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# Visual working-memory capacity load does not modulate distractor processing

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## Abstract

Over the last decade, researchers have explored the influence of visual working-memory (WM) load on selective attention in general, by focusing on the modulation of visual WM load on distractor processing in perception. However, there were three distinct hypotheses (perceptual-load hypothesis, resolution hypothesis, and domain-specific hypothesis) with different predictions. While the perceptual-load hypothesis suggests that visual WM capacity load serves as a type of perceptual load, the latter two hypotheses consider visual WM capacity load acting as a type of central executive load, with a constraint that the domain-specific hypothesis claimed that only a content overlap existed between WM load and the perceptual task. By adding a flanker task into the maintenance phase of visual WM, here we attempted to understand the influence of visual WM load on distractor processing. We systematically manipulated the parameters of the task setting between WM and flanker tasks (Experiments 1–4), the perceptual load of flanker task (Experiment 5), the settings of the flanker stimuli and the WM load (Experiment 6), and the content overlap between WM task and flanker task and the exposure time of flanker task (Experiments 7, 8, and 9). However, in 11 out of 12 sub-experiments we consistently found that the visual WM load did not modulate the distractor processing. The implications of these findings are discussed.

**Keywords** Visual working memory · Selective attention · Distractor processing

## Introduction

Selective attention addresses the tendency of cognitive processing to be confined largely to information that is relevant to on-going behavior (Moore & Zirnsak, 2017). It is among the most fundamental cognitive functions of human beings (Failing & Theeuwes, 2018; Moore & Zirnsak, 2017). A central question in selective attention regards when the task-irrelevant distractions are processed and when they are not (i.e., early vs. late selection, for reviews see Moore & Zirnsak, 2017; Murphy, Groeger, & Greene, 2016). It is now well recognized that the ability to ignore irrelevant distractors is modulated by the type and level of processing load involved in the current task (for reviews, see Lavie, 2005; Lavie, Beck, & Konstantinou, 2014; Murphy et al., 2016; but see Tsal & Benoni, 2010), which has been elaborated in Lavie's load theory (e.g., Lavie, 1995; Lavie, Hirst, De Fockert, & Viding, 2004). Particularly, load theory distinguishes perceptual load and cognitive load. Distractor processing is eliminated under high perceptual load relative to low perceptual load (e.g., Lavie, 1995; Lavie et al., 2014; Lavie & Tsal, 1994; Linnell & Caparos, 2013; Remington, Cartwright-Finch, & Lavie, 2014). As with the cognitive control load, the load theory considers the role of priority-based working-memory (WM) control (for reviews, see de Fockert, 2013; Lavie, 2010), by assuming that WM maintains the processing priority of the ongoing task. A high WM load condition will reduce its availability to exert priority-based top-down control over the on-going task, and thereby leads to increased processing of irrelevant distractors in low perceptual-load circumstances (e.g., Caparos & Linnell, 2010; de Fockert, Rees, Frith, & Lavie, 2001; Lavie, 2005; Lavie et al., 2004; Linnell & Caparos, 2011).

However, WM is not a unitary buffer but contains modules with distinct functions. According to the multi-component model of WM (Baddeley & Hitch, 1974; see Cowan, 2001, for a different review), WM consists of a central executive, a

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phonological loop, and a visuo-spatial sketchpad (so-called visual WM). Whereas the central executive is in charge of coordinating and monitoring ongoing tasks in a top-down manner, the phonological loop and visuo-spatial sketchpad store verbal and visuo-spatial information, respectively (Baddeley, 2003, 2012). So far most of the studies about the influence of WM load on selective attention have addressed the role of the central executive of WM, ignoring the role of WM buffers in charge of information storage on selective attention. To have a full understanding of the interaction between WM and selective attention in general and have a precise comprehension of the function of cognitive load in particular, it is crucial to elucidate whether and how selective attention is modulated by the type of WM load. In the last decade, researchers have begun to investigate this issue by focusing on the role of visual WM load on distractor processing in perception (e.g., Burnham, Sabia, & Langan, 2014; Kim, Kim, & Chun, 2005; Konstantinou, Bahrami, Rees, & Lavie, 2012; Konstantinou, Beal, King, & Lavie, 2014; Konstantinou & Lavie, 2013; Koshino & Olid, 2015; Lin & Yeh, 2014; Oh & Kim, 2004; Roper & Vecera, 2013; Sreenivasan & Jha, 2007; Woodman & Luck, 2004).

However, the results regarding the role of visual WM load on distractor processing are mixed. There are currently three different hypotheses on this issue. The first one is a perceptual-load hypothesis. Lavie and colleagues noticed that the same visual cortices are employed to process the visual features (e.g., orientation) in both perception and WM (e.g., Ester, Serences, & Awh, 2009; Harrison & Tong, 2009); they hence assumed that visual WM load functions as a type of perceptual load. That is, high visual WM load reduced the distractor processing relative to low WM load. They examined the influence of visual WM load on selective attention in a low perceptual task situation (Konstantinou et al., 2012; Konstantinou et al., 2014; Konstantinou & Lavie, 2013). Moreover, they distinguished the central executive load (memorizing fixed-ordered vs. randomly ordered digits) from the visual WM load (memorizing a set of colors) and found that the two types of WM load had opposite effects on distractor processing. In particular, central executive load increased the distracting effect in circumstances such as a flanker task (below we call it flanker effect); however, the flanker effect was significantly reduced in high visual WM load (Konstantinou et al., 2014), which was confirmed by Roper and Vecera (2013). The second one is a domain-specific hypothesis. Lin and Yeh (2014) suggested that only when the WM content and the information in perception were from the same domain did WM load modulate the distractor processing, but by means of a central executive load. Supporting this view, they found that the WM load of shapes did not modulate the letter flanker effect, but increased the shape flanker effect; the WM load of digit (regardless of displaying them via the visual or auditory channel) modulated the letter flanker effect but did not affect the shape flanker effect. The third one is a resolution hypothesis. Since capacity and resolution reflect two different aspects of visual WM (Zhang & Luck, 2008), Zhang and Luck (2015) hypothesized that the resolution manipulation in a task modulated how the WM load functioned: WM task emphasizing capacity (capacity load, memorizing two or four colors) functioned as a type of central executive load, while WM task emphasizing resolution (resolution load, memorizing two low- or high-resolution colors) functioned as a type of perceptual load. In line with this hypothesis, they found that the capacity load increased the letter flanker effect, while the resolution load reduced the letter flanker effect. It is worth noting that from the perspective of Zhang and Luck (2015), all the studies testing the perceptual-load hypothesis and domain-specific hypothesis mainly tapped the capacity load of visual WM. Therefore, the existing empirical evidence supporting the three hypotheses contradicted each other, particularly in terms of the role of visual WM capacity load. While the perceptual-load hypothesis suggests that visual WM capacity load serves as a type of perceptual load, both the domain-specific hypothesis and the resolution hypothesis consider visual WM capacity load acting, at least partially, as a type of central executive load.

Facing this fuzzy situation, we decided to elucidate the influence of visual WM capacity load on the distractor processing. It is possible that the three lines of studies each tapped one part of an "elephant" as that described in the well-known fable "The Blind Men and the Elephant," due to the different parameters being used. We thereby summarized the key parameters in all the related studies in Table 1 to see whether there was any difference in the parameters between these studies. We found that the crucial differences lay in memory settings. Particularly, first, the stimuli in studies supporting perceptual-load hypothesis were displayed in a set of positions that were spread evenly within an area of the screen (Konstantinou et al., 2014; Roper & Vecera, 2013), while the stimuli in other studies were displayed in a horizontal line (Lin & Yeh, 2014; Zhang & Luck, 2015). Second, the stimuli in two out of three experiments supporting perceptual-load hypothesis were distinct colors (e.g., using black, red, yellow; but see Experiment 2b in Konstantinou et al., 2014) that could be verbally coded during memorization, while the stimuli in other studies were difficult to be verbally coded. Although these differences were trivial and theoretically should not dramatically affect the result profiles, we decided to first examine whether these slight differences drove the current discrepancy by manipulating the settings of the memory array, which was followed by a letter flanker task (Experiments 1 and 2). However, as reported below, we did not find any evidence supporting this view, but consistently found that the visual WM capacity load did not modulate the letter flanker effect. We then attempted to examine previous studies (Experiments 3 and 4) by using the similar settings of

Zhang and Luck (2015) and Experiment 1b of Konstantinou et al. (2014),[1] respectively. Again, we observed absent modulation of visual WM capacity load on distractor processing. We next excluded the possibility that the load of the flanker task was too low to be modulated by the visual WM load (Experiment 5), or the settings of the flanker stimuli and the WM load were inappropriate (Experiment 6). Finally, we tested the domain-specific hypothesis by making both the WM and flanker tasks adopt colors (Experiment 7), or non-verbalized shapes (Experiments 8 and 9) as the stimuli. We reached similar findings after controlling the settings of memory array. Overall, we consider that the visual WM capacity load did not modulate the distractor processing.

**Table 1** Summary of previous studies investigating the effect of visual working-memory (WM) capacity load on distractor processing

| Studies | Memory array | | Load | Blank interval between WM task and flanker task | Flanker task | Result (flanker effect) |
|---|---|---|---|---|---|---|
| | Stimuli and exposure time | Verbal coded and spatial arrangement | | | | |
| Zhang and Luck (2015) | - Color patches<br>- 200 ms | - Cannot be verbally coded<br>- Stimuli were displayed in a row | 2 vs. 4 | 2,000 ms | - Stimuli: letter<br>- Encoding: 2,000 ms<br>- Display: in a row | High load > Low load |
| Lin and Yeh (2014) Experiment 3a | - Meaningless shape<br>- 500 ms for low load<br>- 1,500 ms for high load | - Cannot be verbally coded<br>- Stimuli were displayed in a row | 1 vs. 4 | 1,750 ms (1,250 ms mask + 500 ms fixation) | - Stimuli: shape<br>- Encoding: 100 ms<br>- Display: in a circle | High load > Low load |
| Lin and Yeh (2014) Experiment 1a | - Meaningless shape<br>- 500 ms for low load<br>- 1,500 ms for high load | - Cannot be verbally coded<br>- Stimuli were displayed in a row | 1 vs. 4 | 1,750 ms (1,250 ms mask + 500 ms fixation) | - Stimuli: letter<br>- Encoding: 100 ms<br>- Display: in a circle | High load = Low load |
| Konstantinou & Lavie et al. (2014) Experiment 1b | - Color patches<br>- 150 ms | - Can be verbally coded<br>- Stimuli were spread evenly within an area of the screen | 1 vs. 4 | 1,850 ms | - Stimuli: letter<br>- Encoding: 150 ms<br>- Display: in a circle | High load < Low load |
| Konstantinou & Lavie et al. (2014) Experiment 2b | - Meaningless shape<br>- 500 ms | - Cannot be verbally coded<br>- Stimuli were spread evenly within an area of the screen | 1 vs. 4 | 1,850 ms | - Stimuli: letter<br>- Encoding: 150 ms<br>- Display: in a circle | High load < Low load |
| Roper and Vecera (2013) Experiment 1 | - Color patches<br>- 1,000 ms | - Can be verbally coded<br>- Stimuli were spread evenly within an area of the screen | 1, 2, 3, & 4 | 1,500 ms | - Stimuli: letter<br>- Encoding: 100 ms<br>- Display: in a row | High load < Low load |

## Experiment 1: Memory array of Konstantinou et al. (2014) plus flanker task of Zhang and Luck (2015)

In Experiment 1, we replaced the memory array in Zhang and Luck (2015) with the one in Konstantinou et al. (2014). That is, instead of displaying the memory array in a horizontal manner in the screen center, we spread the memory array on a 3 × 3 grid at the screen center. The other aspects were the same as Zhang and Luck (2015). This setting enabled us to test three different predictions. First, if the distinct result patterns between Konstantinou et al. (2014) and Zhang and Luck (2015) were due to different memory settings, then we might replicate the result of Konstantinou et al. (2014). Second, if the distinct result patterns between Konstantinou et al. (2014) and Zhang and Luck (2015) were not rooted in the memory setting, then we might replicate the Zhang and Luck (2015). Third, it is possible that visual WM load did not modulate the flanker effect (e.g., Lin & Yeh, 2014). Additionally, we did not adopt the neutral condition as in Zhang and Luck (2015), since we were interested in the flanker effect but not in the direction of the interference. This setting was also adopted by Konstantinou et al. (2014).

### Method

#### Participants

A priori power analysis was conducted with the program G*Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009). A repeated-measures ANOVA with an effect size of 0.50 (cf. Experiment 1b of Konstantinou et al., 2014), $\alpha = 0.01$ and $1-\beta = 0.99$, gave a statistical power of 99 % and sample size of a minimum of 17 subjects. Accordingly, we recruited 18

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[1] For simplicity, we refer to “Experiment 1b of Konstantinou et al. (2014)” as “Konstantinou et al. (2014)” henceforth.

participants (eight males; 20.00 ± 1.41 years old on average) taking part in the experiment. Moreover, the other experiments in the current study all obeyed this rule by testing at least 18 participants. All participants were undergraduates of Zhejiang University with normal or corrected-to-normal vision. The study was approved by the Research Ethics Board of Zhejiang University.

### Stimuli

The experiment was run on a PC using MATLAB (MathWorks, Inc., Natick, MA, USA) and Psychtoolbox (Brainard, 1997). Stimuli were presented on a 17-in. cathode-ray tube (CRT) monitor (resolution = 1,024 × 768; refresh rate = 60 Hz) with a gray background (180, 180, 180 RGB). Participants were seated in a dark room, approximately 60 cm from the screen.

For the WM task, in line with Konstantinou et al. (2014), one (low load) or four (high load) colored squares (0.8° × 0.8°) were randomly displayed within a 3 × 3 grid (2.8° × 2.8° in visual angle) centered at fixation.[2] Each square was of a different color, chosen randomly from black (0, 0, 0 RGB), blue (0, 0, 255), cyan (0, 255, 255), green (0, 255, 0), magenta (255, 0, 255), red (255, 0, 0), white (255, 255, 255), and yellow (255, 255, 0).[3]

The setting for the flanker task followed Zhang and Luck (2015). Particularly, the target letter, equally likely to be “X” or “N” (0.41° × 0.62°, Arial font, black color), was presented at one of six possible positions along the horizontal meridian (centered 2.5°, 1.5°, and 0.5° from the fixation) with equal probability. A distractor letter (0.67° × 0.90°) that was equally likely to be congruent (e.g., distractor “X” when the target was “X”) or incongruent (e.g., distractor “N” when the target was “X”) with the target letter was presented 1.2° above or below of the fixation point.

### Procedure and design

Each trial began with a 1,000-ms fixation to inform participants of the start of a trial, immediately followed by a 150-ms memory array (see Fig. 1). After another 2,000-ms fixation, the target and distractor for the flanker task appeared on the screen for 2,000 ms and were then replaced by a central fixation for 500 ms. During the time window of 2,500 ms, participants responded to the target letter by pressing the corresponding key for “X” or “N” on the keyboard as quickly and accurately as possible. Finally, a memory probe appeared at one of the locations occupied by the memory array. Participants were required to judge whether the probe was the same as the corresponding memory item within 3,000 ms, by pressing button "J" for “yes” (50%) and "S" for “no.” The memory probe was a match on half of the trials and on the other half, a different color was chosen randomly from stimuli collection. In the visual WM task, responses were not speeded, and no response feedback was given. The inter-trial blank interval was randomly selected from 1,000 to 1,200 ms.

We adopted a 2 (WM-load: low vs. high) × 2 (Flanker congruency: congruent vs. incongruent) within-subjects design. The conditions of WM load were blocked in an ABBA manner counterbalanced across participants, while the congruency conditions were displayed randomly. Each participant completed four blocks of 48 trials each (two low-load and two high-load blocks), resulting in 192 trials in total. Before the formal experiment, participants completed two practice blocks of 16 trials each at least (one low-load and one high-load, in the same order as the first two blocks of the experiment). If they did not understand the task after the practice, a second round of practice was given. The whole experiment lasted about 45 min.

### Analysis

A two-way repeated-measure analysis of variance (ANOVA) was conducted on the accuracy of the WM task, with WM-load (low, high) and Flanker-congruency (congruent, incongruent) as within-subjects factors.

For the flanker task, only trials with correct WM task responses were entered into further analysis. A two-way repeated-measures ANOVA was conducted on the accuracy and reaction time (RT) of the flanker task, separately. The two within-subjects factors were WM-load (low, high) and Flanker congruency (congruent, incongruent). In line with Konstantinou et al. (2014), trials with incorrect responses in the flanker task were removed from the RT analyses.

Additionally, we calculated the Bayes factor (BF; Rouder, Morey, Speckman, & Province, 2012; Rouder, Speckman, Sun, Morey, & Iverson, 2009) to examine the ratio of the alternative hypothesis relative to the null hypothesis. We achieved this via JASP 0.9.0.1. We compared a linear model containing only one main effect with a null model (including subject) to compute the BFs for the main effects, and compared a full model (numerator; including the two main effects and the interaction) with a reduced model (denominator), in which the interaction effect of interest was not included, to compute the BFs for the interaction. A BF of 3 indicates substantial evidence for the selection of one model over the other, whereas a BF of 10 is considered to provide strong evidence for the selection of one model over the other (cf. Jeffreys & Lindsay, 1963).

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[2] The colored squares and the grid in Konstantinou et al. (2014) were 0.38° × 0.38°, 1.38° × 1.38°, respectively. Our setting hence was larger than Konstantinou et al. (2014). This was made to ensure the participants did not have difficulty in WM encoding.

[3] Here we did not use the color pink as in Konstantinou et al. (2014), to improve color distinctions.

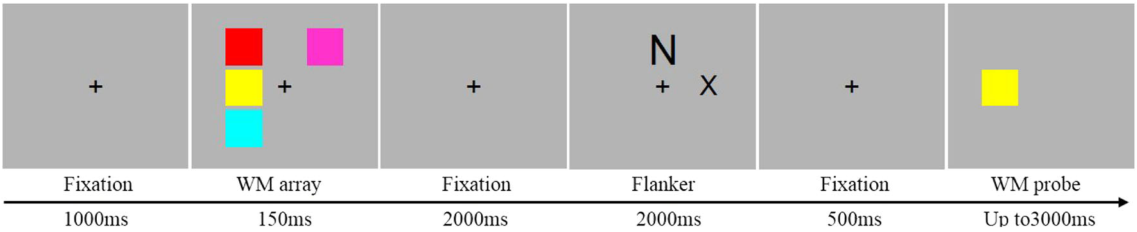

**Fig. 1** The procedure used in Experiment 1. Here a trial with high working-memory (WM) load is shown

## Results

For the WM task, the overall accuracy was 80% (*SD* = 7%) and 94% (*SD* = 4%) for the low- and high-load conditions, respectively. The main effect of WM-load (see Fig. 2a) reached significance, $F(1,17) = 63.14$, $p < .01$, $\eta_p^2 = .79$, $BF = 3.71 \times 10^{12}$, suggesting that the manipulation of WM load was effective. Neither the main effect of Flanker-congruency, $F(1,17) = 3.57$, $p = .08$, $\eta_p^2 = .17$, $BF = .54$, nor the WM-load × Flanker-congruency interaction, $F(1,17) = .07$, $p = .80$, $\eta_p^2 < .01$, $BF = .32$, was significant.

The ANOVA conducted on the accuracy of flanker task (see Fig. 2b) revealed a marginal significant main effect of Flanker-congruency, $F(1, 17) = 3.97$, $p = .06$, $\eta_p^2 = .19$, $BF = 1.09$. The main effect of WM-load did not reach significance, $F(1, 17) = .24$, $p = .63$, $\eta_p^2 = .01$, $BF = .27$. Moreover, the WM-load × Flanker-congruency interaction was not significant, $F(1, 17) = .31$, $p = .58$, $\eta_p^2 = .02$, $BF = .38$.

The ANOVA conducted on the RT of flanker task (see Fig. 2c) revealed a significant main effect of WM-load, $F(1, 17) = 8.14$, $p = .01$, $\eta_p^2 = .32$, $BF = 320.88$, indicating that high WM load increased the RT of flanker task compared to the low-load condition. A significant main effect of Flanker-congruency was also revealed, $F(1, 17) = 41.07$, $p < .01$, $\eta_p^2 = .71$, $BF = 756.07$, indicating that RT was longer in the presence of incongruent as compared with congruent distractors. However, the WM-load × Flanker-congruency interaction was not significant, $F(1, 17) = .22$, $p = .65$, $\eta_p^2 = .01$, $BF = .35$, suggesting that the flanker effect was not affected by the WM load.

## Discussion

In Experiment 1, we combined the memory array setting of Konstantinou et al. (2014) with the flanker task of Zhang and Luck (2015); however, we did not observe any modulation of WM-load on the flanker effect. This finding was not in agreement with Zhang and Luck (2015) and Konstantinou et al. (2014) but was in line with Lin and Yeh (2014).

The finding of Experiment 1 implied that the memory setting did not play a key role in modulating the effect of visual WM load on distractor processing. However, Experiment 1 only tested one typical memory setting (items were displayed in a grid and might be verbally coded), there was an additional memory setting that had not been tested (displaying items in a horizontal line and hard to be verbally coded). We tested this case in Experiment 2.

Additionally, in Experiment 1, participants responded to the flanker task and the WM task using both hands (i.e., left hand pressed "X" [flanker task] and "S" [WM task], right hand pressed "N" [flanker task] and "J" [WM task]). This response setting was different from Zhang and Luck (2015) and may result in response interference between the two tasks. We also

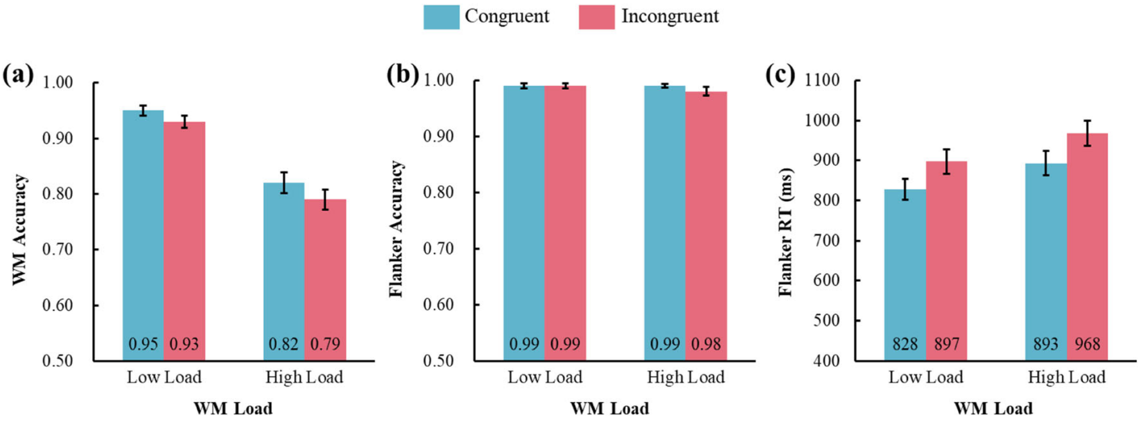

**Fig. 2** Results for Experiment 1. (**a**) Accuracy of the working-memory (WM) task. (**b**) Accuracy of the flanker task. (**c**) Reaction times (RTs) of the flanker task. Error bars show standard errors

tested this alternative by locating the buttons of two tasks on the opposite sides of the keyboard.

## Experiment 2: Memory array of Zhang and Luck (2015) plus flanker task of Konstantinou et al. (2014)

In Experiment 2, we replaced the memory array in Konstantinou et al. (2014) with the one in Zhang and Luck (2015). That is, instead of spreading the memory array within a 3 × 3 grid at the screen center, we presented the memory array in a horizontal manner. The other aspects were generally the same as Konstantinou et al. (2014). Similarly, three different predictions were tested. First, if the discrepancy between Konstantinou et al. (2014) and Zhang and Luck (2015) was due to different memory settings, then we may replicate the result of Zhang and Luck (2015). Second, if the discrepancy between Konstantinou et al. (2014) and Zhang and Luck (2015) was not rooted in the memory setting, then we may replicate Konstantinou et al. (2014). Third, in line with Experiment 1, it is possible that visual WM load did not modulate the flanker effect.

### Method

A group of 18 (seven males; 19.28 ± 1.18 years old on average) participants took part in the experiment.

We adopted the WM task of Zhang and Luck (2015) (see Fig. 3). Particularly, the memory array consisted of one (low load)[4] or four (high load) colored squares that subtended 0.9° × 0.9° of visual angle from a viewing distance of 60 cm (same as Zhang & Luck, 2015). The memorized items were randomly located at four possible locations centered ± 2°and ± 1°from fixation. The memorized colors were quasi-randomly selected from a set of 180 evenly distributed hues on a circle in the perceptually homogeneous CIELAB color space (cf. Zhang & Luck, 2008). The circle was centered in the color space at (L=70, a=20, b=38) with a radius of 60. Moreover, there was a difference of at least 48° in color space between any two colors in the memory array. The probe was a single-colored square, which was displayed at the location of a randomly picked colored square in the memory array. The probe was either the same color as the corresponding color from the memory array (50% of trials) or a different color (96° in color space; 50% of trials).

The stimuli for the flanker task were largely the same as Konstantinou et al. (2014). Particularly, one target letter (0.4° × 0.6°) and five small black dots were presented on a circle (2° in radius). The target letter was equally likely to be an "X" or "N," appearing at one of the six positions of the circle.[5] A distractor letter (0.6° × 1.0°), which was equally likely to be congruent or incongruent with the target letter, appeared 3.5° to the left or the right of the fixation.

Each trial began with a 1,000-ms fixation to inform participants of the start of a trial, after which followed a 200-ms memory array (Fig. 3). Then another 1,500-ms fixation appeared, the flanker task was presented on the screen for 200 ms, and was then replaced by a black "?" for 1,800 ms,[6] during which participants responded to the target letter. After this duration, a memory probe appeared and participants judged whether the probe was the same as the corresponding memory item within 3,000 ms. For the flanker task, participants pressed the quotation key on the keyboard for "X" and semicolon key on the keyboard for "N." Both keys were labeled with the corresponding letter. For the WM task, participants pressed button "S" for "yes" and "A" for "no."

The other aspects were the same as Experiment 1.

### Results

For the WM task, the overall accuracy was 94% (*SD* = 6%) and 74% (*SD* = 9%) for the low- and high-load conditions, respectively. The main effect of WM load (see Fig. 4a) reached significance, $F(1,17) = 67.02$, $p < .01$, $\eta_p^2 = .80$, $BF = 4.80 \times 10^{14}$, suggesting that the manipulation of WM load was effective. Neither the main effect of Flanker-congruency, $F(1,17) = .17$, $p = .69$, $\eta_p^2 = .01$, $BF = .25$, nor the WM-load × Flanker-congruency interaction, $F(1,17) = .04$, $p = .86$, $\eta_p^2 < .01$, $BF = .30$, was significant.

The ANOVA conducted on the accuracy of flanker task (see Fig. 4b) revealed a significant main effect of Flanker-congruency, $F(1, 17) = 14.87$, $p < .01$, $\eta_p^2 = .47$, $BF = 207.44$, suggesting that the accuracy was worse under the incongruent condition relative to the congruent condition. The main effect of WM-load did not reach significance, $F(1, 17) = .17$, $p = .69$, $\eta_p^2 = .01$, $BF = 0.26$. Moreover, the WM-load × Flanker-congruency interaction was not significant, $F(1, 17) = .01$, $p = .92$, $\eta_p^2 < .01$, $BF = .32$.

The ANOVA on the RT of flanker task (see Fig. 4c) revealed a significant main effect of WM-load, $F(1, 17) = 4.89$, $p = .04$, $\eta_p^2 = .22$, $BF = 2.96$, suggesting that high WM load increased the RT of flanker task compared to the low load condition. A significant main effect of Flanker-congruency was also revealed, $F(1, 17) = 10.09$, $p = .01$, $\eta_p^2 = .37$, $BF = 29.29$, indicating that RT was longer in the presence of

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[4] Zhang and Luck (2015) used a low load of memorizing two colors. To have a direct comparison with Experiment 1 and manipulating the load more effectively, we used a low memory load of memorizing one color in Experiment 2.

[5] It is worth noting that the letters in Konstantinou et al. (2014) were "X" and "Z"; to be in line with Experiment 1, we used "X" and "N."

[6] Konstantinou et al. (2014) used a duration of 150 ms, with a question mark of 1,850 ms. The current setting was due to a programming bug. Yet we argue these slight differences should not affect the result pattern.

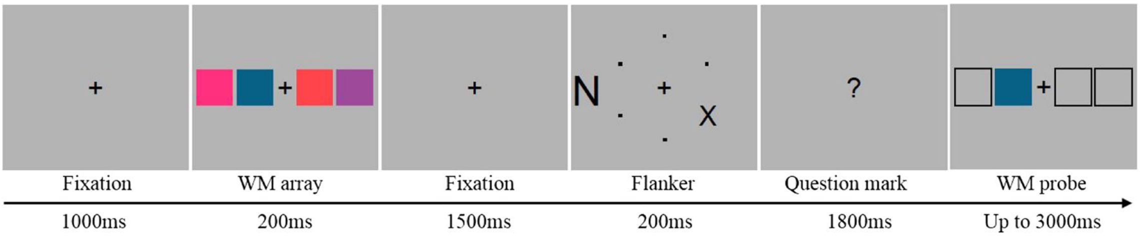

**Fig. 3** The procedure used in Experiment 2. The figure shows a trial with a high working-memory (WM) load

incongruent, as compared with congruent, distractors. The WM-load × Flanker-congruency interaction was not significant, $F(1, 17) = .01$, $p = .92$, $\eta_p^2 < .01$, $BF = .34$, suggesting that the flanker effect was not affected by the WM load.

## Discussion

In Experiment 2, we combined the memory array setting of Zhang and Luck (2015) with the flanker task of Konstantinou et al. (2014). In line with Experiment 1, we did not observe any modulation of WM-load on the flanker effect. Moreover, in Experiment 2 there was no potential response interference between WM task and flanker task. Therefore, the result of Experiment 2 added extra evidence suggesting that the setting of memory array did not play a key role in modulating the effect of visual WM load on distractor processing.

Since Experiments 1 and 2 did not re-establish the findings of Konstantinou et al. (2014) or Zhang and Luck (2015), and we did not use the original settings from the two studies, it is possible that the findings of Konstantinou et al. (2014) and Zhang and Luck (2015) were limited to the specific settings used in the two studies. To this end, Experiments 3 and 4 further examined the role of visual WM capacity load on distractor processing by using a similar setting to Konstantinou et al. (2014) and Zhang and Luck (2015), respectively.

## Experiment 3: Memory array of Konstantinou et al. (2014) plus flanker task of Konstantinou et al. (2014)

Experiment 3 re-examined Experiment 1b of Konstantinou et al. (2014) by largely using the settings in Konstantinou et al. (2014). If Konstantinou et al. (2014) was limited to the specific settings, then high visual WM load would lead to reduced distractor processing relative to low visual WM load condition.

### Method

A group of 22 (13 males; 20.95 ± 3.05 years old on average) participants took part in the experiment.

Figure 5a illustrates the procedure of Experiment 3. The memory task was the same as Experiment 1, and the flanker task was the same as Experiment 2. Moreover, in line with Konstantinou et al. (2014), the memorized squares did not overlap with the letters of the flanker task. Due to a programming bug, participants responded to both tasks in the same way as Experiment 1.

### Results

For the WM task, the overall accuracy was 96% ($SD = 3\%$) and 79% ($SD = 9\%$) for the low- and high-load conditions, respectively. The main effect of WM load reached

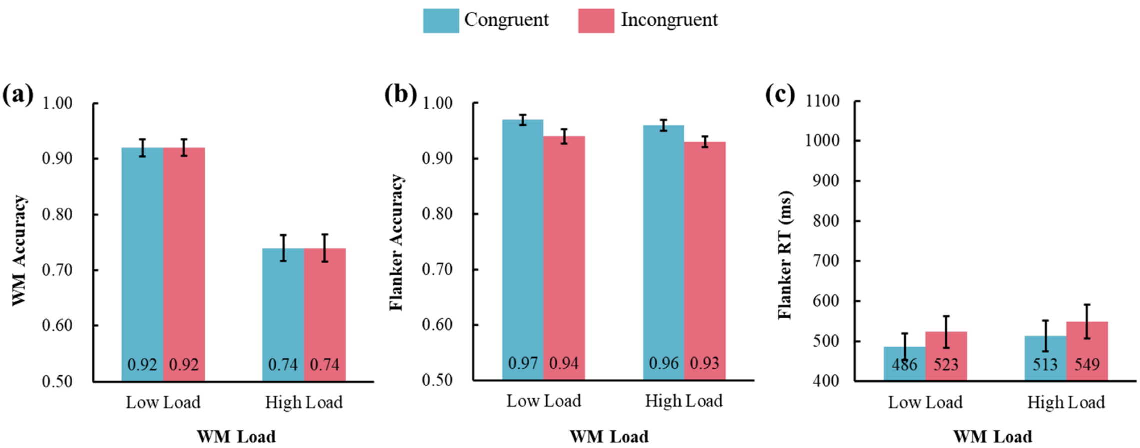

**Fig. 4** Results for Experiment 2. (**a**) Accuracy of the working-memory (WM) task. (**b**) Accuracy of the flanker task. (**c**) Reaction times (RTs) of the flanker task. Error bars show standard errors

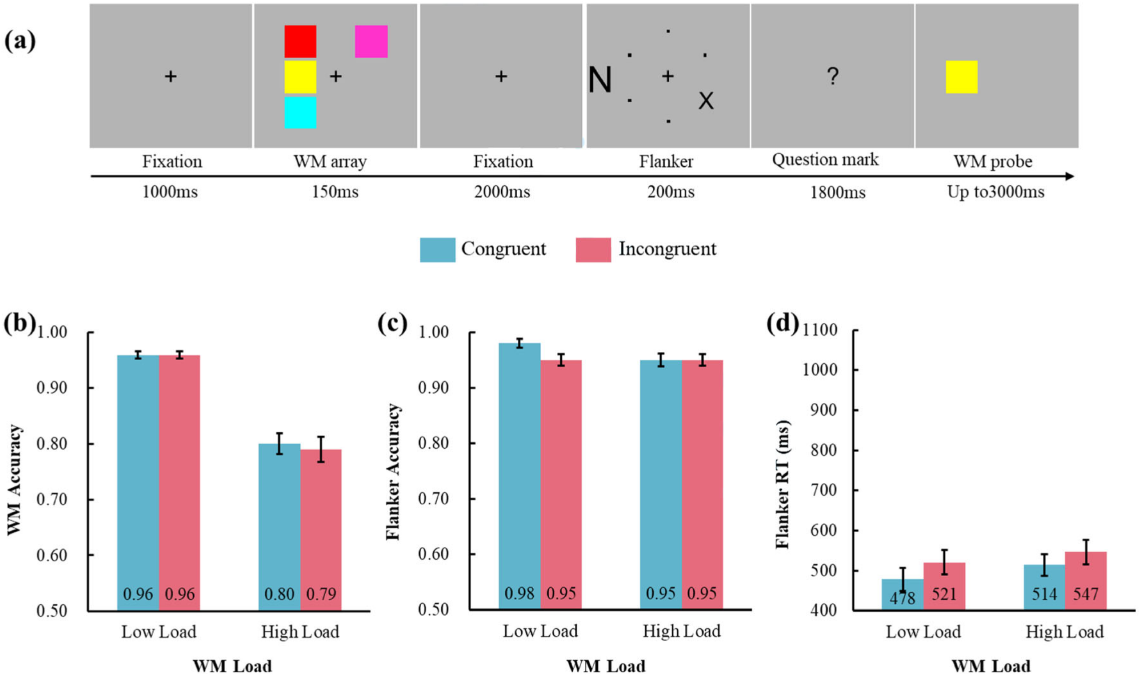

**Fig. 5** Procedure and results for Experiment 3. (**a**) Procedure for Experiment 3 (the stimuli were not draw in scale). (**b**) Accuracy of the working-memory (WM) task. (**c**) Accuracy of the flanker task. (**d**) Reaction times (RTs) of the flanker task. Error bars show standard errors

significance (see Fig. 5b), $F(1,21) = 69.36$, $p < .01$, $\eta_p^2 = .77$, $BF = 1.63 \times 10^{18}$, suggesting that the manipulation of WM load was effective. Neither the main effect of Flanker-congruency, $F(1,21) = .20$, $p = .66$, $\eta_p^2 = .01$, $BF = .28$, nor the WM-load × Flanker-congruency interaction, $F(1,21) = .66$, $p = .43$, $\eta_p^2 = .03$, $BF = .28$, was significant.

The ANOVA on the accuracy of flanker task (see Fig. 5c) revealed that neither the main effect of WM-load, $F(1, 21) = 2.73$, $p = .11$, $\eta_p^2 = .12$, $BF = .73$, nor the main effect of Flanker-congruency, $F(1, 21) = 1.15$, $p = .30$, $\eta_p^2 = .05$, $BF = .40$, was significant. Moreover, the WM-load × Flanker-congruency interaction were not significant, $F(1, 21) = .45$, $p = .51$, $\eta_p^2 = .02$, $BF = .36$.

The ANOVA on the RT of flanker task (see Fig. 5d) revealed a significant main effect of WM-load, $F(1, 21) = 10.04$, $p = .01$, $\eta_p^2 = .32$, $BF = 9.70$, suggesting that high WM load increased the RT of flanker task compared to the low-load condition. A significant main effect of Flanker-congruency was also revealed, $F(1, 21) = 8.09$, $p = .01$, $\eta_p^2 = .28$, $BF = 50.38$, indicating that RTs were longer in the presence of incongruent, as compared with congruent distractors. Critically, the WM-load × Flanker-congruency interaction was not significant, $F(1, 21) = .69$, $p = .42$, $\eta_p^2 = .03$, $BF = .35$, suggesting that the flanker effect was not affected by the WM load.

## Discussion

By largely using the same settings as Konstantinou et al. (2014), we failed to re-establish the findings of Konstantinou et al. (2014), which was in line with Experiments 1 and 2. Meanwhile, it is worth noting that there were at least four differences between the current experiment and Konstantinou et al. (2014). First, both the colored patches and the displayed grid in the current study were approximately two times larger than the ones in Konstantinou et al. (2014). Second, the current flanker task displayed for 200 ms followed by an 1,800-ms question mark; while Konstantinou et al. (2014) presented the flanker task for 150 ms with an 1,850-ms question mark. Third, there was no feedback in the current formal experiment, while Konstantinou et al. (2014) displayed an auditory tone ("beep") for incorrect responses for both tasks. Fourth, the response settings in the two studies were different. Both hands were involved in responding to the two tasks in Experiment 3, while each hand was in charge of a task in Konstantinou et al. (2014; similar to Experiment 2). These differences may potentially lead to different result patterns between experiments.

## Experiment 4: Memory array of Zhang and Luck (2015) plus flanker task of Zhang and Luck (2015)

Experiment 4 re-examined the key findings of Zhang and Luck (2015) by largely using the setting in Zhang and Luck (2015). If the Zhang and Luck (2015) study was limited to the specific settings, then high visual WM load would lead to enhanced distractor processing relative to low visual WM load condition.

Additionally, in Experiments 1 and 3, there was potentially response interference between WM task and flanker task. Although Experiment 2 offered certain evidence implying that the response setting did not affect the result, the experimental settings were different between Experiments 1 and 2. A strict examination would compare the result under the same task setting while manipulating the way of responses. We achieved this in Experiment 4, by using both the response manner in Experiments 1 and 3 (i.e., two hands were involved in two tasks; Experiment 4a) and the response manner in Experiment 2 (i.e., each hand had a corresponding task; Experiment 4b).

## Method

A group of 20 (seven males; 20.60 ± 2.06 years old on average) participants took part in Experiment 4a, and another 18 (three males; 19.22 ± 0.73 years old on average) participants took part in Experiment 4b.

The memory task was the same as in Experiment 1 and the flanker task was the same as in Experiment 2 (see Fig. 6a). In Experiment 4a participants responded to both tasks in the same way as Experiment 1, while in Experiment 4b participants responded to both tasks in the same way as Experiment 2.

## Results

### Experiment 4a

For the WM task, the overall accuracy was 78% (*SD* = 8%) and 94% (*SD* = 4%) for the low- and high-load conditions, respectively. The main effect of WM-load (see Fig. 6b) reached significance, $F(1,19) = 144.24$, $p < .01$, $\eta_p^2 = .88$, $BF = 3.61 \times 10^{17}$, suggesting that the manipulation of WM load was effective. Neither the main effect of Flanker-congruency, $F(1,17) = .40$, $p = .53$, $\eta_p^2 = .02$, $BF = .27$, nor the WM-load × Flanker-congruency interaction, $F(1,17) = .57$, $p = .46$, $\eta_p^2 = .03$, $BF = .36$, was significant.

The ANOVA on the accuracy of flanker task (see Fig. 6c) revealed that neither the main effect of WM-load, $F(1, 19) = 2.39$, $p = .14$, $\eta_p^2 = .11$, $BF = 1.12$, nor the main effect of Flanker-congruency, $F(1, 19) < .01$, $p = .95$, $\eta_p^2 < .01$, $BF = .23$ was significant. The WM-load × Flanker-congruency interaction was not significant, $F(1, 19) = .01$, $p = .95$, $\eta_p^2 < .01$, $BF = .30$.

The ANOVA on the RT of flanker task (see Fig. 6d) revealed a significant main effect of WM-load, $F(1, 19) = 13.50$, $p < .01$, $\eta_p^2 = .42$, $BF = 2926.06$, suggesting that high WM load increased the RT of flanker task compared to the low-load condition. A significant main effect of Flanker-congruency was also revealed, $F(1, 20) = 34.14$, $p < .01$, $\eta_p^2 = .64$, $BF = 5024.05$, indicating that RTs were longer in the presence of incongruent as compared with

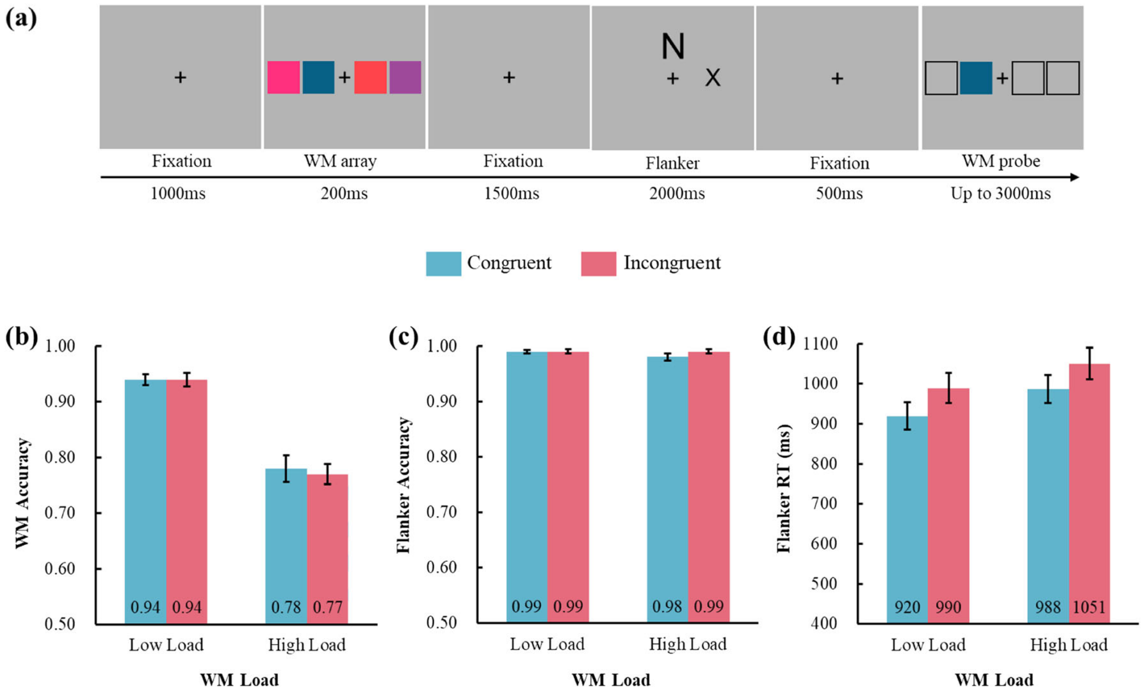

**Fig. 6** Procedure and results for Experiment 4a. (**a**) Procedure for Experiment 4. (**b**) Accuracy of the working-memory (WM) task. (**c**) Accuracy of the flanker task. (**d**) Reaction times (RTs) of the flanker task. Error bars show standard errors

congruent distractors. The WM-load × Flanker-congruency interaction was not significant, *F*(1, 18) = .24, *p* = .63, $\eta_p^2$ = .01, *BF* = .32, suggesting that the flanker effect was not affected by the WM load.

### Experiment 4b

For the WM task, the overall accuracy was 95% (*SD* = 3%) and 71% (*SD* = 12%) for the low- and high-load conditions, respectively. The main effect of WM-load (see Fig. 7a) reached significance, *F*(1,17) = 80.89, *p* < .01, $\eta_p^2$ = .83, *BF* = 1.86 × $10^{16}$, suggesting that the manipulation of WM load was effective. Neither the main effect of Flanker-congruency, *F*(1,17) = .10, *p* = .76, $\eta_p^2$ = .01, *BF* = .24, nor the WM-load × Flanker-congruency interaction, *F*(1,17) = .94, *p* = .35, $\eta_p^2$ = .05, *BF* = .43, was significant.

The ANOVA on the accuracy of flanker task (see Fig. 7b) revealed that neither the main effect of WM-load, *F*(1, 17) = .16, *p* = .70, $\eta_p^2$ = .01, *BF* = .26, nor the main effect of Flanker-congruency, *F*(1, 17) = 3.09, *p* = .10, $\eta_p^2$ = .15, *BF* = 1.45, was significant. The WM-load × Flanker-congruency interaction was not significant, *F*(1, 17) = .03, *p* = .86, $\eta_p^2$ < .01, *BF* = .31

The ANOVA on the RT of flanker task (see Fig. 7c) revealed a significant main effect of WM-load, *F*(1, 17) = 11.15, *p* < .01, $\eta_p^2$ = .40, *BF* = 330.53, suggesting that high WM load increased the RT of flanker task compared to the low-load condition. A significant main effect of Flanker-congruency was also revealed, *F*(1, 17) = 21.58, *p* < .01, $\eta_p^2$ = .56, *BF* = 118.03, indicating that RTs were longer in the presence of incongruent, as compared with congruent, distractors. The WM-load × Flanker-congruency interaction was not significant, *F*(1, 17) = .10, *p* = .76, $\eta_p^2$ = .01, *BF* = .32, suggesting that the flanker effect was not affected by the WM load.

### Discussion

By using largely the same setting as in Zhang and Luck (2015), we failed to re-establish the findings of Zhang and Luck (2015), which was in line with Experiments 1, 2, and 3. Moreover, we found a similar result pattern between Experiments 4a and 4b (although the RT in Experiments 4a was significantly longer than that in Experiment 4b, *p* < .05, which was largely due to the different response settings between Experiments 4a and 4b), further suggesting that response manners did not affect the key findings.

Meanwhile, it is noteworthy that there were at least two differences between Experiment 4 and Zhang and Luck (2015). First, the low-load condition was different. Participants memorized one color in the current experiment, while they had to retain two colors in Zhang and Luck (2015), which we believed should not affect the result pattern. Second, there was no feedback in the current Experiment 4, while Zhang and Luck (2015) displayed a 500-ms computer-generated beep for incorrect responses for both tasks.

## Experiment 5: Null effect was not due to low perceptual load of the flanker task

One alternative to explain the results of Experiments 1–4 was that because the perceptual load of the flanker task was way too low, our perceptual system could filter the distractor efficiently even though the visual WM task had already consumed a certain amount of resource. We tested this possibility by increasing the perceptual load of flanker task.

### Method

A group of 18 (four males; 19.61 ± 0.85 years old on average) participants took part in Experiment 5.

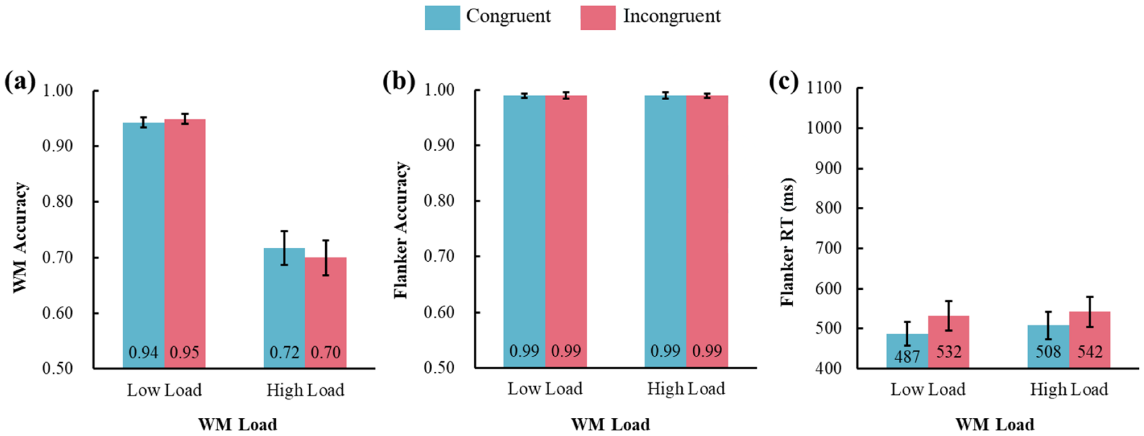

**Fig. 7** Results for Experiment 4b. (**a**) Accuracy of the working-memory (WM) task. (**b**) Accuracy of the flanker task. (**c**) Reaction times (RTs) of the flanker task. Error bars show standard errors

This experiment was the same as Experiment 2 except for the setting of flanker task (see Fig. 8a). Specifically, two random small black dots were replaced by two letters, which were selected randomly from “J,” “K,” “R,” “S,” and “V,” with the same parameters as the target letter. In this case, the perceptual load of the flanker task was increased.

### Results

For the WM task, the overall accuracy was 94% (*SD* = 4%) and 73% (*SD* = 10%) for the low- and high-load conditions, respectively. The main effect of WM-load (see Fig. 8b) reached significance, $F(1,17) = 110.22$, $p < .01$, $\eta_p^2 = .77$, $BF = 1.01 \times 10^{26}$, suggesting that the manipulation of WM load was effective. The main effect of Flanker-congruency, $F(1,17) = 4.71$, $p = .04$, $\eta_p^2 = .13$, $BF = .44$, also reached significance. However, the WM-load × Flanker-congruency interaction, $F(1,17) = .94$, $p = .34$, $\eta_p^2 = .03$, $BF = .40$, was not significant.

The ANOVA on the accuracy of flanker task (see Fig. 8c) revealed that the main effect of WM-load, $F(1, 17) = 7.13$, $p = .01$, $\eta_p^2 = .18$, $BF = 2.07$, reached significance. However, the main effect of Flanker-congruency, $F(1, 17) = .65$, $p = .43$, $\eta_p^2 = .02$, $BF = .29$, was not significant. The WM-load × Flanker-congruency interaction were also not significant, $F(1, 17) = .30$, $p = 0.59$, $\eta_p^2 = .01$, $BF = .27$.

The ANOVA on the RT of flanker task (see Fig. 8d) revealed a significant main effect of WM-load, $F(1, 17) = 28.69$, $p < .01$, $\eta_p^2 = .47$, $BF = 2.47 \times 10^6$, suggesting that high WM load increased the RT of flanker task compared to the low-load condition. A significant main effect of Flanker-congruency was also revealed, $F(1, 17) = 11.97$, $p < .01$, $\eta_p^2 = .27$, $BF = 76.10$, indicating that RT was longer in the presence of incongruent, as compared with congruent, distractors. However, the WM-load × Flanker-congruency interaction was not significant, $F(1, 17) = 2.70$, $p = .11$, $\eta_p^2 = .08$, $BF = .39$, suggesting that the flanker effect was not affected by the WM load.

### Discussion

By increasing the perceptual load of the flanker task, Experiment 5 found that the flanker effect was still not modulated by the visual WM load. This result was in line with Experiments 1–4, suggesting that the null effects in previous experiments were not due to the low perceptual load of the flanker task.

## Experiment 6: Null effect was not due to stimuli setting of flanker task or ineffective high working-memory load

Facing the null effects of WM load on the modulation of distractor processing, two extra alternatives had to be addressed. First, the participants may treat the English letters in

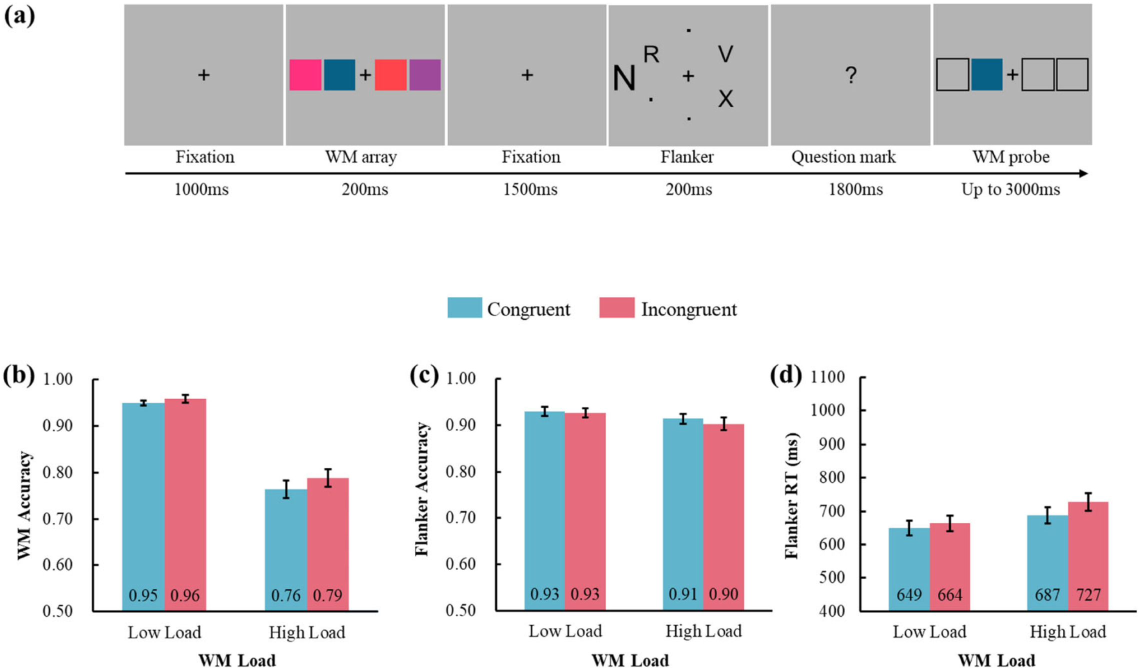

**Fig. 8** Procedure and results for Experiment 5. (**a**) Procedure for Experiment 5. (**b**) Accuracy of the working-memory (WM) task. (**c**) Accuracy of the flanker task. (**d**) Reaction times (RTs) of the flanker task. Error bars show standard errors

the flanker stimuli differently between the current study and previous studies. Participants in most of the previous studies were native English speakers and very familiar with the English letters used in Experiments 1–5. However, the participants in the current study were Chinese, with English as their second language. This might lead to different processing for English letters. Second, although Experiments 1–5 consistently demonstrated a strong main effect of WM load, it might be possible that the WM load was not high enough to modulate the distractor processing. To address those alternatives, we replaced the English letters with Chinese characters and required the participants to memorize six colors in the high WM load condition.

## Method

A group of 18 (five males; 19.83 ± 2.31 years old on average) participants took part in the experiment.

For the WM task, one (low load) or six (high load) colored squares were chosen randomly from ten distinct colors: black (0, 0, 0; RGB), blue (0, 0, 255), cyan (0, 255, 255), green (0, 255, 0), magenta (255, 0, 255), red (255, 0, 0), white (255, 255, 255), yellow (255, 255, 0), pink (255, 192, 203), and purple (128, 0, 128).

For the flanker task, two Chinese characters "是" and "有" replaced the previous two English letters in Experiments 1–5. The target character (0.6° × 0.6°) was randomly selected from one of them, and the distractor character (0.9° × 0.9°) was equally likely to be congruent or incongruent with the target character. The other aspects were the same as Experiment 3 (see Fig. 9a).

## Results

For the WM task, the overall accuracy was 97% (*SD* = 3%) and 68% (*SD* = 9%) for the low- and high-load conditions, respectively. The main effect of WM-load (see Fig. 9b) reached significance, $F(1,17) = 295.09$, $p < .01$, $\eta_p^2 = .95$, $BF = 1.58 \times 10^{28}$, suggesting that the manipulation of WM load was effective. Neither the main effect of Flanker-congruency, $F(1,17) = 0.56$, $p = .46$, $\eta_p^2 = .03$, $BF = .28$, nor the WM-load × Flanker-congruency interaction, $F(1,17) = .39$, $p = .54$, $\eta_p^2 = .02$, $BF = .38$, was significant.

The ANOVA on the accuracy of flanker task (see Fig. 9c) revealed that neither the main effect of WM-load, $F(1, 17) = .01$, $p = .92$, $\eta_p^2 < .01$, $BF = .25$, nor the main effect of Flanker-congruency, $F(1, 17) = .11$, $p = .74$, $\eta_p^2 = .01$, $BF = .26$, was significant. Furthermore, the WM-load × Flanker-congruency interaction was not significant, $F(1, 17) < .01$, $p = .98$, $\eta_p^2 < .01$, $BF = .29$.

The ANOVA on the RT of flanker task (see Fig. 9d) revealed a significant main effect of WM-load, $F(1, 17) = 10.62$, $p = .01$, $\eta_p^2 = .39$, $BF = 13.58$, suggesting that high WM load increased the RT of flanker task compared to the low-load condition. A significant main effect of Flanker-congruency

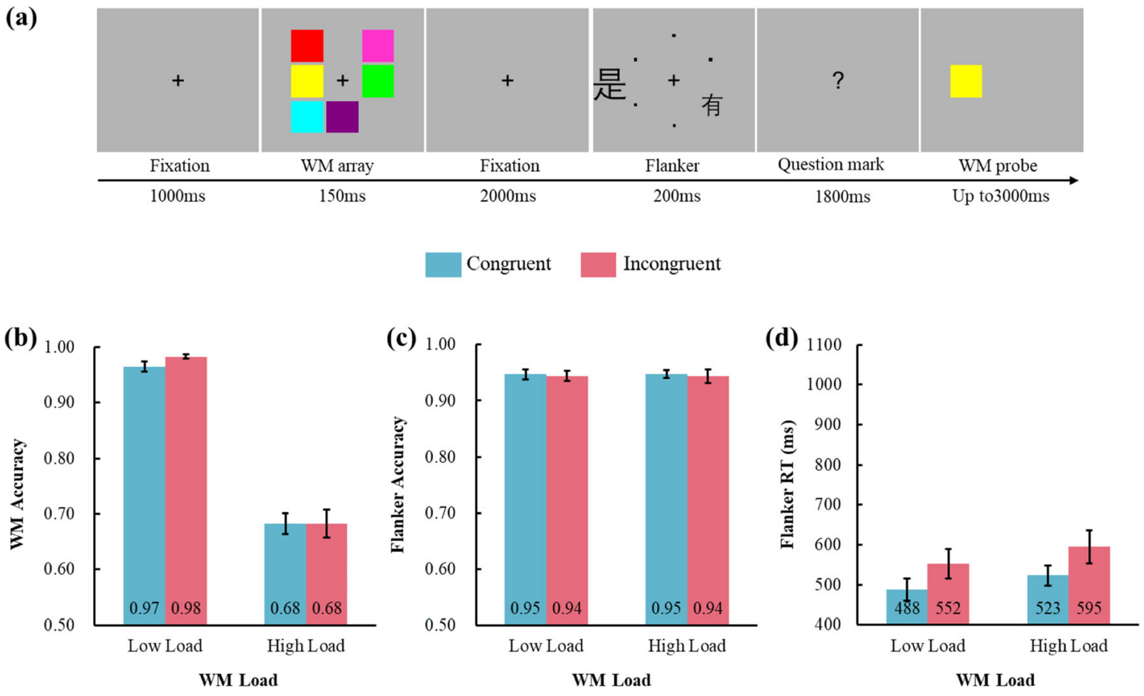

**Fig. 9** Procedure and results for Experiment 6. (**a**) Procedure for Experiment 6. (**b**) Accuracy of the working-memory (WM) task. (**c**) Accuracy of the flanker task. (**d**) Reaction times (RTs) of the flanker task. Error bars show standard errors

was revealed, $F(1, 17) = 18.63$, $p < .01$, $\eta_p^2 = .52$, $BF = 13338.55$, indicating that RT was longer in the presence of incongruent, as compared with congruent, distractors. However, the WM-load × Flanker-congruency interaction was not significant, $F(1, 17) = .24$, $p = .63$, $\eta_p^2 = .01$, $BF = .42$, suggesting that the flanker effect was not affected by the WM load.

### Discussion

In Experiment 6, we used a Chinese character flanker task and required the participants to memorize six colors in the high WM load condition. Again, we found that the flanker effect was not modulated by the visual WM load. Therefore, the absence of WM load modulation on distractor processing in Experiments 1–5 was not due to the stimuli setting of the flanker task or an ineffective high WM load.

## Experiment 7: Color memory array plus color flanker task

So far, the observed null effect in Experiments 1–6 were observed under circumstances in which the stimuli in WM tasks (colored patches) and flanker tasks (letters/Chinese characters) were from different domains. These findings were in line with the prediction of Lin and Yeh (2014), which claimed that WM load modulated the distractor processing only when both the WM and flanker tasks processed the same-domain information. Therefore, the failure to observe the modulation of WM-load on distractor processing in Experiments 1–6 may be due to the lack of content overlap between the two tested tasks. We tested this alternative in Experiment 7 by replacing the letter flanker task with a color flanker task, such that both the WM task and flanker task processed the same type of information. If the domain-specific hypothesis was correct, then we would observe a significant WM-load modulation on the distractor processing.

Additionally, Roper and Vecera (2013) demonstrated that the exposure time of the flanker task also modulated the flanker effect. Particularly, while the flanker effect was significantly reduced or vanished in the high perceptual-load condition when the flanker task was displayed in brief exposure time (e.g., 100 ms), there was a significant and un-reduced flanker effect in the high perceptual-load condition if the flanker task had enough encoding time (e.g., the flanker task was response-terminated). The absence of WM-load modulation on distractor processing may be rooted in the relatively long encoding time of the flanker task. Indeed, the exposure times in the current study were all longer than 100 ms. To test whether the encoding time of the flanker task modulates the distractor processing, in Experiment 6 we also systematically manipulated the exposure time of the flanker task. Particularly, in different groups, the flanker task could be displayed for 200 ms (the same as Experiments 2 and 3), 100 ms, or 34 ms.

### Method

A group of 54 (15 males; 19.96 ± 1.43 years old on average) participants took part in the experiment. They were randomly divided into three groups. Eighteen (five males; 19.78 ± 1.31 years old on average) participants completed the flanker task with a 200-ms duration, 18 (six males; 20.06 ± 1.43 years old on average) participants completed the flanker task with a 100-ms duration, and 18 (four males; 20.06 ± 1.59 years old on average) participants completed the flanker task with a 34-ms duration.

We replaced the letter flanker task with a color flanker task (Fig. 10a). Particularly, the two letters “X” and “N” were replaced by a white oval and a black oval, respectively; the ovals were the same size as the letters. Participants were required to report whether the color of the target oval was black or white. To reduce the interference from other colored stimuli, the fixations, small dots and question marks in the experiment were all set as dark gray (128, 128, 128). Moreover, the black square and the white square in the memory array were replaced as a pink (255, 192, 203) square and a purple (128, 0, 128) square. In different groups, the flanker task could be displayed for 200 ms, 100 ms, or 34 ms. The other aspects were the same as Experiment 2 (see Fig. 10a).

We adopted a 2 (WM-load: low vs. high) × 2 (Flanker-congruency: congruent vs. incongruent) × 3 (Duration: 200 ms, 100 ms, and 34 ms) mixed design, by taking WM-load and Flanker-congruency as within-subjects factors, and duration as a between-subjects factor. Each participant completed 192 trials under one exposure time of memory array. A three-way mixed ANOVA was conducted on the accuracy of the WM task and the accuracy and the RT of the flanker task, separately.

### Results

For the WM task, the overall accuracy was 95% ($SD = 4\%$) and 78% ($SD = 9\%$) for the low- and high-load conditions, respectively. The main effect of WM-load (see Fig. 10b) reached significance, $F(1,51) = 272.16$, $p < .01$, $\eta_p^2 = .84$, $BF = 2.79 \times 10^{47}$, suggesting that the manipulation of WM load was effective. Neither the main effect of Flanker-congruency, $F(1,51) = .08$, $p = .78$, $\eta_p^2 < .01$, $BF = .15$, nor the main effect of Duration, $F(2,51) = 1.24$, $p = .30$, $\eta_p^2 = .05$, $BF = .26$, was significant. All other interactions were not significant, $F$s $< 3$, $\eta_p^2 < .10$, $BF < 2$.

The ANOVA on the accuracy of flanker task (see Fig. 10c) revealed that the main effect of WM-load was significant, $F(1, 51) = 12.07$, $p < .01$, $\eta_p^2 = .19$, $BF = 173.42$, suggesting that

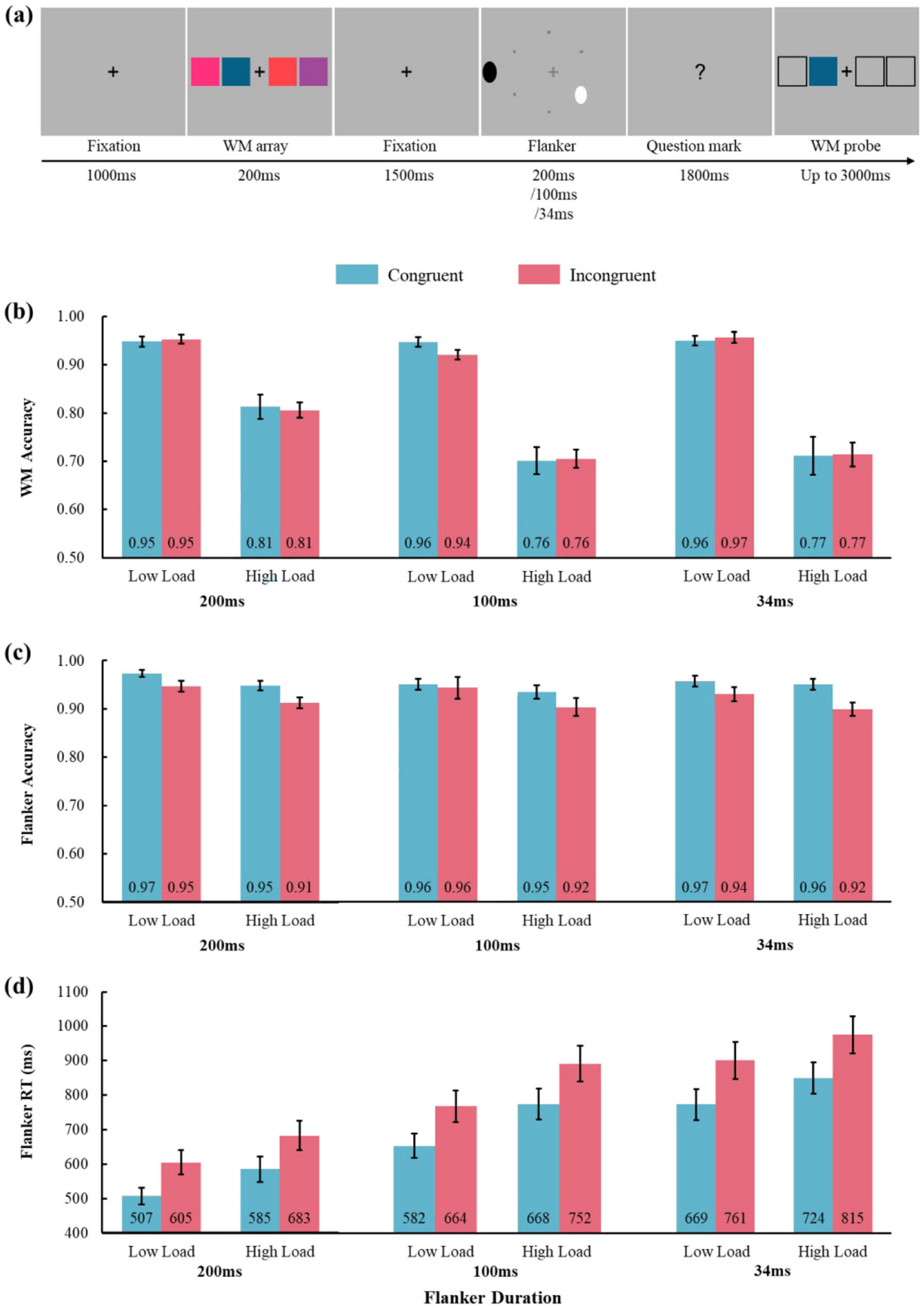

**Fig. 10** Procedure and results for Experiment 7. (**a**) Procedure for Experiment 7. (**b**) Accuracy of the working-memory (WM) task. (**c**) Accuracy of the flanker task. (**d**) Reaction times (RTs) of the flanker task. Error bars show standard errors

the accuracy under the low-load condition was significantly higher than that under the high-load condition. The main effect of Flanker-congruency was also significant, $F(1, 51) = 20.07$, $p < .01$, $\eta_p^2 = .28$, $BF = 2340.83$, indicating that the accuracy under the congruent condition was significantly higher than that under the incongruent condition. The main effect of Duration was not significant, $F(2, 51) = .02$, $p = .98$, $\eta_p^2 < .01$, $BF = .10$, suggesting that the exposure time of flanker task did not affect participants' response accuracy. Critically, neither the WM-load × Flanker-congruency interaction, $F(1, 51) = 2.34$, $p = .13$, $\eta_p^2 = .04$, $BF = .45$, nor the WM-load × Flanker-congruency× Duration interaction, $F(2, 51) = .10$, $p = .91$, $\eta_p^2 < .01$, $BF = .15$, was significant, suggesting that the Congruency effect was not modulated by WM-load or Duration of flanker task. Additionally, neither the WM-load × Duration, $F(2, 51) = .46$, $p = .63$, $\eta_p^2 = .02$, $BF = .14$, nor the Duration × Flanker-congruency interaction, $F(2, 51) = .74$, $p = .48$, $\eta_p^2 = .03$, $BF = .16$, was significant.

The ANOVA on the RT of flanker task (see Fig. 10d) revealed that the main effect of WM-load was significant, $F(1, 51) = 40.05$, $p < .01$, $\eta_p^2 = .44$, $BF = 1.92 \times 10^{10}$, suggesting that the RT under the low-load condition was significantly quicker than that under the high-load condition. The main effect of Flanker-congruency was significant, $F(1, 51) = 84.94$, $p < .01$, $\eta_p^2 = .63$, $BF = 9.86 \times 10^{14}$, indicating that the RT under the congruent condition was significantly quicker than that under the incongruent condition. The main effect of duration reached significance, $F(2, 51) = 5.42$, $p = .01$, $\eta_p^2 = .18$, $BF = 6.47$, implying that participants' RT became quicker as the exposure time of flanker task increased. However, neither the WM-load × Flanker-congruency interaction, $F(1, 51) < .01$, $p = .99$, $\eta_p^2 < .01$, $BF = .20$, nor the WM-load × Flanker-congruency × Duration interaction, $F(2, 51) = .01$, $p = .99$, $\eta_p^2 < .01$, $BF = .13$, was significant, suggesting that the Congruency effect was not modulated by WM-load or Duration of flanker task. Similarly, neither the WM-load × Duration, $F(2, 51) = .70$, $p = .50$, $\eta_p^2 =.03$, $BF = .20$, nor the Duration × Flanker-congruency interaction, $F(2, 51) = .21$, $p = .81$, $\eta_p^2 = .01$, $BF = .10$, was significant.

### Discussion

In Experiment 7, we used a color flanker task to form a content overlap between the WM task and the flanker task. However, in contrast to the prediction of domain-specific hypothesis, we found that WM-load did not affect distractor processing, regardless of the exposure time of memory array. This finding was in line with Experiments 1–6, adding new evidence supporting the view that visual WM-load did not affect distractor processing. It should be noted that the current finding was not contrary to Roper and Vecera (2013). Particularly, Roper and Vecera (2013) used a typical perceptual-load task instead of the current dual-task setting, and the long exposure time they used was determined by the response (more than 500 ms).

On the other hand, because only black and white colors were used in the color flanker task, it is possible that the flanker colors were always achromatic (i.e., luminance) but the WM colors were chromatic, leading to a failed setting in testing the domain-specific hypothesis.[7] Moreover, there was a backward mask after the memory array in Lin and Yeh (2014), which was absent in the current Experiments 1–7. To address these two issues, we ran Experiment 8, using the setting of Lin and Yeh (2014).

## Experiment 8: Shape memory array plus shape flanker task (Lin & Yeh, 2014)

In line with Experiment 3a of Lin and Yeh (2014), nonverbalized shapes were used as the stimuli in both the WM task and flanker task in Experiment 8, and the memory array was backward masked by an asterisk matrix.

### Method

#### Participants

A group of 33 (11 males; 19.83 ± 1.30 years old on average) participants took part in the experiment. The other aspects were the same as in Experiment 1.

#### Stimuli

The stimuli were from Lin and Yeh (2014). For the WM task, one (low load) or four (high load) non-verbalized shapes (1.08° × 1.08°) were randomly selected from nine shapes (see Fig. 11a). The four shapes were presented equally spaced in a horizontal row that subtended 4.45° from edge to edge in the high-load condition, whereas one stimulus was displayed at the screen center in the low-load condition. For the flanker task, the target shape (0.62° × 0.62°) was equally likely to be one of the two nonverbalized objects (Fig. 11b), and the distractor object (0.77° × 0.77°) was equally likely to be congruent or incongruent with the target shape.

In line with Lin and Yeh (2014), the target shape and five black dots were presented on a circle (2.165° in radius), containing six evenly distributed locations. A distractor appeared 3.29° to the left or the right of the fixation.

#### Procedure and design

Figure 12a illustrates the procedure of Experiment 8. Each trial began with a 500-ms fixation to inform participants of

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[7] We thanked an anonymous reviewer for pointing out this possibility.

**Fig. 11** Nonverbalized shapes used in the working-memory (WM) task (**a**) and the flanker task (**b**) of Experiment 8

the start of a trial, immediately followed by a 500-ms (low load) or 1,500-ms (high load) memory array, which was backward masked by a 1,250-ms asterisk matrix (the same number that was equal to the number of the memory array; each asterisk had a visual angle of 1.08° × 1.08°). After another 500-ms fixation, a flanker task appeared on the screen for 100 ms and was then replaced by a question mark. Participants had to respond to the target shape as quickly and accurately as possible within 2,000 ms, by pressing a corresponding key (“Z” for the left hand, “/” for the right hand). Finally, a memory probe appeared at the screen center. Participants were required to judge whether the probe had appeared in the memory array within 3,000 ms, by pressing button “.” for “yes” (50%) in the right hand and “X” for “no” in the left hand. A sticker with labeling was glued on each response button. Those response settings were the same as Lin and Yeh (2014). In the visual WM task, responses were not speeded, and no response feedback was given. The inter-trial blank interval was randomly selected from 1,000 to 1,200 ms.

## Results

For the WM task, the overall accuracy was 92% (*SD* = 7%) and 79% (*SD* = 11%) for the low- and high-load conditions, respectively. The main effect of WM-load (see Fig. 12b) reached significance, $F(1,32) = 96.52$, $p < .01$, $\eta_p^2 = .73$, $BF = 7.94 \times 10^{20}$, suggesting that the manipulation of WM load was effective. The main effect of Flanker-congruency was significant, $F(1,32) = 6.69$, $p = .01$, $\eta_p^2 = .16$, $BF = .68$. However, the WM-load × Flanker-congruency interaction did not reach significance, $F(1,32) = 2.68$, $p = .11$, $\eta_p^2 = .07$, $BF = .53$.

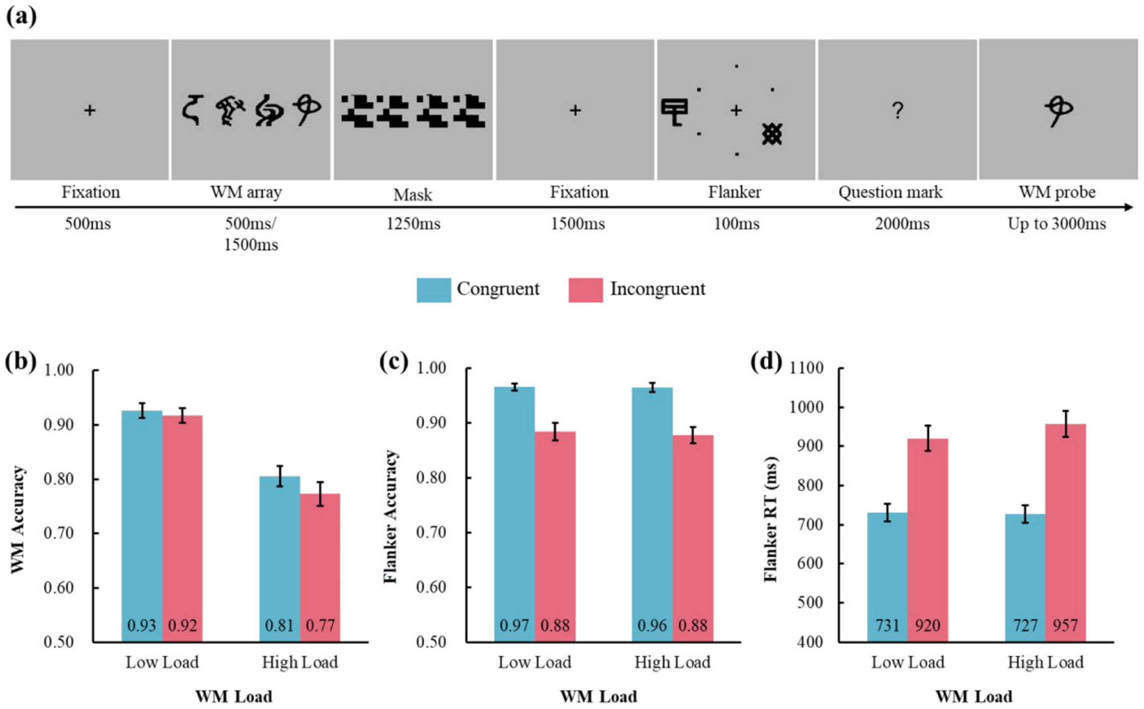

**Fig. 12** Procedure and results for Experiment 8. (**a**) Procedure for Experiment 8. (**b**) Accuracy of the working-memory (WM) task. (**c**) Accuracy of the flanker task. (**d**) Reaction times (RTs) of the flanker task. Error bars show standard errors (Following Lin and Yeh (2014), we also analyzed the data in terms of Median and reached the same results in both the current experiment as well as other experiments reported here.)

The ANOVA on the accuracy of flanker task (see Fig. 12c) revealed that the main effect of WM-load was not significant, $F(1,32) = .14$, $p = .71$, $\eta_p^2 < .01$, $BF = .18$. The main effect of Flanker-congruency was significant, $F(1, 32) = 25.20$, $p < .01$, $\eta_p^2 = .42$, $BF = 1.06 \times 10^{10}$. The WM-load × Flanker-congruency interaction was not significant, $F(1, 32) = .35$, $p = .56$, $\eta_p^2 = .01$, $BF = .26$.

The ANOVA on the RT of flanker task (see Fig. 12d) revealed a non-significant main effect of WM-load, $F(1, 32) = 1.85$, $p = .18$, $\eta_p^2 = .05$, $BF = .26$. A significant main effect of Flanker-congruency was revealed, $F(1, 32) = 102.69$, $p < .01$, $\eta_p^2 = .75$, $BF = 1.46 \times 10^{24}$, indicating that RT was longer in the presence of incongruent as compared with congruent distractors. Critically, the WM-load × Flanker-congruency interaction was significant, $F(1, 32) = 6.23$, $p = .02$, $\eta_p^2 = .15$, $BF = .54$, suggesting that the flanker effect was larger in the high-load condition (230 ms) than that in the low-load condition (189 ms).

## Discussion

In Experiment 8, we replicated the Experiment 3a of Lin and Yeh (2014) showing that the visual WM load increased the flanker effect. Moreover, the effect size of the current study (.15) was comparable to that (.18) in Lin and Yeh (2014). However, it is of note that the memory array in Experiment 8 and Lin and Yeh (2014) had a wider spatial distribution in the high-load condition (4.45°) than that in the low-load condition (1.08°). Moreover, the spatial distribution of the high-load condition was even wider than the spatial distribution of flanker task (4.33°). Therefore, it is possible that the increased flanker effect in high-load conditions was contaminated by the unbalanced spatial distribution of memory array. To test this alternative, we conducted Experiment 9 by balancing the spatial distribution of the memory array.

# Experiment 9: Increased flanker effect vanished after balancing the spatial distribution of memory array

In Experiment 9 we presented the same number of stimuli in both load conditions to control the spatial distribution of memory array: Four distinct shapes in the high-load condition, and four identical shapes in the low-load condition.

## Method

A group of 22 (four males; 20.75 ± 1.65 years old on average) participants took part in the experiment. In the low-load condition (see Fig. 13a), we represented four identical shapes. In the high-load condition (see Fig. 13b), we placed four nonverbalized shapes in a 2 × 2 matrix (2.20° × 2.20°) instead of a line, such that the memory array was displayed within the circle (2.165° in radius) of the flanker task. Figure 14a illustrates the procedure of Experiment 9. The other aspects were the same as Experiment 8.

## Results

For the WM task, the overall accuracy was 95% ($SD = 3\%$) and 80% ($SD = 9\%$) for the low- and high-load conditions, respectively. The main effect of WM-load (see Fig. 14b) reached significance, $F(1,21) = 91.46$, $p < .01$, $\eta_p^2 = .81$, $BF = 2.68 \times 10^{17}$, suggesting that the manipulation of WM load was effective. Neither the main effect of Flanker-congruency, $F(1,21) = .01$, $p = .94$, $\eta_p^2 < .01$, $BF = .23$, nor the WM-load × Flanker-congruency interaction, $F(1,21) = .20$, $p = .66$, $\eta_p^2 = .01$, $BF = .31$, reached significance.

The ANOVA on the accuracy of flanker task (see Fig. 14c) revealed that the main effect of WM-load was not significant, $F(1,21) = .24$, $p = .63$, $\eta_p^2 = .01$, $BF = .22$. The main effect of Flanker-congruency was significant, $F(1, 21) = 12.01$, $p < .01$, $\eta_p^2 = .36$, $BF = 1540.59$. However, the WM-load × Flanker-congruency interaction was not significant, $F(1, 21) = .23$, $p = .63$, $\eta_p^2 = .01$, $BF = .42$.

The ANOVA on the RT of flanker task (see Fig. 14d) revealed a non-significant main effect of WM-load, $F(1, 21) = .07$, $p = .79$, $\eta_p^2 < .01$, $BF = .21$. A significant main effect of Flanker-congruency was revealed, $F(1, 21) = 57.57$, $p < .01$, $\eta_p^2 = .73$, $BF = 3.40 \times 10^{13}$, indicating that RT was longer in the presence of incongruent as compared with congruent distractors. However, the WM-load × Flanker-congruency interaction was not significant, $F(1, 17) = .02$, $p = .89$, $\eta_p^2 < .01$, $BF = .33$, suggesting that the flanker effect was not affected by the WM load.

## Discussion

After balancing the spatial distribution of memory array between low- and high-load conditions, we did not reveal any effect of WM load on the flanker effect. This finding implies that the results of Experiment 8, as well as Lin and Yeh (2014), may be contaminated by the unbalanced spatial distribution of memory array. Therefore, the results of Experiment 9 were in line with Experiment 7, suggesting that visual WM capacity load does not modulate the distractor processing, even when the stimuli in both the WM and flanker tasks were from the same domain.

## Mini meta-analysis

So far in all eight out of nine experiments (12 sub-experiments, 246 participants) we found that visual WM capacity load did not modulate the distractor processing. Since most of them are null effects, drawing conclusions should

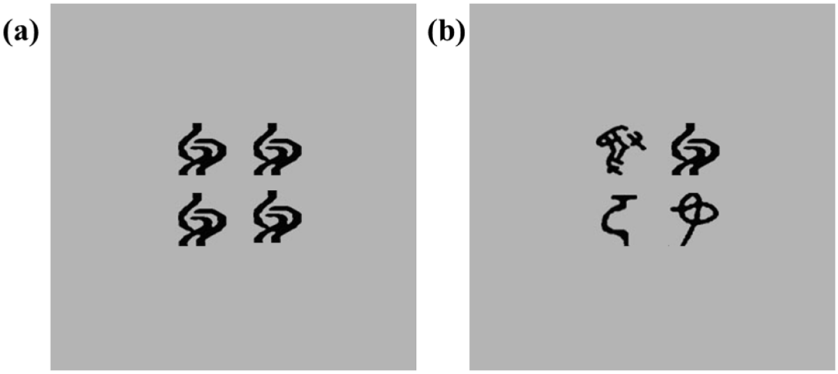

**Fig. 13** (**a**) Low- and (**b**) high-load conditions in Experiment 9

only be cautious. Here we conducted a mini meta-analysis, by pooling all the data of the nine experiments together and calculating the effect size and Bayes factor. Specifically, we conducted a three-way mixed-measures ANOVA on performance of both the WM task and the flanker task, by taking WM-load (low, high) and Flanker-congruency (congruent, incongruent) as the within-subjects factors, and Experiment (Experiment 1, Experiment 2, Experiment 3, Experiment 4a, Experiment 4b, Experiment 5, Experiment 6, Experiment 7, Experiment 8, and Experiment 9) as the between-subjects factor.

For the WM task (Fig. 15a), the overall accuracy was 95% (*SD* = 4%) and 77% (*SD* = 9%) for the low- and high-load conditions, respectively. The main effect of WM-load reached significance, $F(1, 245) = 1096.98$, $p < .01$, $\eta_p{}^2 = .82$, $BF = 2.94 \times 10^{204}$, suggesting that the manipulation of WM load was effective. The main effect of Experiment was also significant, $F(11, 245) = 2.10$, $p = .02$, $\eta_p{}^2 = .09$, $BF = 0.62$. The main effect of Flanker-congruency was not significant, $F(1, 245) = 1.20$, $p = .27$, $\eta_p{}^2 = .01$, $BF = .08$. The Load × Experiment interaction was significant, $F(11, 245) = 5.47$, $p < .01$, $\eta_p{}^2 = .20$, $BF = 2.29 \times 10^{14}$. Critically, The WM-load × Flanker-congruency interaction was not significant, $F(1, 245) = .82$, $p = .37$, $\eta_p{}^2 < .01$, $BF = .13$. The other interactions did not reach significance.

The ANOVA on the accuracy of flanker task (Fig. 15b) revealed that the main effects of Flanker-congruency, *F*(1,

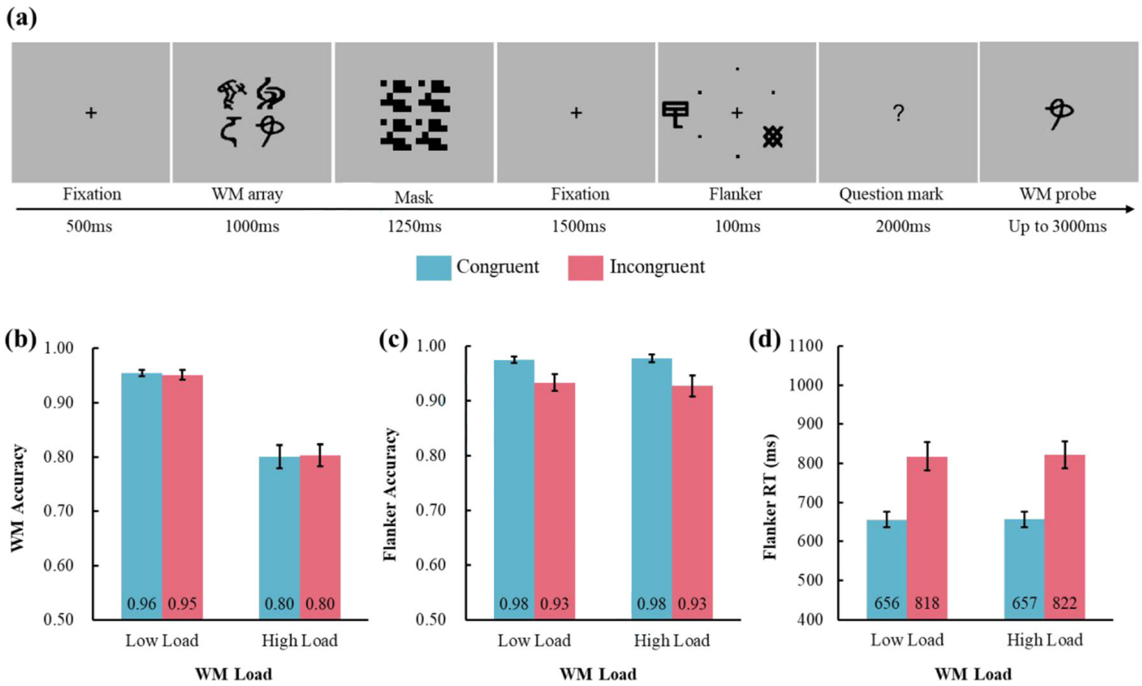

**Fig. 14** Procedure and results for Experiment 9. (**a**) Procedure for Experiment 9. (**b**) Accuracy of the working-memory (WM) task. (**c**) Accuracy of the flanker task. (**d**) Reaction times (RTs) of the flanker task. Error bars show standard errors

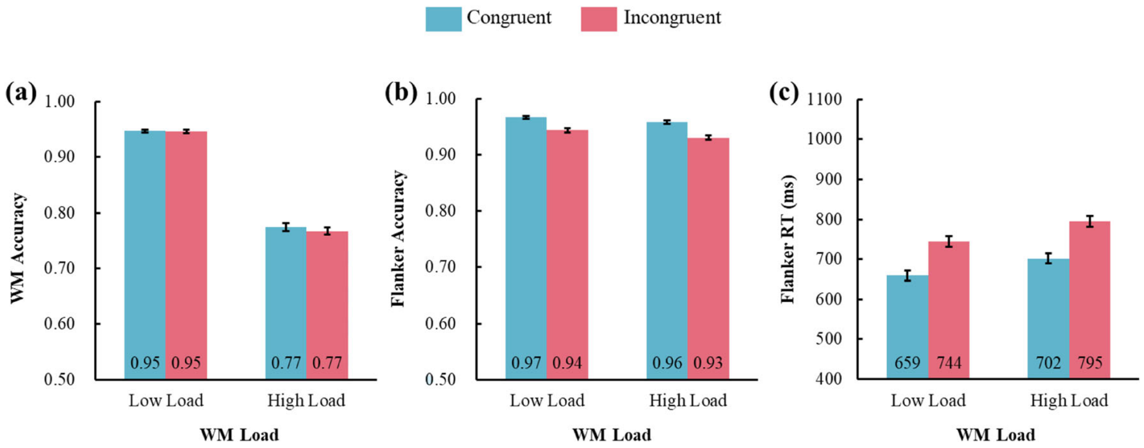

**Fig. 15** Results for averaging all the data across Experiments 1–9. (**a**) Accuracy of the working-memory (WM) task. (**b**) Accuracy of the flanker task. (**c**) Reaction times (RTs) of flanker task. Error bars show standard errors

245) = 57.47, $p < .01$, $\eta_p^2 = .19$, $BF = 2.62 \times 10^{17}$, WM-load, $F(1, 234) = 17.53$, $p < .01$, $\eta_p^2 = .07$, $BF = 241.44$, and Experiment, $F(11, 245) = 10.32$, $p < .01$, $\eta_p^2 = .32$, $BF = 6.79 \times 10^{12}$, were significant. The Flanker-congruency × Experiment interaction was also significant, $F(11, 245) = 7.32$, $p < .01$, $\eta_p^2 = .25$, $BF = 9.44 \times 10^{14}$. However, the WM-load × Flanker-congruency interaction was not significant, $F(1, 245) = 1.57$, $p = .21$, $\eta_p^2 = .06$, $BF = .17$. The other interactions were not significant.

The ANOVA on the RT of flanker task (Fig. 15c) revealed that the main effects of WM-load, $F(1, 245) = 119.70$, $p < .01$, $\eta_p^2 = .33$, $BF = 3.20 \times 10^{25}$, Flanker-congruency, $F(1, 245) = 308.24$, $p < .01$, $\eta_p^2 = .56$, $BF = 1.64 \times 10^{68}$, and Experiment, $F(11, 245) = 30.48$, $p < .01$, $\eta_p^2 = .58$, $BF = 2.36 \times 10^{36}$, were significant. The WM-load × Experiment interaction, $F(11, 245) = 2.954$, $p < .01$, $\eta_p^2 = .12$, $BF = 272.868$, and the Flanker-congruency × Experiment interaction, $F(1, 245) = 13.61$, $p < .01$, $\eta_p^2 = .38$, $BF = 1.93 \times 10^{32}$, were also significant. However, the WM-load × Flanker-congruency interaction, $F(1, 245) = 1.07$, $p = .30$, $\eta_p^2 < .01$, $BF = .14$, did not reached significance. The other interactions failed to reach significance.

The results reported above suggest that although the WM load was manipulated successfully ($\eta_p^2 = .82$, $BF = 2.94 \times 10^{204}$), it did not modulate the flanker effect in neither accuracy ($\eta_p^2 = .06$, $BF = .17$) nor RT ($\eta_p^2 < .01$, $BF = .14$). In light of the low effect sizes and below 1/3 BF values, we argued that visual WM capacity load did not modulate the distractor processing.

## General discussion

Elucidating factors affecting selective attention is critical to uncover the mechanism of selective attention. Although it has been well accepted that WM exerts a considerable impact over selective attention, how visual WM load affects selective attention remains largely unclear. The current study focused on a discrepancy in this line: The role of visual WM capacity load on distractor processing. There were three distinct views regarding this critical issue: (1) the perceptual-load hypothesis suggests that visual WM capacity load serves as a type of perceptual load, (2) the resolution hypothesis considers visual WM capacity load as a type of central executive load, and (3) the domain-specific hypothesis claims that visual WM capacity load serves as a type of central executive load when the WM content and the information in perception are from the same domain.

We examined this question in five steps. We first attempted to reconcile the contradictory results between studies by switching the parameters of the memory array used in two previous studies (i.e., Zhang & Luck, 2015, and Konstantinou et al., 2014; Experiments 1 and 2); however, we failed to find any modulation of the visual WM capacity load on the flanker effect. We then attempted to re-establish the findings of Zhang and Luck (2015) and Konstantinou et al. (2014) (Experiments 3 and 4) by using largely the same set of memory array and flanker task, and we obtained similar results to those revealed in Experiments 1 and 2. In the third step, we tested three alternatives in two experiments. One alternative was that the perceptual load of flanker task was too low to be affected by the visual WM capacity load. Accordingly, we increased the perceptual load of the letter flanker task (Experiment 5). However, the visual WM capacity load still did not modulate the distractor processing. The second and third alternatives were that Chinese participants processed the English letters differently from native English speakers, and the high WM load condition was not sufficiently high. We examined these alternatives by using a Chinese character-based flanker task and requiring participants to memorize six colors in the high WM load condition (Experiment 6). We still failed to find a modulation effect of visual WM capacity load. We noticed that all the findings of Experiments 1–6 were congruent with the domain-specific hypothesis (Yeh & Lin, 2014) since the WM content and the information processing in the flanker task were from different domains. To testify the domain-specific hypothesis, in the fourth step we tested the domain-specific hypothesis by making both the WM task and the flanker task use colors (Experiment 7) or non-verbalized shapes (Experiments 8 and 9) as the stimuli of interest. Experiment 7 also tested an alternative that the encoding time of the flanker task was too long such that the flanker could be processed as that in the low perceptual load condition. While Experiment 8 replicated the findings of Lin and Yeh (2014), Experiments 7 and 9 both consistently found a non-significant modulation of the visual WM capacity load when the spatial distribution of memory array was well controlled. In the last step, we conducted a meta-analysis by pooling all the data of the current study together. We showed that the effect size of the visual WM capacity load was very low and the BF value was in favor of the null hypothesis, providing extra evidence supporting the absence of modulation of visual WM capacity load on distractor processing.

Because the current study mainly revealed a set of null effects (except for Experiment 8), there may be other explanations for the inconsistent results between the previous studies. Currently, we cannot give any exact reason(s) leading to the discrepancy. However, according to the findings across nine experiments reported here, we suggest that the visual WM capacity load does not affect the distractor processing. It is worth noting that if we made a rough estimation of the flanker effect by pooling all the previous studies adopting the letter flanker task, we would have reached a similar conclusion to that of the current study. That said, we had to admit that although we attempted to use the same parameters as the previous studies in the current Experiments 3 and 4, there were certain parameter differences between the current study and previous studies that had been listed in the discussion part of each experiment. These parameter differences may lead to different patterns between studies (e.g., Luck & Vogel, 1997; Wheeler & Treisman, 2002). It is worth noting that there was a common difference between the current study and previous studies: All previous studies provided feedback for incorrect responses (a 500-ms computer beep in Zhang & Luck, 2014; an auditory beep in Konstantinou et al., 2014; a 500-ms auditory tone in Lin & Yeh, 2014). However, we consider the feedback issue could not explain the observed discrepancy. Particularly, we replicated the finding of Lin and Yeh (2014) without any feedback in Experiment 8. Moreover, a recent study (Lee & Yi, 2018) also failed to replicate the key finding of Konstantinou et al. (2014) by using the same parameters (including the feedback) of Konstantinou et al. (2014). These facts implied that the parameter deviations in the current study may not be a critical factor driving distinct results. Taking a step back, the current study at least necessitates a rethinking of previous findings on the modulation effect of visual WM capacity load on distractor processing, which might be affected by multiple factors. For instance, there might be a moderator variable modulating the relation between visual WM capacity load and distractor processing: Under one level of the moderator factor, the visual WM capacity load increased the distractor processing, while under the other level of the moderator factor the visual WM capacity load decreased the distractor processing. These two effects canceled each other when pooling all the data together. One potential candidate of the moderator variable was WM capacity, as it has been found that WM capacity modulates information filtering (see Luck & Vogel, 2013, for a review). Future studies may take the individual differences of visual WM capacity into consideration. Additionally, the current study only addressed the role of visual WM capacity load; however, Zhang and Luck (2015) implied that visual WM resolution load also had an impact on selective attention, functioning as a type of perceptual load. Both the current study and Zhang and Luck (2015) suggest that the role of visual WM load on selective attention may not be a simple issue, deserving more careful investigation in the future.

We consider that the null influence of the visual WM capacity load on the distractor processing is reasonable. First, the core assumption of perceptual-load hypothesis was inspired by the neuroimaging finding that visual WM resorts to the same sensory visual cortices (e.g., primary cortex) as those used in perception (sensory recruitment hypothesis; e.g., Ester et al., 2009; Harrison & Tong, 2009). Konstantinou et al. (2012, 2014), Konstantinou and Lavie (2013) hence proposed that the visual WM load would increase the demand for sensory processing, which led to reduced distractor processing. However, although the visual processing involved in the letter flanker task also recruits certain sensory visual cortices, the involved primary cortices between visual objects (e.g., color) and English letters were quite different (e.g., Dehaene & Cohen, 2011; Haist et al., 2001; Joseph, Cerullo, Farley, Steinmetz, & Mier, 2006; Mullen, Dumoulin, & Hess, 2007), or they were from different domains from the perspective of Lin and Yeh (2014) (see also Baddeley, 2012). It is, to some extent, difficult to predict that the visual WM load would compete the cortical resources with the flanker task in general. Intuitively, this argument implies a load modulation in the direction of the perceptual load when the visual WM load and the perceptual task compete for the same cortical resources (Cohen, Konkle, Rhee, Nakayama, & Alvarez, 2014; Jiang, Remington, Asaad, Lee, & Mikkalson, 2016). However, Lin and Yeh (2014) showed the reversed evidence, and our Experiments 7, 8, and 9 also negated this implication, suggesting that the underlying assumption might be incorrect. Indeed, Bettencourt and Xu (2016) recently demonstrated fMRI evidence against this sensory recruitment hypothesis of WM, suggesting that sensory cortex is nonessential in visual WM maintenance, but higher-level cortex like parietal cortex is important. Xu (2017) further reviewed the existing evidence supporting the sensory recruitment hypothesis and pointed out that the available evidence provides weak support. The revealed visual WM-related activities in sensory areas may be related to the top-down feedback signals from the higher-level cortex in charge of visual WM maintenance. Therefore, it is not surprising to see that the visual WM capacity load does not modulate the distractor processing in a flanker task. On the other hand, the current Experiments 7, 8, and 9 offered novel evidence supporting the view that the sensory cortex might not play a key role in retaining visual objects in WM (cf. Xu, 2017; but see Scimeca, Kiyonaga, & D'Esposito, 2018, for a different view).

Second, both Lin and Yeh (2014) and Zhang and Luck (2015) implied that higher visual WM capacity load led to increased distractor processing. However, the finding of Zhang and Luck (2015) was contrary to the prediction of Lin and Yeh (2014) even though the key manipulation was quite similar. Moreover, the offered explanations in both studies were not convincing enough. Particularly, according to Lin and Yeh (2014), when the WM task and the letter task were from the same domain, the two tasks would compete for the same resource pool, which would decrease the top-down attentional control. However, this deduction was not direct, because a direct prediction of this resource competition would be reduced distractor processing (i.e., as a type of perceptual load). As in Zhang and Luck (2015), increased visual WM capacity load led attention to be spread across coarser spatial scales, which, to the best of our knowledge, has not received any empirical evidence, although there is evidence for high central executive load (e.g., Ahmed & de Fockert, 2012a, b).

Finally, the flanker task reflects the scope of spatial attention. However, all the current visual WM tasks predominately addressed visual objects. Previous studies have found that rehearsing visual objects in WM requires object-based attention (e.g., Awh, Dhaliwal, Christensen, & Matsukura, 2001; Barnes, Nelson, & Reuter-Lorenz, 2001; Matsukura & Vecera, 2009; Shen, Huang, & Gao, 2015). Because spatial attention and object-based attention are two distinct types of resource (e.g., Duncan, 1984; Egly, Driver, & Rafal, 1994; Cohen & Tong, 2015; see Chen, 2012, for a review), loading one resource pool theoretically should not affect the performance of the other one. This explanation offered an intriguing yet promising prediction: high spatial WM load would reduce the distractor processing. Further study is necessary to test this prediction.

Before ending, we need to point out that we did not refute the view that visual WM capacity load modulates selective attention, albeit the current distractor processing reflects one key function of selective attention. For instance, Luck and colleagues found that spatial WM, but not object WM, had a negative influence over visual search efficiency (Woodman & Luck, 2004; Woodman, Vogel, & Luck, 2001), which was confirmed in later studies (e.g., Kim et al., 2005; Oh & Kim, 2004). Furthermore, Konstantinou and colleagues have found neural and behavioral evidence showing that the high visual WM capacity load led to reduced detection sensitivity to the incoming visual stimuli (Konstantinou et al., 2012; Konstantinou & Lavie, 2013). The current study implies that the effect of visual WM capacity load on distractor processing and visual detection of potential target might have distinct mechanisms. Indeed, the flanker task and the visual detection task reflected distinct aspects of attention. The flanker task largely reflects the role of top-down attention selection, while visual detection is mainly related to stimulus-driven attention selection. Moreover, there has been evidence revealing that distinct neural networks underlie the top-down attention selection and stimulus-driven selection. The top-down attention needs the involvement of the intraparietal cortex and superior frontal cortex, and the stimulus-driven attention activates the temporoparietal cortex and inferior frontal cortex, which is largely lateralized to the right hemisphere (Buschman & Miller, 2007; Shulman & Corbetta, 2002).

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**Data availability** All the data are available at: https://osf.io/fns8a
All the programming codes are available at: https://osf.io/6rdz8

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