-based attention in maintaining bindings in VWM than SV? To examine this issue, we conducted Experiment 2.

3. Experiment 2: Do Object Visualizers and Spatial Visualizers Invest Different Amount of Object-Based Attention in Holding Bindings in VWM?

3.1. Method

3.1.1. Participants

The chosen parameters of G*Power were the same as in Experiment 1, leading to the minimal required sample size of 12.

Twenty OVs (12 females, 18-20 years old; $M_{\text{object-scores}} = 3.88$, 95%CI [3.72, 4.04], $M_{\text{spatial-score}} = 2.29$, 95%CI [2.17, 2.42]) and 20 SVs (8 females, 18-20 years old; $M_{\text{object-scores}} = 2.70$, 95%CI [2.54, 2.86]; $M_{\text{spatial-score}} = 3.36$, 95%CI [3.23, 3.48]) were randomly selected from the OV and SV pools in this experiment. The difference in gender was not significant between the two groups ($\chi^2 = 1.61$, $p = 0.206$).

3.1.2 Materials and apparatus

The stimuli used in the memory array and probe were the same as in Experiment 1. The secondary task was a feature report task (Matsukura and Vecera 2009). The box-line stimuli consisted of two superimposed objects: a box (0.67° width) with a gap and a tilted line. The box was either short (0.67°) or tall (1.14°) and had a gap (0.20° width) centered either on the left or right. The line (1.53° long) was dashed or dotted and tilted 8° to the left or right. The box-line stimulus was followed by a visual mask that was 1.62° in width and 2.10° in height. There were four feature report questions related to the box or the line: (1) box height (short vs. tall), (2) box gap orientation (left vs. right), (3) line type (dashed vs. dotted), and (4) line tilting (left vs. right).

The apparatus and software were the same as those used in Experiment 1.

3.1.3. Design and procedure

A 2 (cognitive style: OV vs. SV) $\times 2$ (secondary task: *task-present* vs. *task-absent*) $\times 2$ (probe: *feature* vs. *binding*) mixed experimental design was utilized, in which cognitive style served as a between-subjects factor and the secondary task and the probe served as within-subjects factors. The secondary task is whether the participants were required to remember the box-line stimuli, and answered the following two questions. The probe is the types of stimuli that participants were required to remember and detect: for the feature probe condition, the stimuli are the colors or the shapes, which were presented separately; for the binding probe condition, the stimuli are the combination of the colors and shapes. Thus, there were 6 blocks: a color feature probe with the secondary task, a color feature probe without the secondary task, a shape feature probe with the secondary task, a shape feature probe without the secondary task, a binding probe with the secondary task, and a binding probe without the secondary task.

During the experiment, participants were seated in a quiet room approximately 57 cm from the screen. As shown in Figure 4, each trial started with a fixation cross for 500ms in the center of the

screen. Then, the memory array was presented for 500ms. Next, after a 500ms delay, a box-line stimulus was presented for 200ms, followed by a 200ms visual mask. Two questions were then sequentially presented. Under the task-present condition, participants were instructed to remember the box-line stimulus and report two box-line features by pressing “F” or “J” based on the presented alternatives. The first question was about the box, and the second was about the line (see above). Under the task-absent condition, participants were instructed to ignore the questions by pressing the “spacebar” on the keyboard. The feature probe screens lasted a maximum of 2000ms. Once participants made a response by pressing the corresponding key on the keyboard, the procedure immediately continued to the next step. After another 500ms delay, a probe was presented for 2000ms in the lower center of the screen. Under the feature probe condition, participants were introduced to determine whether the color or the shape was identical to the memory array by pressing a response key (pressing “F” for a “yes” response or “J” for a “no” response). In 50% of the trials, the probe was one of the memory array. While in the remaining trials, the probe was a new feature or shape that was not appeared in the memory array. Under the binding conditions, the settings were identical to those in Experiment 1. Each block contained 48 trials, resulting in a total of 288 trials. Participants complete 20 practice trials before each block. The order of six blocks was counterbalanced between participants. A 5mins break was taken between blocks. The task lasted approximately 70mins.

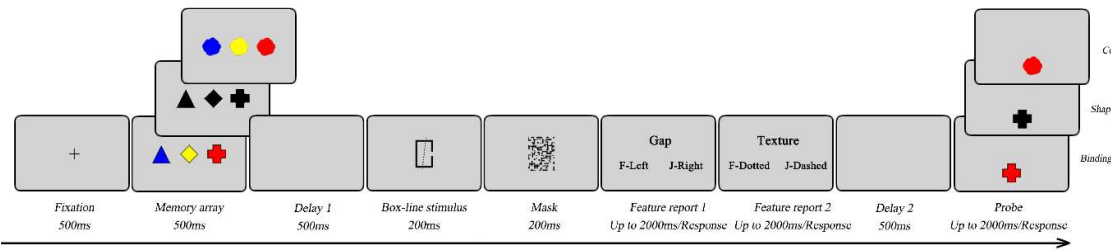


Figure 4. A schematic illustration of a trial used in Experiment 2. The figure depicts the trials of the feature and the binding probe conditions, in which a secondary task was used. Here a trial is presented with the probe present in the memory array.

3.1.4. Analysis

The accuracy was analyzed in using a three-way mixed, repeated measures ANOVA. Furthermore, we calculated the difference between the task-absent and task-present condition as the cost of consuming object-based attention by the secondary task. Cost was analyzed by a planned contrasts in using the paired samples or the independent samples *t*-tests for interactions according to the conditions.

3.2. Results

The accuracy of the secondary tasks across conditions in Experiment 2 and 3 was above 80%. There was no significant effect on both probe type and cognitive styles for accuracy and reaction time (RT) of the secondary tasks (see the Appendix A for details).

A 2 cognitive style × 2 secondary task × 2 probe three-way mixed, repeated measures ANOVA on the accuracy was conducted. The main effect of the secondary task was significant, $F(1, 38) = 132.30, p < 0.001, \eta_p^2 = 0.78$. Participants performed better under the task-absent condition ($M = 0.84, 95\%CI [0.82, 0.86]$) than under the task-present condition ($M = 0.73, 95\%CI [0.70, 0.75]$). The main effect of the probe was significant, $F(1, 38) = 240.85, p < 0.001, \eta_p^2 = 0.86$, showing that the performance under the feature probe condition ($M = 0.86, 95\%CI [0.84, 0.88]$) was better than that under the binding probe condition ($M = 0.71, 95\%CI [0.69, 0.72]$). The main effect of the cognitive style was not significant ($M_{Ovs} = 0.79, 95\%CI [0.76, 0.81]$ vs. $M_{SVs} = 0.78, 95\%CI [0.75, 0.80]$), $F(1, 38) = 0.38, p = 0.541, \eta_p^2 = 0.01$.

The interaction between the cognitive style and the secondary task was significant, $F(1, 38) = 8.77, p = 0.005, \eta_p^2 = 0.19$. A simple effect analysis showed that the OV_s ($M = 0.86, 95\%CI [0.83, 0.88]$) performed better than SV_s ($M = 0.82, 95\%CI [0.79, 0.84]$) under the task-absent condition, $F(1, 38) = 5.55, p = 0.024, \eta_p^2 = 0.13$; while they performed comparable under the task-present condition ($M_{OVs} = 0.72, 95\%CI [0.68, 0.75]$ vs. $M_{SVs} = 0.74, 95\%CI [0.70, 0.77]$), $F(1, 38) = 0.55, p = 0.462, \eta_p^2 = 0.01$. The interaction between the secondary task and the probe was significant, $F(1, 38) = 9.26, p = 0.004, \eta_p^2 = 0.20$. A simple effect analysis showed that for feature probe condition, the accuracy under the task-absent condition ($M = 0.90, 95\%CI [0.88, 0.92]$) is better than that under the task-present condition ($M = 0.82, 95\%CI [0.79, 0.85]$), $F(1, 38) = 52.54, p < 0.001, \eta_p^2 = 0.58$; for the binding probe condition, the accuracy under the task-absent condition ($M = 0.82, 95\%CI [0.79, 0.85]$) is better than that under task-present condition ($M = 0.64, 95\%CI [0.61, 0.66]$), $F(1, 38) = 96.96, p < 0.001, \eta_p^2 = 0.72$. Furthermore, the costs under the different probe conditions were analyzed by a planned contrasts in using a paired samples *t*-tests. Result showed that the cost under the binding probe condition ($M = 0.14, 95\%CI [0.11, 0.17]$) was larger than the feature probe condition ($M = 0.09, 95\%CI [0.06, 0.11]$), $t(39) = 2.80, p = 0.008$, Cohen's $d = 0.90$. The interaction effect between the cognitive style and the probe was not significant, $F(1, 38) = 2.62, p = 0.114, \eta_p^2 = 0.06$.

The three-way interaction was significant, $F(1, 38) = 7.97, p = 0.008, \eta_p^2 = 0.17$. A simple-simple effect analysis showed that under the task-absent condition, the OV_s performed better than the SV_s under the binding condition, $F(1, 38) = 14.08, p < 0.001, \eta_p^2 = 0.27$, but not under the feature condition, $F(1, 38) = 0.001, p = 0.980, \eta_p^2 = 0.00$. Under the task-present condition, the OV_s and SV_s performed comparable in both feature and binding probe condition, $F(1, 38) = 0.96, p = 0.335, \eta_p^2 = 0.03$ (see Figure 5b).

To further examine the effect of the secondary task, we conducted two independent samples *t*-tests on the costs under the different probe conditions for OV_s and SV_s, respectively. Under the feature condition, the costs were comparable for OV_s and SV_s, $t(38) = 0.38, p = 0.703$, Cohen's $d = 0.12$. While under the binding condition, the cost was larger for OV_s than SV_s, $t(38) = 3.79, p < 0.001$, Cohen's $d = 1.23$ (see Figure 5a).

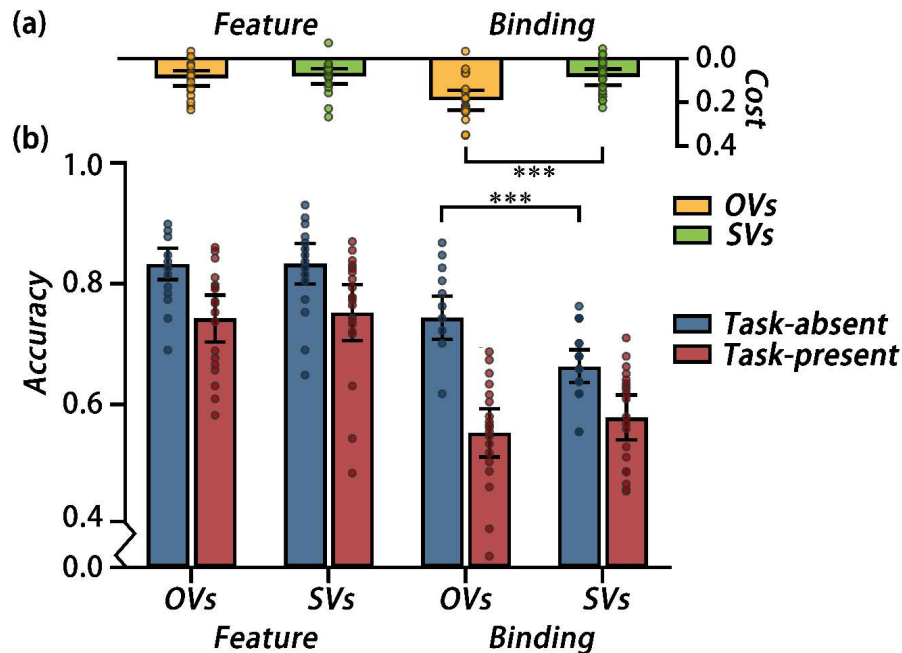


Figure 5. The mean accuracy for Experiment 2, each dot corresponds to the data of an individual participant. (a) The cost of the secondary task. The cost was calculated as the difference between the task-absent and task-present

conditions (task-absent minus task-present). **(b)** Response accuracy in each condition for OV and SVs. Error bars represent the 95% CIs, *** $p < 0.001$.

3.3. Discussion

In Experiment 2, we investigated whether OV and SVs invest different amount of object-based attention in holding bindings in VWM. During the maintenance of features and bindings in VWM, participants reported two questions about the box-line stimuli in the secondary task, which consumed object-based attention. A three-way interaction was found. By taking the difference between the VWM performance with and without the secondary task, we analysed the cost of consuming object-based attention. Result shows that OV has larger cost than SV when holding bindings, while OV and SV have comparable costs when holding features. Which consist with our hypothesis. What is the exact mechanism underlying how OV and SV modulate the object-based attention when holding bindings in VWM? In Experiment 3, we explored this issue using ERP technology.

4. Experiment 3: How Object and Spatial Visualizers Hold Bindings in VWM? Evidence from ERP

4.1. Method

4.1.1. Participants

The chosen parameters of G*Power were the same as in Experiment 1, leading to the minimal required sample size of 16.

Forty students were randomly selected from the remaining OV and SVs. Five participants were excluded due to insufficient artifact-free trials of electroencephalography (EEG) recordings ($n = 3$) or due to malfunctioning of the EEG recorder ($n = 2$), leaving 18 OV (13 females, 18-21 years old; $M_{\text{object-scores}} = 3.81$, 95%CI [3.66, 3.96]; $M_{\text{spatial-score}} = 2.33$, 95%CI [2.19, 2.47]) and 17 SV (8 females, 18-22 years old; $M_{\text{object-scores}} = 3.81$, 95%CI [3.66, 3.96]; $M_{\text{spatial-score}} = 2.33$, 95%CI [2.19, 2.47]) for whom the data were analyzed. The two groups did not differ in gender ($\chi^2 = 2.31$, $p = 0.129$).

4.1.2. Materials and apparatus

The stimuli, apparatus and software were the same as those used in Experiment 2.

4.1.3. Design and procedure

A 2 (cognitive style: OV vs. SV) $\times$ 2 (secondary task: *task-present* vs. *task-absent*) mixed design was utilized, in which cognitive style served as a between-subjects factor and the secondary task served as a within-subjects factor. There were two blocks: binding probe with the secondary task-absent or -present.

Participants were seated in a quiet room approximately 57 cm from the screen. The procedure was the modified from the Experiment 2 binding probe condition (see Figure 6), the modifications are as follows. First, the fixation varying in duration between 400ms and 600ms to avoid the anticipation effect. Second, the durations of the feature report question and the probe were fixed at 2000ms to equate the duration of each trial for the analysis. Third, to exclude the factor that SV may have lower object VWM capacity leading to have less amount of disruption by the secondary task, the number of feature report questions in the secondary task was reduced to one, which was randomly selected from the two options (i.e., either the box or the line). The remaining settings were identical to those in the binding probe condition in Experiment 1. Each block contained 50 trials and was presented twice, resulting in a total of 200 trials. Participants complete 20 practice trials before each block. The order of six blocks was counterbalanced between participants. A 10mins break was taken between the blocks. The task lasted approximately 60mins.

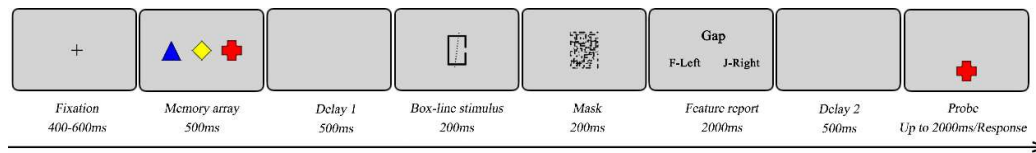


Figure 6. A schematic illustration of a trial used in Experiment 3. Here a trial is presented with the probe present in the memory array.

4.1.4. Behavioral analysis

The accuracy was analyzed in using a two-way mixed, repeated measures ANOVA.

4.1.5. Electroencephalogram recording and analysis

Recording. EEG signals were recorded by 64-channel Ag/AgCl electrodes that were mounted in an elastic cap (NeuroScan, El Paso, Texas, USA) according to the 10–20 system, with the reference on the left mastoid and a ground electrode on the medial frontal aspect. A vertical electrooculogram (VEOG) was recorded from electrodes located 1cm below and above the left eye. The horizontal EOG (HEOG) was recorded as the left versus the right orbital rim. VEOG was used to detect blink artifacts, and HEOG was used to detect horizontal eye movement artifacts. The impedances of all electrodes were maintained at less than 5k Ω . The signals were digitized at 1000Hz.

Preprocessing. Offline analysis was conducted using the EEGLAB toolbox in MATLAB (The MathWorks, Inc., Natick, MA, USA). The data were first down-sampled to 500Hz to save storage space and filtered with an IIR Butterworth filter with a 0.5–30Hz bandpass. The data were subsequently re-referenced to the 1/2 voltage value of the right mastoid and were epoched from -200ms to 3000ms around the onset of the memory array. Epochs with incorrect behavioral responses (both the VWM task and the secondary task) or with excessive noise were excluded. Epochs were baseline-normalized using the whole epoch as the baseline to improve independent component analysis (ICA; Groppe et al. 2009). Through visual inspection of the ICA results, we identified components that captured eye blinks and horizontal eye movements. These components were removed from the EEG data; on average, 2.43 ± 0.24 independent components were removed. The post-ICA epochs were baseline-corrected and underwent automatic artifact rejection based on a threshold of $\pm 100 \mu\text{V}$ for the time range of -200–3000ms to discard epochs contaminated by residual artifacts. This led to the removal of approximately 3.35% of trials per participant. After data processing, participants with a remaining number of trials per condition lower than 40 were excluded from the analysis.

ERP analysis. The epochs were baseline-corrected using a period from -200ms to 0ms relative to the onset of the memory array and averaged for each condition to obtain grand average waveforms. Based on the previous studies and the timing of grand average ERPs, the mean amplitude of P2 was calculated at the electrode sites of Fz and FCz at 160–200ms (Pinal et al. 2015, Wolach and Pratt 2001). And the mean amplitude of LPC was calculated at the electrode sites of Pz and POz at 2000–2250ms during the secondary task period, that is, 1000–1250ms after the presentation of the feature report task (Gunseli et al. 2014a, Gunseli et al. 2014b). The mean amplitudes of P2 and LPC were analyzed in using a two-way mixed repeated measures ANOVA.

4.2. Results

4.2.1. Behavioral results

A 2 cognitive style $\times$ 2 secondary task two-way mixed, repeated measures ANOVA on the accuracy was conducted. The main effect of the secondary task was significant, $F(1, 33) = 139.12$, $p < 0.001$, $\eta_p^2 = 0.81$, showing that the performance was better in the task-absent condition ($M = 0.78$,

95%CI [0.76, 0.81]) than in the task-present condition ($M = 0.67$, 95%CI [0.65, 0.70]). The main effect of the cognitive style was marginal significant, $F(1, 33) = 3.55$, $p = 0.068$, $\eta_p^2 = 0.10$, showing that OV_s ($M_{OVs} = 0.75$, 95%CI [0.72, 0.78]) performed better than SV_s ($M_{SVs} = 0.71$, 95%CI [0.68, 0.74]). The interaction was marginal significant, $F(1, 33) = 3.21$, $p = 0.082$, $\eta_p^2 = 0.09$. A simple effect analysis showed that the OV_s ($M = 0.81$, 95%CI [0.78, 0.85]) performed better than SV_s ($M = 0.75$, 95%CI [0.72, 0.79]) under the task-absent condition, $F(1, 33) = 5.17$, $p = 0.030$, $\eta_p^2 = 0.14$; while they performed comparable under the task-present condition ($M_{OVs} = 0.69$, 95%CI [0.66, 0.72] vs. $M_{SVs} = 0.66$, 95%CI [0.63, 0.69]), $F(1, 33) = 1.22$, $p = 0.277$, $\eta_p^2 = 0.04$. We conducted an independent samples t -tests on the costs, showing that the cost was marginal larger for OV_s ($M = 0.13$, 95%CI [0.10, 0.15]) than SV_s ($M = 0.09$, 95%CI [0.07, 0.12]), $t(33) = 1.79$, $p = 0.082$, Cohen's $d = 0.62$.

4.2.3 ERP results

P2. A 2 cognitive style $\times$ 2 secondary task two-way mixed, repeated measures ANOVA on the P2 amplitude was conducted. The main effect of the secondary task was not significant ($M_{\text{task-absent}} = 4.30\mu\text{V}$, 95%CI [3.08, 5.52] vs. $M_{\text{task-present}} = 2.91\mu\text{V}$, 95%CI [2.67, 5.15]), $F(1, 33) = 1.79$, $p = 0.190$, $\eta_p^2 = 0.05$. The main effect of the cognitive style was not significant ($M_{OVs} = 4.89\mu\text{V}$, 95%CI [3.22, 6.56] vs. $M_{SVs} = 3.32\mu\text{V}$, 95%CI [1.60, 5.03]), $F(1, 33) = 1.80$, $p = 0.189$, $\eta_p^2 = 0.05$. The interaction was significant, $F(1, 33) = 4.60$, $p = 0.039$, $\eta_p^2 = 0.12$. A simple effect analysis showed that for OV_s, the P2 amplitude was lower under the task-present condition than that under the task-absent condition, $F(1, 33) = 6.24$, $p = 0.018$, $\eta_p^2 = 0.16$. For SV_s, no difference was observed between task-absent and -present conditions, $F(1, 33) = 0.32$, $p = 0.578$, $\eta_p^2 = 0.01$ (see Figure 7 and 8).

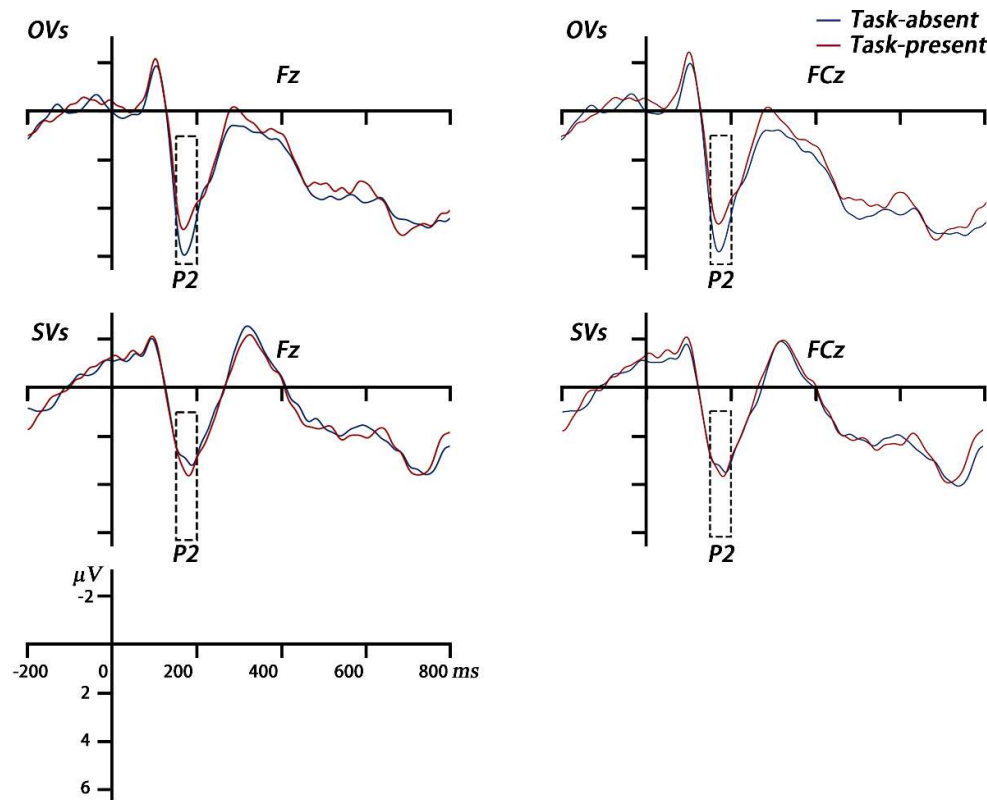


Figure 7. The grand-averaged waveforms during VWM encoding. Averaged P2 waveforms for OV_s and SV_s in the task-absent and task-present conditions are shown at the Fz and FCz electrode sites. The rectangles show the time windows (from 160ms to 200ms after the onset of the memory array) used for the statistical analyses.

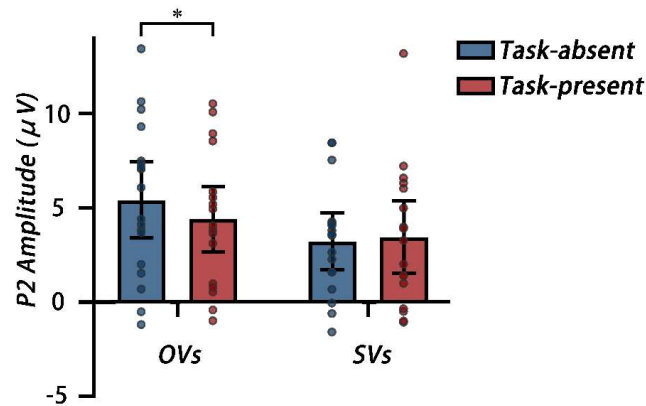


Figure 8. Mean P2 amplitudes from 160ms to 200ms after the memory array onset across the Fz and FCz electrode sites for the task-absent and task-present conditions, each dot corresponds to the data of an individual participant. * $p < 0.05$.

LPC. A 2 cognitive style $\times$ 2 secondary task two-way mixed, repeated measures ANOVA on the LPC amplitude was conducted. The main effect of the secondary task was significant, $F(1, 33) = 18.58$, $p < 0.001$, $\eta_p^2 = 0.36$, showing that the LPC amplitude under the task-present condition ($M = 2.18\mu V$, 95%CI [1.32, 3.04]) was larger than those under the task-absent condition ($M = 0.76\mu V$, 95%CI [0.18, 1.34]). The main effect of the cognitive style was not significant ($M_{OVs} = 1.82\mu V$, 95%CI [0.91, 2.74] vs. $M_{SVs} = 1.12\mu V$, 95%CI [1.18, 2.06]), $F(1, 33) = 1.20$, $p = 0.281$, $\eta_p^2 = 0.03$. The interaction between was significant, $F(1, 33) = 4.66$, $p = 0.038$, $\eta_p^2 = 0.12$. A simple effect analysis showed that for OV, the LPC amplitude was larger under the task-present condition than under the task-absent condition, $F(1, 33) = 21.54$, $p < 0.001$, $\eta_p^2 = 0.40$; for SVs, no difference was observed between the two conditions, $F(1, 33) = 2.25$, $p = 0.143$, $\eta_p^2 = 0.06$ (see Figures 9 and 10).

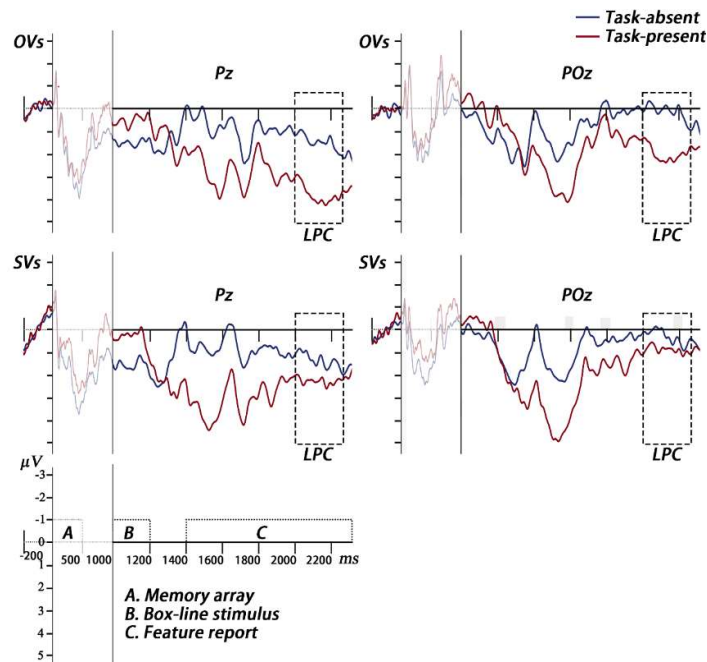


Figure 9. The grand-averaged waveforms during the secondary task performing. Averaged LPC waveforms for object and spatial visualizers in the task-absent and task-present conditions are shown at the Pz and POz

electrode sites. The rectangles show the time windows (from 2000ms to 2250ms after the onset of the memory array) used for the statistical analyses.

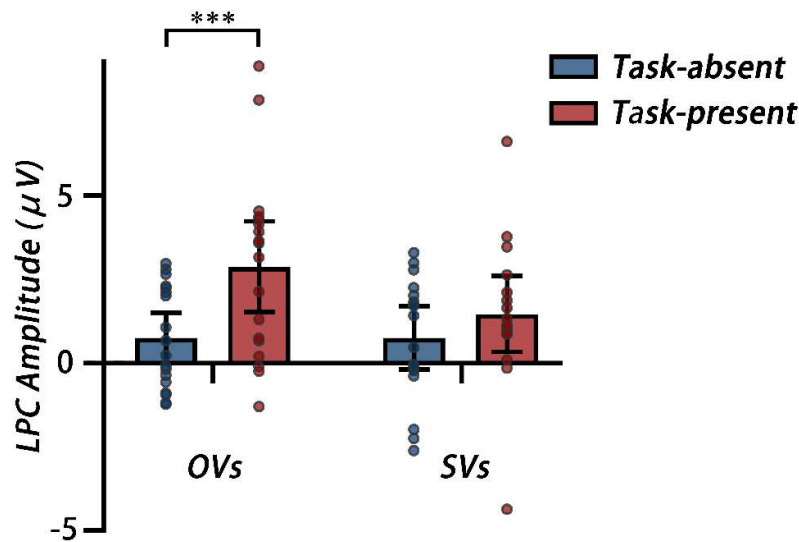


Figure 10. Mean LPC amplitudes from 2000ms to 2250ms after the memory array onset across the Pz and POz electrode sites for the task-absent and task-present conditions, each dot corresponds to the data of an individual participant. *** $p < 0.001$.

4.3. Discussion

In Experiment 3, we investigated how OV and SVs allocate object-based attention when holding bindings in VWM. Participants reported one question of the box or the line in the secondary task during the maintenance of bindings in VWM. ERP was recorded during the VWM encoding and the secondary task performing. Behavioral result showed that the cost of consuming object-based attention for OV was marginal larger than that of SVs. The ERP results showed that when holding bindings in VWM, compared to under the task-absent condition, OV evoked lower P2 during VWM encoding and larger LPC during the secondary task performing under the task-present condition; while SVs evoked equal P2s and LPCs under both conditions. The divergent neural patterns between OV and SVs suggest the differences in how they engage resources when maintaining bindings in VWM.

5. General discussion

In the present study, we explored whether the visualizer cognitive style modulates the role of object-based attention in maintaining bindings in VWM. Behavioral results showed that, compared to SVs, OV showed advantage in holding binding representations, and had a larger cost from the secondary task consuming object-based attention in maintaining bindings compared to maintaining features. ERP results showed that, compared to SVs, OV elicited lower P2 during VWM encoding and larger LPC during the secondary task performing in the task-present condition than task-absent condition.

5.1. Visual Cognitive Style Modulates the Role of Object-based Attention in Holding Bindings in VWM

Previous studies have found that holding bindings in VWM requires more object-based attention than holding features, which highlighting a crucial role for object-based attention in binding maintenance in VWM (Che et al. 2019, Gao et al. 2017, He et al. 2020, Lu et al. 2019, Shen et al. 2015,

Wan et al. 2020, Zhou et al. 2021). In the present study, we found that when confronted with task-consuming object-based attention, OV_s incurred larger cost of consuming object-based attention in holding bindings in VWM than SV_s did, while OV_s and SV_s showed comparable cost in holding features. These results indicate that the visualizer cognitive style modulates the demand for object-based attention while holding bindings in VWM.

OV_s and SV_s have different visual processing styles. OV_s tend to encode multiple parts of an object as a single unit and process information holistically; whereas SV_s focus on discrete parts of an object and process information analytically (for review, see Kozhevnikov & Blazhenkova, 2013). According to the integrated competition model (Duncan et al. 1997), when an individual directs object-based attention to a feature of a multiple-feature object, activity in the neural regions dealing with that feature will first be enhanced and then spread to neural regions dealing with the other features within that object. Accordingly, less object-based attention may induce lower neural activity dealing with features of object, leading to an unstable VWM representation. In the present study, compared to SV_s, OV_s who process information holistically can more easily integrate multi-features into one object, depending more on object-based attention (e.g., Hu et al. 2020). Therefore, when performing the secondary task, OV_s invest more object-based attention and their neural activity in processing multiple-feature objects was reduced, relative to that of the SV_s.

OV_s and SV_s differ in the relative efficiency of the neural pathways responsible for processing bindings. It was demonstrated that OV_s have greater efficiency in the ventral pathway in object-related tasks compared to SV_s (Motes et al. 2008). The ventral pathway is responsible for object processing and to be relatively more involved in object-based attention (Cavanagh et al. 2023, Cohen and Frank 2015). In the present study, participants completed a VWM task requiring holding features or bindings while performing a secondary task necessitating object-based attention. OV_s with greater efficiency in the ventral pathway tend to adjust their resources investment more flexibly according to the requirement of object-based attention, compared to SV_s. Therefore, OV_s had a larger cost in holding bindings than features in VWM depending on whether or not the secondary task consumed object-based attention; while SV_s with lower efficiency in the ventral pathway had equal costs in holding features and bindings between the tasks that did or did not consume object-based attention.

5.2 On-Demand Resources of Object-based Attention in Holding Bindings

In Experiment 3, participants were required to complete a binding VWM task with or without a secondary task. The P2 was recorded during the presentation of the memory items. Results showed that OV_s elicited a lower P2 during VWM encoding under the task-present condition than the task-absent condition, whereas SV_s elicited equal P2s across conditions. P2 serves as a neural marker of attentional allocation in VWM (Smith 1993, Wolach and Pratt 2001). In Smith's (1993) study, participants were required to remember words in a 'study-phase' and then judge whether or not those words had been previously studied in a 'test-phase'. During the 'study-phase', the P2 was larger for words that were correctly recognized during the 'test-phase' compared to those that were not recognized. Researcher proposed that P2 might be involved with the engagement of attentional or working memory resources. In another study (Wolach & Pratt, 2001), participants were sequentially presented with two memory digits and two distractors. P2 was recorded during the presentation of both memory digits and distractors. The memory digits elicited larger P2 than the distractors. The larger P2 indicated the increased attention allocation to the memory digits than the distractors in working memory. Thus, in our study, the lower P2 indicates that OV_s allocated attenuated attention during binding VWM encoding under the task-present condition than under the task-absent condition. Moreover, given that object-based attention contributes to the encoding of binding representations in VWM (Cohen and Frank 2015, Schoenfeld et al. 2014), our finding suggests that, compared to the task-absent condition, OV_s allocated less object-based attention when encoding bindings with a secondary task in VWM; whereas SV_s allocate equivalent object-based attention across both conditions. This reduced allocation of object-based attention resources during VWM

encoding may enable OVs to conserve more attention resources for subsequent tasks during VWM maintenance, compared to SVs.

As for LPC, some studies point to a relationship between LPC and the effort required to perform working memory tasks (Cavanagh et al. 2023, Cohen and Frank 2015, Gunseli et al. 2014a, Gunseli et al. 2014b, Ruchkin et al. 1990). In one study (Gunseli et al. 2014a), participants were required to maintain VWM representations for the subsequent simple search task (target color different from distractors) and difficult search task (target color same as distractors). Larger LPC was evoked in the difficult search task than simple search task, indicates that LPC indexes the effort invested in the VWM maintenance. In the present study, participants required to complete a secondary task while retaining bindings. The secondary task increased the overall task difficulty and the demand of object-based attention, competed for limited resources with the binding maintaining process. OVs invested more effort in maintaining bindings when performing the secondary task, manifested as a larger LPC. While SVs invested consistent effort in binding maintenance, regardless of the presence or absence of the secondary task, manifested as similar LPCs across the task conditions.

Taken together, these findings suggest that, compared to SVs, OVs can more flexibly adjust their object-based attention investment in binding VWM and their effort to allocate relevant object-based attention in performing the secondary task according to the task demand. This demonstrates a voluntary way for individuals to modulate the object-based attention during binding VWM, such on-demand resources constitute the mechanism underlying the role of object-based attention in retaining bindings in VWM. The theory of object-based attention in retaining bindings in VWM is further elucidated as an on-demand resources when allocating such attention.

In general, our results reveal that object-based attentional investment in holding bindings in VWM is modulated by the visualizer cognitive style, with OVs having a larger investment compared with SVs. The mechanism underlying this modulation is based on the allocation of on-demand resources to meet the task requirements.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of the School of Psychology at Shandong Normal University.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

VWM	Visual working memory
OV	Object visualizer

SV	Spatial visualizer
OSIQ	Object-Spatial Imagery Questionnaire
OSIQ-R	Chinese revised version of the Object-Spatial Imagery Questionnaire
ANOVA	Analysis of variance
RT	Reaction time
LPC	Late positive component
ERP	Event-related potential
EEG	Electroencephalography
VEOG	Vertical electrooculogram
HEOG	Horizontal electrooculogram
ICA	Independent component analysis

Appendix A

Appendix A.1. Performance of the Secondary Tasks

For Experiment 2, the accuracy and RT data were analyzed using a two-way mixed, repeated measures ANOVA. The cognitive style (OVs vs. SVs) was the between-subjects factor and the probe type (*feature* vs. *binding*) was the within-subjects factor. For the RT data, only trials with correct responses and within three standard deviations from the mean were analyzed. For Experiment 3, the accuracy and RT data were analyzed using an independent-samples *t*-test between OVs and SVs.

The accuracy and RT of the secondary task in Experiments 2 and 3 are shown in Table A1. For Experiment 2, the main effect of the cognitive style and the probe type was not significant in accuracy ($p_1 = 0.509$; $p_2 = 0.867$) or RT ($p_1 = 0.621$; $p_2 = 0.694$). The interaction of the cognitive style and the probe type was not significant, neither for accuracy ($p = 0.686$) nor RT ($p = 0.220$). For Experiment 3, no significant difference was observed between OVs and SVs in accuracy ($p = 0.744$) or RT ($p = 0.794$). The results suggest that the secondary task exerts a similar effect on both the cognitive styles and the probe type.

Table A1. Accuracy and RT of the secondary task in each probe condition in Experiment 2 and 3.

Exp.	Probe Type	Accuracy [95% CI]		RT (<i>ms</i>) [95% CI]	
		OVs	SVs	OVs	SVs
2	Feature	0.86 [0.83, 0.89]	0.85 [0.82, 0.88]	1019 [968, 1070]	988 [937, 1039]
	Binding	0.83 [0.78, 0.88]	0.86 [0.82, 0.91]	1015 [952, 1078]	998 [934, 1061]
3	Binding	0.84 [0.79, 0.88]	0.83 [0.78, 0.88]	1049 [988, 1109]	1037 [975, 1100]

* OV. Object visualizer; SV. Spatial visualizer; Exp. Experiment.

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