Object-based attention in retaining binding in working memory: Influence of activation states of working memory

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Abstract

It has been suggested that retaining bindings in working memory (WM) requires more object-based attention than retaining constituent features. Recent studies have found that when memorized stimuli are presented sequentially, the most recent stimulus is in a highly accessible privileged state such that it is retained in a relatively automatic and resource-free manner, whereas the other stimuli are in a non-privileged state. The current study investigated whether the activation states of WM modulate the role of object-based attention in retaining bindings in WM. To address this question, we presented three colored shapes sequentially and added a transparent-motion task (Experiment 1) or a mental rotation task (Experiment 2) into the WM maintenance phase to consume object-based attention. We consistently found that consuming object-based attention led to a larger impairment to bindings relative to constituent features, which is independent of the WM activation states, suggesting that object-based attention is critical in retaining bindings in WM across activation states of WM.

Keywords Activation states · Binding · Object-based attention · Working memory

Introduction

The building and holding of a limited set of integrated representations from distinct features (i.e., binding) is a fundamental function of the working memory (WM) (Allen, Baddeley, & Hitch, 2014; Baddeley, 2000). The mechanism underlying the “binding” process is among the key issues in cognitive science (see Schneegans & Bays, 2018, for a review). Conventional studies on perception have suggested that attending to visual features at the same location enables these features to become bound as an integrated representation (e.g., feature integration theory; Treisman, 1996, 1998; Treisman & Gelade, 1980). Therefore, it has been posited and well accepted that the deployment of attention is a prerequisite for successful binding in perception. In contrast to this consensus in perception, the role of attention in processing binding in WM has remained unclear (e.g., Allen, Baddeley, & Hitch, 2006; Allen, Havelka, Falcon,

Evans, & Darling, 2015; Allen, Hitch, & Baddeley, 2009; Allen, Hitch, Mate, & Baddeley, 2012; Baddeley, Allen, & Hitch, 2011; Gao et al., 2017; Johnson, Hollingworth & Luck, 2008; Peterson & Naveh-Benjamin, 2017; Peterson, Decker, & Naveh-Benjamin, 2018; Shen, Huang, & Gao, 2015; Wheeler & Treisman, 2002; Zokaei, Heider, & Husain, 2014; for reviews, see Allen, 2015; Schneegans & Bays, 2018).

In the recent two decades, it has been debated as to whether retaining bindings in WM is more resource-demanding (i.e., requires extra attention) than retaining constituent features. Wheeler and Treisman (2002) pioneered this question, claiming that more spatial attention is required in retaining bindings than in retaining constituent features. Some studies have indirectly supported this resource-demanding view (e.g., Fougny, Asplund, & Marois, 2010; Fougny & Marois, 2011); however, later studies directly examined this view and most of them revealed negative evidence (for reviews, see Allen, 2015; Schneegans & Bays, 2018). These studies predominantly used a dual-task paradigm. Particularly, participants were shown a set of stimuli and were required to memorize single features or the bindings between them in different blocks. Critically, a secondary task was added to compete for resource with the WM task. If extra resource was required in processing bindings in WM, the secondary task would lead to a larger impairment on binding relative to constituent single features (i.e., selective binding impairment). Using this paradigm, two separate strands

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of research have been conducted. The first strand followed Wheeler and Treisman (2002), investigating whether extra spatial attention was required in retaining bindings in WM. For instance, Johnson et al. (2008) inserted a visual search task, which requires sequential shifts of spatial attention, during the maintenance phase of a WM task. They found a similar degree of disruption between binding and constituent features, which had been confirmed by other studies (e.g., Delvenne, Cleeremans, & Laloyaux, 2010; Langerock, Vergauwe, & Barrouillet, 2014; Lu, Ma, Zhao, Gao, & Shen, *in press*; Shen et al., 2015; Yeh, Yang, & Chiu, 2005). Those findings implied that no more spatial attention is needed in retaining bindings in WM. The second strand addressed the nature of episodic buffer (Baddeley, 2000), which is an added storage buffer to the multiple-component model of WM (Baddeley & Hitch, 1974). The initial multiple-component model claimed that a WM system consists of a central executive and two slave subsystems, namely, the phonological loop and visuo-spatial sketchpad. The added episodic buffer had been proposed to actively bind information from phonological and visuo-spatial subsystems, as well as long-term memory into a coherent episodic representation; the binding process was assumed to be fulfilled with the help of attention from the central executive (here we call it central attention; see also Fougny, 2008). Baddeley and colleagues explored this key assumption extensively (e.g., Allen et al., 2006; Allen et al., 2009; Allen, Hitch, Mate, & Baddeley, 2012; Karlsen, Allen, Baddeley, & Hitch, 2010; for reviews, see Allen, 2015; Baddeley, Allen, & Hitch, 2010, 2011). To consume central attention, participants were required to perform a concurrent digit task (articulatory rehearsal vs. backward counting) while conducting a WM task. In line with the finding from spatial attention, Baddeley and colleagues consistently found that although the concurrent task impaired the WM performance, there was a similar degree of disruption between binding and constituent features, suggesting that processing bindings in WM does not require more central attention than processing single features. Moreover, this implication was supported by studies from other laboratories (e.g., Brown & Brockmole, 2010; Ding et al., 2015; Langerock et al., 2014; Morey & Bieler, 2013; Van Lamsweerde & Beck, 2012; Van Lamsweerde, Beck, & Elliott, 2015; Vergauwe, Langerock, & Barrouillet, 2014; but see Peterson & Naveh-Benjamin, 2017, and Peterson et al., 2018, for a different view for item-item binding). Together, these two strands of research have implied that retaining binding in WM is passive, not requiring more resource than retaining constituent features. Baddeley even revised the initial assumption of episodic buffer, considering it as passively receiving binding representations that have been formed elsewhere before entering the episodic buffer (Baddeley et al., 2010, 2011; Baddeley, 2012).

It is worth noting that this passive view of binding process in WM has been challenged. We recently pointed out that since a hallmark of binding representation is by nature a coherent and integrated unit, object-based attention, which is a distinct type of attentional resource from spatial attention and central attention (Chen, 2012; Duncan, 1984), may play a pivotal role in retaining such integrated units (Gao et al., 2017; Lu et al., *in press*; Shen et al., 2015). We tested this hypothesis by adding a secondary task consuming object-based attention to the WM maintenance phase. In line with the prediction of object-based attention hypothesis, we consistently revealed that the concurrent task resulted in a considerably larger impairment in the binding condition relative to the feature conditions (see also Che, Ding, Ling, Wang, Gu, & Li, 2019; Fougny & Marois, 2009). Moreover, this is a reliable and consistent pattern of effect that emerges across different bindings (e.g., unitized visual binding wherein constitute features share one location, cross-space binding, cross-time binding, etc.) and secondary tasks that consume object-based attention (e.g., the Duncan's object feature-report task, mental rotation task, and transparent-motion task). Taken together, we considered that retaining bindings in WM is an active process, requiring more object-based attention relative to retaining single features.

However, recent studies implied that the role of attention in retaining bindings in WM might be modulated by the activation states of bindings in WM (e.g., Allen et al., 2006; Atkinson et al., 2018; Atkinson, Waterman, & Allen, 2019; Berry, Waterman, Baddeley, Hitch, & Allen, 2018; Hu, Hitch, Baddeley, Zhang, & Allen, 2014; Hitch, Hu, Allen, & Baddeley, 2018; Hu, Allen, Baddeley, & Hitch, 2016). Specifically, Allen and colleagues demonstrated that there are two distinct activation states for representations in WM when the stimuli were sequentially presented (e.g., Allen & Ueno, 2018; Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2014; Hu et al., 2016; Ueno, Allen, Baddeley, Hitch, & Saito, 2011a; Ueno, Mate, Allen, Hitch, & Baddeley, 2011b). If the presented stimuli are equally prioritized, the most recent stimulus is in a highly accessible privileged state. The representation in the privileged state has significantly better performance, and it is retained in a relatively resource-free (or automatic) manner. A concurrent task consuming central attention does not impair the WM performance of both single features and bindings. Other earlier presented stimuli, on the other hand, are retained in a non-privileged state: A concurrent task consuming central attention equally impairs the WM performance of single features and bindings. Moreover, even though there is a goal-relevant item in a sequence (e.g., the first one) that can be actively prioritized for retention with the help of central attention, this does not prevent the automatic consolidation of subsequently attended (and less goal-relevant) items, and the most recent item is still in a privileged state (see also Maxcey-Richard & Hollingworth, 2013). Intriguingly, the resource-free processing for the items in the privileged state receives support from the exploration of selective maintenance in

WM. Researchers investigated whether selectively maintaining a representation in WM required sustained attention. They first required the participants to selectively retain an object in WM, by presenting a retro-cue after the offset of memory array, a well-accepted way for setting an item in a privileged state (Griffin & Nobre, 2003). Then they added a secondary task to consume spatial attention (Hollingworth & Maxcey-Richard, 2013) or feature-based attention (Rerko, Souza, & Oberauer, 2014). In line with Allen et al.'s findings, these studies consistently revealed that the selectively maintained item did not require more attention, because the facilitation effect due to the privileged state was not reduced after completing a secondary resource-consuming task. Finally, Che et al. (2019) found that the similarity of memorized bindings modulated the role of object-based attention. When two items in the memory array shared a common color, adding a secondary task consuming object-based attention did not selectively impair the two similar bindings. One alternative to this finding is that the two similar bindings are grouped together and obtain a privileged state. Therefore, it is possible that retaining bindings in the privileged state is resource-free, thus does not require more attention, including object-based attention. If this were true, then there would be two mechanisms for retaining bindings in WM: items in a non-privileged state required extra object-based attention to keep an integrated format, whereas those in the privileged state did not. To the best of our knowledge, however, no study has explicitly examined whether the activation states of bindings in WM modulate the role of object-based attention. This issue is important, because it addresses a key boundary of the object-based attention hypothesis, and sheds light on the property of privileged state in WM.

In the current study, we therefore examined the influence of WM activation states on binding processing by directly manipulating the activation states of bindings. To meet this aim, we presented three colored shapes sequentially (e.g., Atkinson et al., 2018, 2019; Hu et al., 2014; Hu et al., 2016). Meanwhile, in keeping with Shen et al. (2015), we tapped object-based attention by adding a transparent-motion task (Experiment 1) or a mental rotation task (Experiment 2) into the maintenance phase of WM. We predicted that if the activation states of bindings in WM modulate the role of object-based attention, then the selective binding impairment will vanish for the most recent stimuli that are in the privileged state (i.e., resource-free), but exist for those in the non-privileged state (i.e., resource-demanding). However, if the object-based attention plays a key role in processing binding in WM, regardless of activation states, then a selective binding impairment will be observed, regardless of the display order.

¹ Although Duncan's object-feature report task is a classic task in demonstrating object-based attention (Duncan, 1984), the composed stimuli (rectangular and line) in this task and memorized shapes in this study belong to the same category. To avoid the stimuli in the secondary task overwriting the representations of memorized items (e.g., Ueno, Allen, et al., 2011a; Ueno, Mate, et al., 2011b), we did not use Duncan's task as the secondary task in this study.

Experiment 1: Consuming object-based attention via a transparent motion task

Experiment 1 used a transparent motion task to consume object-based attention¹ that was developed by Valdes-Sosa and colleagues (e.g., Valdes-Sosa, Cobo, & Pinilla, 1998, 2000). Valdes-Sosa et al. presented two superimposed transparent moving surfaces to participants; these surfaces were defined by two interspersed and differentially colored sets of dots (i.e., random dot kinematograms (RDKs)). Participants were required to judge the speed and direction of the surfaces. Because the dots had a short lifetime and only a fraction of the dots (e.g., 50%) moved in a common direction while others moved randomly, participants had to direct their attention to a specific transparent surface instead of focusing on individual dots. In line with other object-based attention studies (e.g., Duncan, 1984; Egly, Driver, & Rafal, 1994b; Egly, Rafal, Driver, & Starrveveld, 1994a; Huang, 2010; see Chen, 2012 for a review), a landmark of object-based attention processing was revealed: Accuracy for reporting two features from one surface was significantly better than from two surfaces. This effect is explained as all features of an attended object are processed concurrently. Accordingly, each surface in the transparent-motion task can be conceived as an object, the processing of which takes place at an early stage of visual processing (Pinilla, Cobo, Torres, & Valdes-Sosa, 2001; Schoenfeld et al., 2003). Even if participants were required to process one feature of the surface, the speed and color of the surface will also be extracted into the object representation. The transparent-motion task nowadays has been well accepted in exploring the mechanisms of object-based attention (e.g., Ciaramitaro, Mitchell, Stoner, Reynolds, & Boynton, 2011). Moreover, we previously employed a transparent motion task as the secondary task and successfully consumed the object-based attention by revealing a larger impairment to binding relative to constituent features, which had been confirmed by experiments adopting Duncan's object-feature report task (Gao et al., 2017; Shen et al., 2015).

Method

Participants

An *a priori* power analysis was conducted with the program G*Power 3.1.9.2 (Faul, Erdfelder, Buchner, & Lang, 2009). For a $2 \times 3 \times 3$ (see the design below) repeated-measures analysis of variance (ANOVA), with a moderate effect size of $f = 0.20$ (estimated from a pilot study), $\alpha = 0.05$ and $1 - \beta = 0.85$, an N of 16 was sufficient to detect an effect with a statistical power of 0.85 for a three-ordered interaction. Forty-five (26 males) valid participants with an average age of 21.27 years ($SD = 2.10$) took part in this experiment. All participants were

Zhejiang University undergraduates who provided signed consent, had normal color vision, and had normal or corrected-to-normal visual acuity. The study was approved by the Research Ethics Board of Zhejiang University.

Apparatus and stimuli

Participants were seated in a dark room, approximately 60 cm from the screen. Stimuli were presented against a gray (128, 128, 128; RGB color codes) background on a 19-in. CRT monitor with a resolution of $1,024 \times 768$ pixels at 60-Hz refresh rate.

The memory array contained three colored shapes (i.e., color-shape binding). The to-be-memorized colors and shapes were selected randomly from a pool of six distinct values of each type (see the first and second row in Fig. 1). For the probed stimuli, colored blobs, hollow shapes, and colored shapes were used in the color-only, shape-only, and binding conditions, respectively (see Fig. 1 for an example).

Stimuli in the transparent-motion (see Fig. 2) consisted of 50 black dots (0.1° in diameter) that moved within a $3^\circ \times 3^\circ$ virtual square region in the screen center. Across trials, 35 dots moved coherently in the top-left (50% of trials) or top-right (50% of trials) direction, whereas the other 15 dots moved randomly in the six unused directions. Dots moved with a speed of 1.3° or $2.0^\circ/\text{s}$ and were selected randomly for each trial.

Design and procedure

We adopted a 2 (Task-load: low vs. high) $\times 3$ (Memory-condition: color, shape, and color-shape binding) $\times 3$ (Serial-position: mem1, mem2, mem3) within-subject design. According to the Task-load factor, the whole experiment was divided into two sessions, the order of which was counterbalanced between participants. Each session had three blocks according to the content of memorization: color block, shape block, and binding block, the orders of which were counterbalanced.

Each color or shape block contained 48 trials. Each binding block contained 60 trials with two types of memory array: All the items in memory array had distinct feature values in 48 trials (80%), and two items in memory array shared one feature value in 12 trials (foiled trials, 20%; six trials shared a color, and six trials shared a shape). The foiled trial setting had been used in previous studies (e.g., Allen et al., 2006; Karlsen et al., 2010) to encourage participants memorizing all the items in the memory array. Overall, there were 312 trials, including 288 valid and 24 foiled trials; the latter were excluded from the analysis. The probe could be an old item in memory array in 50% of the trials. Moreover, when the probe was an old one, it was selected evenly from the three memorized items (the three items were termed mem1, mem2, and mem3, respectively, according to the display order). Before the formal experiment, participants completed practice trials containing only a WM task and only a transparent-motion task to familiarize themselves with each task; participants completed at least ten trials of the dual tasks before each block. Participants had a rest every 24 and 30 trials in the feature block and the binding block, respectively. The whole experiment lasted an average of 70 min.

Each trial began with the word “Ready” (in Chinese) presented on the center of the screen to indicate the initiation of a trial. A trial began by participants pressing the spacebar button in the keyboard. Then four digits (1 2 3 4) were presented for 500 ms; participants were required to repeat the four digits loudly during the whole trial. Following a 500-ms fixation (a black cross; $0.76^\circ \times 0.76^\circ$), three colored shapes were presented sequentially (there was a spatial gap of 1.31° between stimuli if they appeared simultaneously), each was presented for 250 ms with a 250-ms blank interval in between (see Fig. 2). Then 500 ms after the offset of the last memorized item, a transparent-motion task was presented for at most 1,200 ms, within which participants had to finish the secondary task. The transparent motion task disappeared immediately once participants made a response. Then a blank interval was presented, the duration of which was determined by meeting the criterion

Fig. 1 Color, shape, and binding in Experiments 1. The colors are purple (255, 0, 255; RGB color codes), yellow (255, 255, 0), blue (0, 0, 255), green (0, 255, 0), red (255, 0, 0), and white (255, 255, 255), from left to

right. The shapes ($1.31^\circ \times 1.31^\circ$ of visual angle in average) are triangle, star, chevron, circle, cross, and diamond, from left to right

Fig. 2 Schematic representation of a trial used in Experiment 1. The yellow arrows in the transparent motion task indicate the moving direction of the dots but are absent in the actual experiments

that the inter-stimuli-interval between mem3 and probe was 2,000 ms (i.e., 2,000 ms minus response time of transparent-motion task). Finally, a probe was displayed at a position 1.6° lower than the screen center and participants had to respond within 2,000 ms. The inter-trial blank interval was self-paced and ended by pressing the spacebar to start a new trial.

In the transparent-motion task, participants made a button press to indicate whether the surface moved top-left (F on the keyboard) or top-right (J on the keyboard) in the high-load condition, and pressed the spacebar on the keyboard in the low-load condition without any judgement. If participants did not make a response to the transparent motion task within 1,200 ms, it would be treated as a wrong response to the motion task in both low- and high-task-load conditions. Regarding the WM task, participants were instructed to determine whether the probe was present in the memory array by pressing “J” for presence and “F” for absence. When the probe was absent from the memory array, a new feature or binding that had not appeared in the memory array was presented. The new binding was formed by combining two features from two randomly selected objects in the memory array.

Analysis

If participants failed in the foiled trials of binding (with an average accuracy of 50%), then the related data were not included in the analysis. We did not exclude any participants according to this criterion. Only trials with a correct response on the transparent-motion task were analyzed further. The descriptive data of the WM task are reported in Table 1.

We first examined whether the transparent-motion task led to a selective binding impairment, regardless of serial position of the memorized stimuli. We conducted a two-way repeated-measures ANOVA on the accuracy of the WM task, by taking Task-load (low vs. high) and Memory-condition (color, shape, and binding) as within-

subject factors. To have a direct comparison with previous studies on this topic (e.g., Allen et al., 2006; Gao et al., 2017; Shen et al., 2015), the accuracy of the WM task was reported as corrected recognition (hits–false alarms) (Snodgrass & Corwin, 1988). For a significant Task-load $\times$ Memory-condition interaction, we first calculated the difference between low-task-load and high-task-load conditions, then ran planned contrasts by separately comparing the difference under the binding condition with the difference under the two feature conditions.

Since we replicated the selective binding impairment, we then examined the influence of serial position of memorized stimuli on selective binding impairment. Considering that only in the trials probing old items could we obtain the position information of probe in the memory array, we analyzed the performance of probing old trials. This condition prevented us from using correct recognition as the index. Instead, we used the accuracy of old trials (e.g., hit rates) to perform the related analysis. A three-way repeated-measures ANOVA on hit rates of the WM task was performed, by taking Task-load (low vs. high), Memory-condition (color, shape, and binding), and Serial-position (mem1, mem2, and mem3) as within-subject factors.

Additionally, we calculated the Bayes factor (BF_{10} ; Jeffreys, 1961; Rouder, Morey, Speckman, & Province, 2012) to examine the ratio of the likelihood probability between the null hypothesis (H_0) relative to the alternative hypothesis (H_1), using JASP statistical software (JASP Team, 2018, version 0.9.2.0). A BF_{01} of 3 constitutes substantial evidence for the H_0 over the H_1 , whereas a BF_{01} of 10 is considered to be strong evidence for the H_0 over the H_1 (Jeffreys, 1961). We reported the BF to represent the BF_{01} . Thus, $BF < 1/3$ indicates evidence for the presence of the main effect or interaction under consideration, while $BF > 3$ indicates evidence for the absence of the effect under consideration. To compute the BFs, we set Cauchy priors at default (for t -tests: $r = 0.707$; for ANOVAs: $r = 0.5, 1$, and 0.354 for fixed

Table 1. Memory task accuracy, hit rate, and correct rejection (CR) under each condition in Experiment 1 (E1) and Experiment 2 (E2). The data in parentheses are *MSE*

		Color			Shape			Binding		
		Accuracy	Hit	CR	Accuracy	Hit	CR	Accuracy	Hit	CR
E1	Low	92.04	91.77	92.24	86.60	87.46	85.35	77.88	76.21	79.13
	load	(0.81)	(0.88)	(1.17)	(1.37)	(1.64)	(2.11)	(1.26)	(2.00)	(1.77)
E2	High	90.12	86.37	93.35	85.01	84.37	85.19	71.35	65.13	77.03
	load	(1.21)	(2.14)	(1.15)	(1.11)	(1.68)	(1.55)	(1.20)	(2.05)	(1.99)
E1	Low	85.84	82.22	89.39	72.86	77.60	68.27	74.38	70.95	77.79
	load	(1.43)	(2.36)	(1.62)	(1.86)	(2.89)	(3.25)	(1.56)	(1.92)	(2.25)
E2	High	83.83	77.80	89.92	71.32	77.10	65.60	66.26	62.04	70.41
	load	(1.69)	(2.52)	(1.62)	(1.59)	(2.74)	(4.01)	(1.87)	(2.88)	(2.75)

effects, random effects, and covariates, respectively). For the ANOVA, we reported the $BF_{\text{Inclusion}}$ value for each factor in the model (i.e., a main effect or an interaction effect), which indicates the likelihood of the data under the models that included an effect compared to equivalent models stripped of the effect (i.e., Bayesian model averaging) while excluding higher-order interactions.

Results

The overall accuracy of the transparent-motion task was 96.68% and 89.34% for the low-load and high-load conditions, respectively. The response time of the transparent-motion task was 476 ms and 689 ms for the low-load and high-load conditions, respectively.

Selective binding impairment by transparent-motion task

The corrected recognition under each condition is shown in Fig. 3. The two-way ANOVA revealed a significant main effect of Task-load, $F(1,44) = 32.69$, $p < .01$, $\eta_p^2 = .43$, $BF = 2.94E-3$, suggesting that performance was significantly better under the low-load than the high-load condition. The main effect of Memory-condition was significant, $F(2,88) = 102.71$, $p < .01$, $\eta_p^2 = .70$, $BF = 3.42E-37$; post hoc contrasts (Bonferroni-corrected) revealed that performance was significantly better under color (0.82) than under shape (0.71, $p < .01$), and performance was significantly better under shape (0.71) than under binding (0.49, $p < .01$). The interaction between Task-load and Memory-condition was significant, $F(2,88) = 4.11$, $p = .02$, $\eta_p^2 = .09$, $BF = 0.67$.

Planned contrasts that deconstructed the interaction showed that relative to low load, high load significantly impaired the binding performance, $t(44) = 5.45$, $p < .01$, Cohen's $d = 0.85$, but did not significantly affect the performance of color, $t(44) = 1.79$, $p = .08$, Cohen's $d = 0.27$, or shape, $t(44) = 1.21$, $p = .23$, Cohen's $d = 0.18$. Moreover, the disruption caused by the secondary transparent motion task was significantly larger under

binding ($M = .13$) than under color ($M = .04$), $t(44) = 2.51$, $p = .02$, Cohen's $d = 0.37$, and under shape ($M = .03$), $t(44) = 2.48$, $p = .02$, Cohen's $d = 0.37$. There was no significant difference between color and shape, $p > .10$.

Influence of serial position on selective binding impairment

The hit rates under each condition are shown in Fig. 4. The three-way ANOVA revealed a significant main effect of Task-load, $F(1, 44) = 28.49$, $p < .01$, $\eta_p^2 = .39$, $BF = 2.88E-7$, suggesting that performance was significantly lower under high load (0.79) than low load (0.85). The main effect of Memory-condition reached significance, $F(2, 88) = 54.42$, $p < .01$, $\eta_p^2 = .55$, $BF = 3.08E-38$. Post hoc contrasts (Bonferroni-corrected) revealed that performance was significantly better under color (0.89) than under binding (0.71, $p < .01$), and the performance was better under shape (0.86) than under binding (0.71, $p < .01$); there was no significant difference between color (0.89) and shape (0.86, $p = .13$). The main effect of Serial-position reached significance, $F(2, 88) = 5.08$, $p = .01$, $\eta_p^2 = .10$, $BF = 0.30$. Post hoc analysis revealed that the accuracy was significantly higher for mem3 (0.85) than for mem1 (0.81, $p < .05$) and mem2 (0.81, $p < .05$). However, there was no significant difference between mem1 and mem2 ($p = 1.00$). Therefore, the current experiment observed a recency effect. Neither the Task-load $\times$ Serial-position, $F(2, 88) = 0.14$, $p = .87$, $\eta_p^2 < .01$, $BF = 35.71$, nor Memory-condition $\times$ Serial-position, $F(4, 176) = 2.22$, $p = .07$, $\eta_p^2 = .05$, $BF = 9.71$, was significant. Critically, there was a significant Task-load $\times$ Memory-condition interaction, $F(2, 82) = 5.28$, $p < .01$, $\eta_p^2 = .11$, $BF = 0.39$, demonstrating a selective binding impairment. However, the Memory-condition $\times$ Serial-position $\times$ Task-load interaction was not significant, $F(4, 176) = 0.49$, $p = .75$, $\eta_p^2 = .01$, suggesting that selective binding impairment equally existed in all three serial positions. Confirming this null effect, the BF for the Memory-condition $\times$ Serial-position $\times$ Task-load interaction was 41.67, favoring a model without the three-order interaction.

Fig. 3 Results for Experiment 1. Correct recognition (hit rate – false alarm) under each condition is presented; for data on accuracy, hit rate, and false alarms please see Table 1. Error bars indicate standard errors

Discussion

Experiment 1 demonstrated a recency effect (i.e., highest hit rates in mem3), suggesting that the final presented item had a processing privilege. Two main findings were revealed. First, by inserting a transparent-motion task into the WM maintenance phase, we replicated the selective binding impairment in a sequentially presented manner, suggesting that selective binding impairment holds, regardless of the display manner of the memory array (simultaneous vs. sequential display). Second, we revealed that selective binding impairment existed across the three serial positions, suggesting that the object-

based attention plays a key role in both privileged and non-privileged states of WM. Moreover, this effect was very strong as the BF value was 41.67.

However, one may argue that the different number of features (feature load) between feature conditions and binding condition contaminated the selective binding impairment in Experiment 1. Participants had to retain twice more features in the binding condition (six features) than in the feature condition (three features), which led to worse performance for retaining bindings than for retaining features even when no secondary task was added. The worse performance in binding may further result in larger binding impairment when adding

Fig. 4 Hit rates for Experiment 1. Error bars indicate standard errors

an extra secondary task. We argued that the current result was immune to this alternative. First, we revealed a non-significant difference in accuracy between color-location binding and color when no object-based secondary task was performed in Shen et al. (2015, cf. Experiment 3). However, we found that the added object-based task incurred a larger impairment for binding than for color or location, implying that feature load was not the key factor driving the degree of impairment. Our later studies (Gao et al., 2017; Lu et al., *in press*) directly examined this alternative by requiring participants to memorize both features simultaneously in the feature condition, such that the same number of features was retained between the feature condition and the binding condition. In line with Shen et al. (2015), we found that while the performance of one feature condition was comparable to that of the binding condition, a significant selective binding impairment was revealed. Second, previous studies have found that even though the performance was worse for binding than for constituent features when the secondary task was absent, a similar degree of impairment between binding and feature conditions was found when a task consuming spatial attention was inserted (Lu et al., *in press*; Johnson et al., 2008; Shen et al., 2015). In the same vein, Allen et al. (2006), Langerock et al. (2014), and Ding et al. (2015) revealed worse performance for binding than for constituent features; however, the concurrent task consuming central attention did not result in a selective binding impairment. Together, these studies suggested that feature load was not the key factor leading to the observed larger binding impairment.

Nevertheless, because previous studies addressing the potential contamination of feature load all adopted a simultaneous presentation manner, it remains unclear whether the feature load matters in a sequential-display circumstance. To this end, Experiment 2 was conducted to further examine the current issue by excluding the potential contamination of feature load. We required participants to remember three colors and three shapes simultaneously in the feature condition and three corresponding bindings in the binding condition. Hence the same number of features was retained between bindings and single features.

Additionally, to investigate whether the observed null effect of serial position on selective binding impairment was limited to a transparent motion task, we used a mental rotation task to consume object-based attention. Although the conduct of mental rotation requires the involvement of a central executive (e.g., Hegarty, Shah, & Miyake, 2000), researchers found that the object WM, in which object-based attention plays a key role (Matsukura & Vecera, 2009, 2011), serves as the buffer in which the mental rotation occurs (Hyun & Luck, 2007; Prime & Jolicoeur, 2010). Moreover, we demonstrated that similar to Duncan's object-feature report task and transparent motion task, a concurrent mental rotation task led to a selective binding impairment relative to the feature

conditions (see Experiments 1–3 in Shen et al., 2015). If the findings of Experiment 1 were not limited to the transparent motion task, Experiment 2 would replicate the key findings of Experiment 1.

Experiment 2: Consuming object-based attention via a mental rotation task

Method

Participants

For a $2 \times 2 \times 3$ (see the design below) repeated-measures ANOVA with a moderate effect size of $f = 0.20$ (estimated from a pilot study), $\alpha = 0.05$ and $1 - \beta = 0.85$, a $N = 21$ was sufficient to detect an effect with a statistical power of 0.86 for a three-ordered interaction. Thirty-two valid (13 males) participants with an average age of 21.76 years ($SD = 2.46$) took part in the experiment. Three participants were replaced due to chance-level performance on the WM task or secondary task. The other aspects were the same as Experiment 1.

Apparatus and stimuli

For the mental rotation task, a $0.5^\circ \times 1.0^\circ$ rotated black R in its canonical (50% of the trials) or a mirror-reversed form was presented in the center of the screen. The stimulus was rotated clockwise or counterclockwise from an upright position by a random angle between 72° and 144° . The canonical/mirror-reversed form and rotation angle were combined randomly. Participants had to judge whether the letter was in its canonical or mirror-reversed form. The letter was not rotated in the low-load condition, but it was rotated in the high-load condition.

The other aspects were the same as Experiment 1.

Design and procedure

Considering that sequentially presenting stimuli needed a relatively long time (at least 1 h, see Experiment 1), and that the cost between color and shape was comparable in Experiment 1, we pooled the color and shape conditions as one feature condition to shorten the duration of experiment. Therefore, Experiment 2 adopted a 2 (Task-load: low vs. high) $\times 2$ (Memory-condition: feature vs. binding) $\times 3$ (Serial-position: mem1, mem2, and mem3) within-subject design; feature and binding conditions had the same number of trials. According to Task-load factor, the whole experiment was divided into two sessions. Each session had one feature and one binding block. In the feature block, participants were told to remember both colors and shapes; color was tested in 50% of the trials, and shape was tested in the other 50%. A feature block

Fig. 5 Schematic representation of a trial used in Experiment 2

contained 48 trials. The binding blocks were the same as in Experiment 1. Overall, there were 216 trials in total, including 192 valid and 24 foiled trials; the latter were excluded from the analysis. For the secondary task, we replaced the transparent-motion task with a mental rotation task. In the mental rotation task, participants pressed “J” for a mirror-reversed letter and “F” for a canonical letter within 1,000 ms. The whole experiment lasted about 45 min.

The other aspects were the same as in Experiment 1. Figure 5.

Analysis

If participants failed in the foiled trials of binding (with an average accuracy of 50%), then the related data were not included in the analysis. We did not exclude any participants according to this criterion. Only trials with a correct response on the mental rotation task were analyzed. The descriptive data of the WM task are listed in Table 1.

In line with Experiment 1, we first examined whether the mental rotation task led to a selective binding impairment regardless of serial position of the memorized stimuli. To check the selective binding impairment, we split the data of feature condition into color and shape, and conducted a two-way repeated measures ANOVA on the accuracy of WM task, by taking Task-load (low vs. high) and Memory-condition (color, shape, and binding) as within-subject factors. For significant Task-load $\times$ Memory-condition interaction, we first calculated the difference between low-load and high-load conditions, then ran planned contrasts by separately comparing the difference under the binding condition with the difference under the two feature conditions.

We then examined the influence of serial position of memorized stimuli on selective binding impairment, focusing on hit rates. A three-way repeated-measures ANOVA was performed by taking Task-load (low vs. high), Memory-condition (feature² vs. binding), and Serial-position (mem1, mem2, and mem3) as within-subject factors.

The other aspects were the same as in Experiment 1.

Results

The overall accuracy of the mental rotation task was 98.52% and 93.8% for the low-load and high-load conditions, respectively. The response time for the mental rotation task was 554 ms and 637 ms for low-load and high-load conditions, respectively.

Selective binding impairment by mental rotation

The corrected recognition under each condition is shown in Fig. 6. The two-way ANOVA revealed a significant main effect of Task-load, $F(1,31) = 15.91$, $p < .01$, $\eta_p^2 = 0.34$, $BF = 3.07E-2$, suggesting that performance was significantly better under the low-load than under the high-load condition. The main effect of Memory-condition was significant, $F(2,62) = 59.40$, $p < .01$, $\eta_p^2 = 0.66$, $BF = 1.78E-19$. Post hoc contrasts (Bonferroni-corrected) revealed that performance was significantly better under color (0.70) than under binding (0.40, $p < .05$) and under shape (0.41, $p < .05$), yet no difference was found between the latter two ($p > .50$)³. The interaction between Task-load and Memory-condition was significant, $F(2,62) = 4.04$, $p = .02$, $\eta_p^2 = 0.12$, $BF = 0.49$.

² We checked the effect of task load on color and shape in different positions by conducting a three-way repeated-measures ANOVA on the accuracy of the WM task. Task-load (low load vs. high load), Memory-condition (color vs. shape), and Serial-position (mem1, mem2, and mem3) were within-subject factors. None of the interactions related to Serial-position reached significance: Task-load $\times$ Serial-position, $F(2, 62) = 0.68$, $p = .51$, $\eta_p^2 = .02$, $BF = 10.10$; Memory-condition $\times$ Serial-position, $F(2, 62) = 0.65$, $p = .53$, $\eta_p^2 = .02$, $BF = 8.33$; Memory-condition $\times$ Serial-position $\times$ Task-load interaction, $F(2, 62) = 0.06$, $p = .94$, $\eta_p^2 = .00$, $BF = 9.61$.

³ The significant difference between shape and binding in Experiment 1 disappeared in Experiment 2. This discrepancy was based in the different memory settings. Participants memorized three shapes in the shape condition of Experiment 1, but they memorized three colors and three shapes simultaneously in the shape condition of Experiment 2. Therefore, there were different feature loads between Experiments 1 and 2. The increased feature load in Experiment 2 decreased the difference between shape and binding in Experiment 2.

Fig. 6 Results for Experiment 2. Correct recognition (hit rate – false alarm) for each condition is presented; the data for accuracy, hit rate, and false alarms are given in Table 1. Error bars indicate standard errors

Planned contrasts that deconstructed the interaction showed that relative to low load, high load significantly impaired the binding performance, $t(31) = 6.21$, $p < .01$, Cohen's $d = 1.10$, but did not significantly affect the performance of color, $t(31) = 1.10$, $p = .28$, Cohen's $d = .20$, or shape, $t(31) = 0.71$, $p = .49$, Cohen's $d = .13$. Moreover, the disruption caused by the mental rotation task was significantly larger under binding ($M = .16$) than under color ($M = .04$), $t(31) = 2.82$, $p < .05$, Cohen's $d = .50$, and under shape ($M = .03$), $t(31) = 2.47$, $p < .05$, Cohen's $d = .44$. There was no significant difference on impairment between color and shape, $p > .10$.

Influence of serial position on selective binding impairment

The accuracy with each condition is shown in Fig. 7. The three-way ANOVA revealed a significant main effect of Task-load, $F(1, 31) = 14.07$, $p < .01$, $\eta_p^2 = .31$, $BF = 0.08$, suggesting that performance was significantly lower under high load (0.70) than under low load (0.75). The main effect of Memory-condition reached significance, $F(1, 31) = 67.01$, $p < .01$, $\eta_p^2 = .68$, $BF = 1.92E-9$, suggesting that the performance was significantly higher for feature (0.79) than for binding (0.67). The main effect of Serial-position was significance, $F(2, 62) = 6.17$, $p < .01$, $\eta_p^2 = .17$, $BF = 5.49E-3$. Post hoc analysis revealed that the accuracy was significantly lower for mem2 (0.67) than for mem1 (0.76; $p < .05$) and for mem3 (0.75; $p < .01$), whereas the difference disappeared between mem1 and mem3 ($p = .83$). Neither the Task-load $\times$ Serial-position, $F(2, 62) = 0.75$, $p = .48$, $\eta_p^2 = .02$, $BF = 12.34$,

nor the Memory-condition $\times$ Serial-position, $F(2, 62) = 0.94$, $p = .40$, $\eta_p^2 = .03$, $BF = 7.81$, were significant. Critically, the Memory-condition $\times$ Task-load interaction was significant, $F(1, 31) = 6.03$, $p = .02$, $\eta_p^2 = .16$, $BF = 0.93$, demonstrating a selective binding impairment. However, the Memory-condition $\times$ Serial-position $\times$ Task-load interaction was not significant, $F(2, 62) = 0.56$, $p = .57$, $\eta_p^2 = .18$, suggesting that selective binding impairment existed in all three serial positions. Confirming this null effect, the BF for the Memory-condition $\times$ Serial-position $\times$ Task-load interaction was 6.56, favoring a model without interaction.⁴

Discussion

Experiment 2 balanced the number of features between feature and binding conditions, and used a new secondary task to consume object-based attention. Importantly, Experiment 2 replicated the key findings of Experiment 1. Therefore, the findings of Experiment 1 were not due to the unbalanced feature load between feature condition and binding condition, and were not limited to a specific type of secondary task. Moreover, there was no significant difference between memorizing shapes and memorizing bindings overall (see Fig. 6), suggesting that the unbalanced task difficulty between feature

⁴ Considering that the performance was comparable between shape and binding (see Results in the previous session), we performed an analysis focusing on shape and binding, and reached similar results to those reported here (including the figure pattern).

Fig. 7 Hit rates for Experiment 2. Error bars indicate standard errors

condition and binding condition could not explain the findings in Experiments 1 and 2.

As opposed to Experiment 1, Experiment 2 demonstrated both a primacy effect and a recency effect. Previous studies suggested that a recency effect is conspicuously revealed in a visual WM task where the stimuli are presented sequentially (e.g., Atkinson et al., 2018, 2019; Berry et al., 2018; Hitch et al., 2018; Hu et al., 2014; Hu et al., 2016; Maxcey-Richard & Hollingworth, 2013; Phillips & Christie, 1977). Phillips (1983) proposed that an active process of visualization is normally applied to the final item in a series, leading to a recency effect. However, this visualization can also be redeployed voluntarily to privilege an earlier item, which improves memory for that item. Indeed, Allen and colleagues found that encouraging a strategy of actively visualizing the first item in a sequence could significantly boost its recall and generate a primacy effect in the serial position curve, while impairing but not erasing the recency effect (Atkinson et al., 2018, 2019; Berry et al., 2018; Hitch et al., 2018; Hu et al., 2014; Hu et al., 2016). Therefore, participants in Experiment 2 could have possibly adopted a strategy of privileging the first item, although we did not encourage them doing so, and the reason for adopting this strategy was unclear. In this case, both the first and the last items were in a privileged state, which is in line with some recent studies (e.g., Atkinson et al., 2018, 2019; Hitch et al., 2018; Hu et al., 2014; Hu et al., 2016). From this perspective, the current experiment presented a novel situation where when two items were in a privileged state, object-based attention played a key role.

General discussion

The current study explored whether the role of object-based attention in retaining bindings in WM is modulated by binding

activation states in WM. We examined this issue by presenting three colored shapes sequentially, leading to a privileged state – at least, for the last presented stimuli. We also added a secondary task to the maintenance phase of WM to consume object-based attention. Experiments 1 and 2 consistently revealed a maintenance advantage for the last stimuli, whereas Experiment 2 also revealed an advantage for the first presented stimuli in a sequence. Critically, we found that the added concurrent task selectively impaired binding performance, regardless of the activation states in WM. This finding was not contaminated by the unbalanced number of features, or unbalanced task difficulty between binding condition and feature condition. Moreover, the selective binding impairment was generalized from a transparent motion task to a mental rotation task, both of which consume object-based attention. Together, our study suggested that retaining bindings in the privileged state is not resource-free relative to retaining constituent single features; instead, it also requires more object-based attention. Therefore, the role of object-based attention in retaining bindings in WM is not modulated by the activation states in WM.

The current study contributes to the object-based attention hypothesis of retaining bindings in WM in at least three aspects. First, we tested a critical boundary of the object-based attention hypothesis. Since previous studies have consistently found that processing an item in the privileged state does not need extra central, feature-based, or spatial attention (e.g., Atkinson et al., 2018, 2019; Berry et al., 2018; Hitch et al., 2018; Hollingworth & Maxcey-Richard, 2013; Maxcey-Richard & Hollingworth, 2013; Hu et al., 2014; Hu et al., 2016; Rerko et al. 2014), retaining bindings in the privileged state may be resource-free. In contrast to this implication, the current study provides clear-cut evidence demonstrating that an item in the privileged state requires more object-based attention relative to single features to keep its bound format. Therefore, the privileged state does not affect the processing

manner of multi-featured bindings, and object-based attention plays a key role regardless of activation states in WM. Second, while the role of central attention in retaining bindings in WM has been extensively explored by presenting stimuli in both a simultaneous manner and a sequential manner, the extant studies supporting the object-based attention hypothesis all adopted a simultaneous presentation format (Che et al., 2019; Gao et al., 2017; Lu et al., *in press*; Shen et al., 2015). However, in daily life we often process the stimuli in a sequential manner; empirical evidence suggests that the presentation manner of stimuli may affect WM processing (e.g., Gao et al., 2016; Ricker & Cowan, 2014). It is therefore important to check whether the object-based attention hypothesis fits in such a complex circumstance. Our study was the first to present the bindings sequentially while object-based attention was exhausted during the WM maintenance phase. The current study closed a gap in binding exploration, and revealed a key role for object-based attention in a sequential presentation circumstance, suggesting that the presentation format of memory array does not affect the role of object-based attention. More broadly, the WM studies on the role of object-based attention and central attention together imply that the binding processing in WM is not modulated by the presentation manner of the stimuli. Third, the current finding suggests that the key finding of Che et al. (2019) could not be explained in terms of privileged state. If the key finding of Che et al. (2019) was due to the two similar bindings being retained in a privileged state, a selective binding impairment should not be observed. Our study provides direct evidence refuting this suggestion. Additional studies are needed to explain the underlying mechanism of Che et al. (2019).

One may argue that the selective binding impairment in the current study was because the stimuli in the secondary task overwrote the binding representations in WM. Specifically, Allen et al. convincingly demonstrated that even a to-be-ignored suffix after the memory array considerably impairs binding representations, which are fairly fragile (e.g., Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2016; Ueno, Allen, et al., 2011a; Ueno, Mate, et al., 2011b). The stimuli in the secondary task will inevitably serve as a suffix and overwrite the binding representations. Although it is reasonable, two key characteristics of the suffix effect do not support this alternative. First, the suffix selectively impairs binding performance when the suffix contains at least one feature from the stimuli pool of memory array (e.g., Ueno, Allen, et al., 2011a; Ueno, Mate, et al., 2011b). However, neither color (black) nor other physical features of the stimuli in the secondary task were among the features being adopted in the memory array. Second, the suffix only selectively impairs the bindings that are in a privileged state. In contrast, we demonstrated a selective binding impairment regardless of the activation states in WM. It is also worth noting that the same physical information was perceived between the low- and

high-load conditions in both Experiment 1 and Experiment 2, which would predict a similar degree of overwriting. These facts suggest that the current selective binding impairment was driven by consuming object-based attention. On the other hand, we did not suggest that the added secondary task does not impair the WM performance at all. Allen et al. found that a suffix without any feature from the memory set impaired the recency effect (Hu et al., 2014; Ueno, Mate, et al., 2011b). Indeed, the degree of recency effect was smaller in the current study than in previous studies without any visual stimuli in the WM maintenance phase (e.g., Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016; Ueno, Allen, et al., 2011a; Ueno, Mate, et al., 2011b). Therefore, the current finding is essentially in line with the view that representations in the privileged state are highly vulnerable to interference (e.g., Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016; Ueno, Allen, et al., 2011a; Ueno, Mate, et al., 2011b).

The current study also sheds light on the property of privileged state in WM. The current study for the first time tapped the influence of a secondary task consuming object-based attention on the privileged state in WM. In line with previous studies (e.g., McElree & Doshier, 1989; Oberauer & Hein, 2012), we found that the final item in a sequence has a privileged state. Moreover, we did not find a significant Task-load $\times$ Serial-position interaction, suggesting that the sequence curve profile (i.e., privileged state) was not affected by the task load. Therefore, the current study replicated and extended other dual-task studies on the privileged state (Atkinson et al., 2018; Hitch et al., 2018; Hollingworth & Maxcey-Richard, 2013; Hu et al., 2014, 2016; Rerko et al., 2014; Ueno, Allen, et al., 2011a; Ueno, Mate, et al., 2011b). In particular, previous studies had addressed the role of central attention, feature-based attention, and spatial attention on privileged state, but not the role of object-based attention. However, an item in the privileged state might be an integrated and coherent representation, the processing of which relies on object-based attention (Duncan, 1984). In this sense, the privileged state might serve to enhance the integration nature of the representation, which calls for object-based attention. In other words, object-based attention might play a key role in forming the privileged state. The current study enabled us to test this hypothesis directly. In two experiments, we consistently revealed that object-based attention did not play a key role in maintaining the privileged state. Therefore, the current study ruled out an important alternative to mechanism of privileged state, and added a new piece of evidence supporting the view that the privileged state in WM persists without sustained attention. However, we had to admit that although it is well acknowledged in the WM field that the last item of the sequentially displayed memory array is in a privileged state with regard to processing advantage (see Hitch, Allen, & Baddeley, 2020; McElree, 2006 for reviews), the exact features of the privileged state deserve more careful

consideration. For instance, researchers currently tend to define an item being in a privileged state when its WM performance (accuracy in most of the cases) is significantly better than other items (e.g., the current study; Atkinson et al., 2018; Atkinson et al., 2019; Hu et al., 2016; Maxcey-Richard & Hollingworth, 2013). However, whether this operative definition is robustly held should be accepted with caution (e.g., the first item in Experiment 2).

Finally, a critical caveat must be considered. In particular, although we found a significant recency effect in both experiments, because we inserted a secondary task into the WM maintenance phase, it is possible that the inserted secondary task pushed the most recently presented item out of the privileged state. The revealed recency effect reflects the logarithmic decay effect that is onset when the representation is pushed out of the privileged state by the onset of a new task.⁵ If this was the case, we failed to probe the privileged state in WM. We argue that this caveat does not hold according to the current understanding of a privileged state in the WM literature. Here we had to differentiate the privileged state from the focal attention in WM. Recent studies have suggested that although pushing an item into the privileged state requires the involvement of attention (Janczyk & Berryhill, 2014), the privileged state persists without focal attention (Hollingworth & Maxcey-Richard, 2013; Maxcey-Richard & Hollingworth, 2013; Rerko et al., 2014; see also the discussion in the previous paragraph). Diverting focal attention away from the item in the privileged state, for instance by adding a secondary task during the WM maintenance phase (e.g., visual search, color classification; Hollingworth & Maxcey-Richard, 2013; Rerko et al., 2014) or by first probing another representation in WM (Rerko et al., 2014), does not change the privileged state in WM. More relevant to the current study, Allen and colleagues had systematically examined the characteristics of the privileged state of WM in a sequential display circumstance (e.g., Allen, Baddeley & Hitch, 2014, 2017; Atkinson et al., 2018; Hitch et al., 2018; Hu, et al., 2014; Hu et al., 2016). They found that the privileged state of the most recent item is stable: It cannot be impaired by asking the participants to prioritize another object or to conduct a secondary digit task (articulatory suppression or backward counting). Similarly, Maxcey-Richard and Hollingworth (2013) found that even in a more natural WM task (scene viewing), the privileged state of the most recent item robustly held even though the participants were required to prioritize another object or generate a saccade to a new object. The current finding was in line with this view (see the discussion in the previous paragraph). Taking together, we suggest that at the current stage, the manipulation of inserting a secondary task in the WM maintenance phase moved attention away, but did not impair the privileged state. Future study may consider finding a sensitive neuro-marker to track the activation states of WM representations (see de Vries, Driel, & Olivers, 2019,

for an endeavor in this direction), providing direct evidence to ensure the original activation state holds when a secondary task is conducted.

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