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Effects of load on the guidance of visual attention from working memory

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ABSTRACT

An active recent line of research on working memory and attention has shown that the visual attention can be top-down guided by working memory contents. The present study examined whether the guidance effect is modulated by memory load, i.e., the amount of information maintained in working memory. In a set of three experiments, participants were asked to perform a visual search task while maintaining several objects in working memory. The memory-driven attentional guidance effect was observed in all experiments when there were spare working memory resources. When memory load was increased from one item to two items, there was no sign that the guidance effect was attenuated. When load was further increased to four items, the guidance effect disappeared completely, indicating a clear impact of memory load on attentional guidance.

1. Introduction

When extracting relevant information from a complex visual environment, attentional guidance is often needed as an effective mechanism to optimize target selection (Wolfe, 2007). During visual search, guidance of attention towards a likely target can be achieved in two ways (Buschman & Miller, 2007; Wolfe et al., 2003). In the bottom-up or stimulus-driven way, stimuli with distinctive attributes such as large target–distractor dissimilarity (Müller, Heller, & Ziegler, 1995), novelty or singleton (Johnston et al., 1990) can pop out easily from a visual scene and capture attention. In the top-down or user-driven way, attention is guided by some knowledge or information an observer possesses either implicitly (e.g., contextual cueing, Chun & Jiang, 1998, 2003) or explicitly (e.g., verbal description of the target, Wolfe et al., 2003, 2004).

As a specific case, research has shown that there is attentional guidance by representations in working memory (WM) (Chelazzi et al., 1993; Logan & Gordon, 2001). Soto and colleagues required participants to search for a tilted line target among three vertical lines while holding in WM a colored shape cue (Soto, Humphreys, & Heinke, 2006; Soto et al., 2005). Critically, each item in the search display was enclosed inside a colored shape. Search performance was impaired when the memory item re-appeared surrounding one of the distractor items, compared with when it was absent in the search display. The results were interpreted to suggest that WM contents, even though not part of the target template to search for, can still guide attention and bias its orientation to items with matching information (see also Olivers, Meijer, & Theeuwes, 2006).

Woodman and Luck (2007), however, found that the attention was directed away from rather than biased towards a memory-matching-distractor in visual search, a result also observed by Downing and Dodds (2004). Soto and Humphreys (2008) suspected that what Woodman and Luck (2007) found may somehow result from loading WM too much with the use of articulatory suppression and the need to maintain three objects. In support of this, Soto and Humphreys (2008) found no change of attentional guidance when load increased from one to two objects, but the effect was eliminated at load 2 combined with articulatory suppression. Although these results are not sufficient to reveal why opposite effects were found across the two abovementioned studies, they at least indicate that WM load is an important factor to be considered when studying attentional guidance. Study of this factor may also help to illuminate the nature of the guidance effect, for example, whether such guidance operates automatically or under voluntary control (Hasher & Zacks, 1979; Schneider & Shiffrin, 1977).

In the present study, we followed Soto and Humphreys (2008) to further examine the impact of memory load on attentional guidance. We would simplify the situation by removing the articulatory suppression component and vary the load factor alone. On the one hand, if both WM load and articulatory suppression compete for cognitive resources, which would then affect the guidance effect per the Soto and Humphreys (2008) study, it would be necessary to assess their impact separately. On the other hand, participants

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in Woodman and Luck (2007) and Soto and Humphreys (2008) were essentially performing three tasks at the same time, articulatory suppression, visual search, and load maintenance. If human frontal functions are limited to pursuing no more than two concurrent goals (Charron & Koechlin, 2010), coordination between three tasks would exceed this limit and lead to performance patterns highly contaminated by strategic factors.

2. Experiment 1

Soto and Humphreys (2008) found that when WM load increased from 1 to 2, attentional guidance was robust and stayed unaffected. We adopted the paradigm in their first experiment and asked whether higher load including a level approaching the WM capacity (Cowan, 2001; Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001) would affect the guidance effect.

2.1. Methods

2.1.1. Participants

Twenty students (aged between 19 and 23 years old, mean age = 20.1 years) with normal or corrected-to-normal visual acuity and normal color vision participated in this experiment. All were right-handed. Informed consent was obtained at the beginning of the session following a research protocol approved by the Institutional Review Board of the South China Normal University (Guangzhou, China).

2.1.2. Stimuli

All visual stimuli were presented in a gray background on a color CRT monitor (resolution: 1024 × 768; frame rate: 60 Hz) about 57 cm away from the viewer. There were 81 objects constructed by crossing nine colors (red, blue, yellow, cyan, green, orange, pink, black, and white) and nine line drawings of shapes (listed in Fig. 1), each subtending a visual angle of approximately 1.9° × 1.9°. The thickness of the border line of the shapes was about 0.5° in visual angle. When there was only one object to hold in memory, the object appeared at the screen center. When there were two objects, they were positioned 2° above and below the screen center. When there were four objects, they were located at the corner of a 4° × 4° imaginary rectangle.

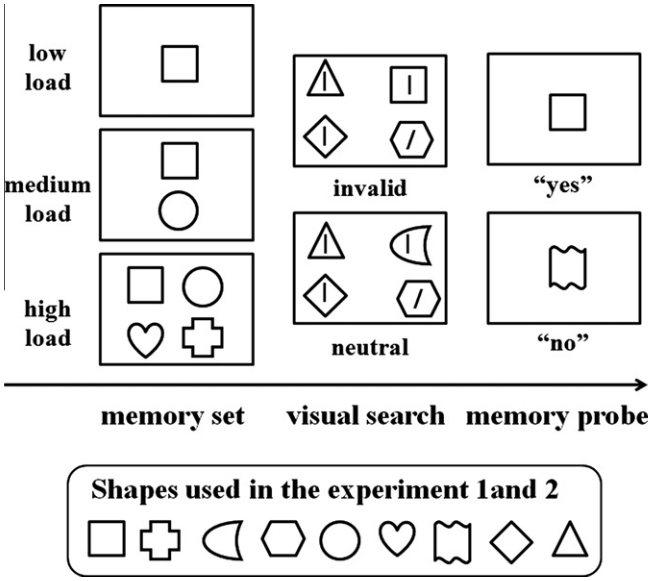

Fig. 1. The sequence of events in a sample trial in Experiment 1. Each shape has a different color.

The search array was composed of four black lines (0.57° × 1.2°) with each embedded inside a colored shape. The three distractor lines were vertical and the one target line was tilted 38° either to the left or right. The search items were arranged around an imaginary circle (radius = 6°), presented at either 1, 4, 7, 10 or 2, 5, 8, 11 o'clock locations.

2.1.3. Procedure

As shown in Fig. 1, each trial started with a 1° × 1° fixation cross for 1000 ms in the center of the screen, followed by the presentation of the memory set. There were three load conditions, low, medium, and high with 1, 2, and 4 objects respectively. The memory set was displayed longer when there were more objects (1000 ms for 1 object, 2000 ms for two objects, and 4000 ms for four objects) to allow adequate encoding. Once the memory set display was turned off, there was a 1000 ms blank screen, followed by the search array till response within 5000 ms. The response was separated by another 1000 ms blank interval from the onset of a memory probe. Participants were asked to study the memory set, searched for the target line, and then responded to the probe. They were required to respond as accurately and fast as possible to judge the orientation of the target line by pressing 'F' for left or "J" for right. They were to decide whether the probe was the same as or different from any object in the memory set and to press "F" or "J" accordingly. The memory probe and one specific object in memory set were matched both in color and shape in half of the trials, and differed in color, shape or both with equal possibility in the other half. Only accuracy was emphasized in the memory probe task. The next trial started 2000 ms after the response to the memory probe.

Other than the load factor, there were two types of trials. In the invalid trials, one of the objects in the memory set re-appeared in the search array to contain a distractor line. In the neutral trials, there was no feature overlap between the memory set objects and colored shapes in the search display. For load higher than 1, each object in the memory set was equally likely to re-appear in the subsequent search array as the object surrounding a distractor.

Each participant did 30 practice trials, and then completed four blocks of 48 trials. Each block included 16 trials for each level of load, 8 for the invalid condition and 8 for the neutral condition.

3. Results

For the load effect on the accuracy measure of the memory probe task, a repeated-measures ANOVA showed a significant main effect of load ($F(2,38) = 15.59$, $p < .0005$). As the load was increased, memory recognition became less accurate, being

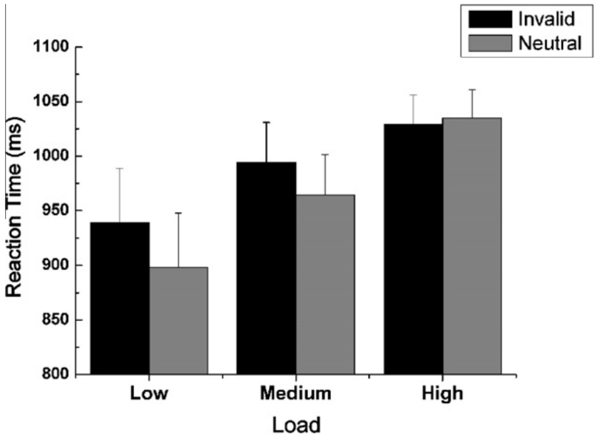

Fig. 2. Mean response time (RT) for all conditions in Experiment 1. Error bars represent standard errors.

98.1%, 94.0%, and 89.9% for the low, medium, and high load, respectively (for all pair-wise comparisons, p values <.05). The results indicate an effective manipulation of WM load.

For the search task, mean performance accuracy was reasonably good (94.1%). As in Soto et al. (2005), RT analysis in this study were conducted including only trials with correct responses in both the search task and the memory probe task, discarding outliers three standard deviations beyond the grand mean. A 3 (load: low, medium vs. high) by 2 (matching type: invalid vs. neutral) repeated-measures ANOVA on response times (RTs) in the visual search task showed a main effect for load ($F(2,38) = 5.74$, $p < .01$) and for matching type ($F(1,19) = 11.22$, $p < .005$). Most importantly, there was also a significant interaction between load and matching type ($F(2,38) = 3.57$, $p < .05$).

As shown in Fig. 2, planned comparisons showed that RTs in the invalid trials were significantly greater than in the neutral trials for low load (939 vs. 898 ms, $t(19) = 4.16$, $p < .001$) and medium load (994 vs. 964 ms, $t(19) = 2.49$, $p < .05$), but not high load (1029 vs. 1035 ms, $t(19) = 0.38$, $p > .5$). The guidance effect as measured with RT, i.e., $\mathrm{RT}_{\mathrm{invalid}} - \mathrm{RT}_{\mathrm{neutral}}$, was no different between the low and medium load conditions (41 vs. 30 ms, $t(19) = 0.58$, $p > .5$).

4. Discussion

The results replicate the literature and demonstrate a clear attentional guidance effect when the load was low, i.e., when participants were holding only one object in memory. They further show that the guidance effect was strong and did not attenuate when the load changed from 1 to 2, consistent with the results of Soto and Humphreys (2008).

The most interesting finding is that the guidance effect disappeared completely at a high work memory load when participants were holding four objects in their memory. This indicates a situation where WM load alone has a clear impact on attentional guidance. One direct interpretation of this finding is that the cognitive resources needed for guidance were exhausted by the high WM load. There were, however, two alternative interpretations.

First, in Experiment 1, all objects in memory set could re-appear in the visual search. It was possible they would compete for a fixed amount of resources for guidance, and each object in the high load condition would not get enough resources, leading to the disappearance of the guidance effect. Note it is assumed here that the resources for guidance are different from the resources that can be loaded by maintaining items in WM.

Second, the colored shapes in Experiment 1 were relatively easier to verbalize, thus verbal encoding strategy may be another variable to affect the attentional guidance (Olivers, Meijer, & Theeuwes, 2006; Soto & Humphreys, 2007). According to a recent research of Dombrowe, Olivers, and Donk (2010), the guidance effect from verbal WM decreases with increasing stimulus-onset asynchrony (SOA) and may even disappear at an SOA of 3500 ms. In comparison, the guidance effect from visual WM could sustain as long as 3500 ms. As high load was associated with a long SOA of 5000 ms, the disappearance of the guidance effect in Experiment 1 at high load could be attributed to the long SOA per the Dombrowe et al. study, if our participants maintained the memory set in verbal WM. There was another possibility, which is, the attentional guidance from visual WM may decay at an SOA as long as 5000 ms. These possibilities were further addressed in the next two experiments.

5. Experiment 2

Experiment 2 was to examine the possibility whether the increased competition for guidance in WM could be responsible for the disappearance of guidance at high load in Experiment 1. To this end, we pre-defined a single location (below the screen center) designating to the participants the memory object that may reappear in the search display. Such manipulation was to make the memory object-to-reappear stand out from other objects eliminating possible resource competition from other objects. If increased competition of resources for guidance was the critical factor leading to the disappearance of guidance at high load in Experiment 1, we would expect the guidance effect to persist at high load as the only possible memory object that may guide attention was pre-cued clearly and immune from the competition. If the high load exhausted cognitive resources critical for guidance, we would observe similar findings as in Experiment 1, i.e., the guidance effect should be eliminated at high load.

5.1. Methods

5.1.1. Participants

Seventeen new participants (aged between 16 and 20 years, mean age = 18.5 years) from the same subject pool as in Experiment 1 were recruited for this experiment. Informed consent was also obtained as described in Experiment 1.

5.1.2. Stimuli and procedure

The stimuli and procedure were identical to that in Experiment 1 except that there were only two load conditions. In the medium load condition, there were two colored shapes located 2° below and above the center of screen. In the high load condition, there were four colored shapes; one located 2° right below the screen center and three objects located 2° above the screen center in a horizontal line, separated from each other horizontally by a distance of 2°. Only the shape below the screen center may re-appear in the subsequent search display embedding a distractor line. This point was made known to the participants.

6. Results

ANOVA on the accuracy data in the memory probe task showed a significant main effect of load ($F(1,16) = 53.19$, $p < .001$). Mean accuracy was lower in the high load condition than in the medium load condition (82.3% vs. 90.8%), indicating effective manipulation of memory load.[1]

The accuracy of the visual search task was high (98.8%). Analysis on RTs (Fig. 3) in the visual search task showed no main effect for either load or matching type (p values > .1) but a significant interaction between the two ($F(1,16) = 4.40$, $p < .05$). RT for the invalid trials was significantly longer than for the neutral trials in the medium load condition (1084 vs. 1038 ms, $t(16) = 3.53$, $p < 0.005$), but no different between the two in the high load condition (1036 vs. 1036 ms).

7. Discussion

The results of Experiment 2 replicated the pattern of Experiment 1 showing a strong guidance effect at medium load and its absence at high load. This indicates that the particular way to sin-

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[1] There was a possibility that the absence of guidance at load 4 could result from that participants did not encode the item presented below fixation, and instead directed their limited processing capacity to the three items above fixation. This, however, was disconfirmed when we conducted for Experiment 2, a 2 (load: medium vs. high) by 2 (location: above vs. below) ANOVA on the accuracy of memory probe when the item in memory set reappeared as the memory probe. The results showed a significant effect for load, $F(1,16) = 23.78$, $p < .001$, but neither for location nor for their interaction (p values >0.5), suggesting that the items above and below the fixation in memory set were equally encoded. Experiment 3 showed the same tendency.

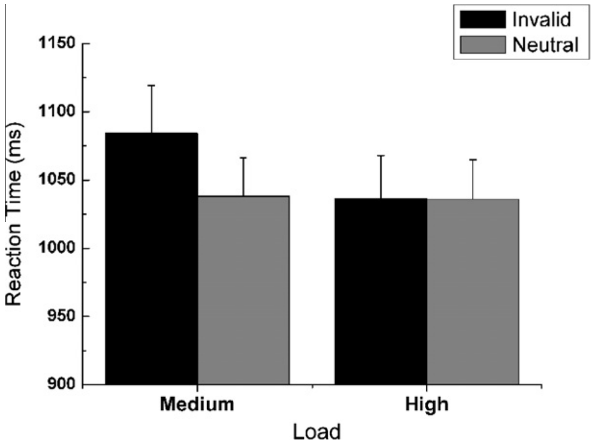

Fig. 3. Mean RT for all conditions in Experiment 2. Error bars represent standard errors.

gle out one memory set object, eliminating the increased competition for guidance as load was increased, was not responsible for the disappearance of the guidance effect at high load in Experiment 1.

The guidance effect size at medium load was 16 ms more for Experiment 2 compared with Experiment 1 (though not significant, 30 vs. 46 ms, $t(35) = 0.95$, $p > 0.3$). A single-out item may be more likely to induce the guidance effect compared with when an item appeared in a set of items.

8. Experiment 3

Experiment 3 was to examine whether the verbal encoding strategy or the long SOA was the critical factor responsible for the disappearance of guidance at high load in Experiments 1 and 2. The design was identical to Experiment 2 except two modifications. First, to exclude the influence of the verbal encoding strategy, in the present experiment, we changed the colored shapes to stimuli that were difficult to verbalize and had to be maintained in visual WM. Second, to dissociate the effect of load and decay effect due to increased SOA, we added a load condition where the load was identical to the medium load condition and the SOA was identical to the high load condition. If the SOA was the main reason for the disappearance of the guidance effect, no guidance effect should appear with the SOA of 5000 ms in the medium and high load conditions according to the results of Experiments 1 and 2. If the load was the main reason for the disappearance, the guidance would be observed at medium load regardless of SOA, but not at high load.

8.1. Methods

8.1.1. Participants

Fifteen new participants (aged between 22 and 25 years, mean age = 23.8 years) from the same subject pool were recruited. Informed consent was obtained in the same way as in Experiment 1.

8.1.2. Stimuli and procedure

The procedure was identical to that in Experiment 2 except the following. First, the colored shapes were nine colored circles that were difficult to name. The thickness of the border line of the circles was about 0.5° in visual angles. The colors were adopted from Tan et al. (2008) and defined by the RGB system with values (red, green, and blue) as follows: (88, 50, 50), (100, 158, 167), (179, 76, 120), (150, 120, 180), (150, 90, 120), (50, 90, 160), (30, 158, 80), (3, 152, 40), and (49, 142, 120). Participants were instructed to ignore the shape of the circles and only remember their colors. Second, we added a medium load condition with 2000 ms encoding time and a 3000 ms interval time, corresponding to an SOA of 5000 ms.

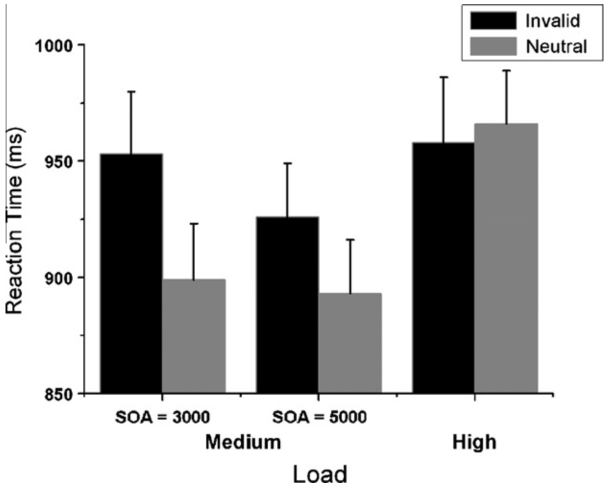

Fig. 4. Mean RT for all conditions in Experiment 3. Error bars represent standard errors.

9. Results

Analysis of the accuracy data in the memory probe task showed a significant main effect of load ($F(2,28) = 26.18$, $p < .001$). The mean accuracy in the high load condition was lower than that in both of the medium load conditions with a 3000 ms SOA (85.2% vs. 93.9%, $t(14) = 5.91$, $p < 0.05$) and a 5000 ms SOA (85.2% vs. 93.1%, $t(14) = 5.02$, $p < 0.05$), indicating effective manipulation of memory load. The two medium load conditions did not differ from each other ($t(14) = 1.06$, $p > 0.31$).

The accuracy for the search task was very high (99.0%). ANOVA on the RT data (Fig. 4) in the visual search task showed a significant main effect of load ($F(2,28) = 7.97$, $p < .005$) and matching type ($F(1,14) = 11.5$, $p < .005$). Most importantly, the two-way interaction was also significant ($F(2,28) = 6.7$, $p < .005$). Planed t-tests showed that mean RT for the invalid trials were significantly greater than the neutral trials under the medium load condition with a 3000 ms SOA (953 vs. 899 ms) and a 5000 ms SOA (926 vs. 893 ms). No such difference was found for the high load condition (958 vs. 966 ms).

To examine the effect on the guidance effect as SOA was increased, we compared the magnitudes of guidance between the two SOA conditions at the medium load. The guidance effect tended to decline from the 3000 ms SOA to the 5000 ms SOA (54 ms vs. 33 ms), though not reaching significance ($t(14) = 1.03$, $p > 0.3$).

10. Discussion

After controlling for the confound of verbal encoding strategy that may possibly be adopted in the first experiments, the results here replicated the effect of WM load on attentional guidance as observed in Experiments 1 and 2, demonstrating a clear guidance effect for the medium load but no such guidance for the high load. Crucially, in the present experiment, we observed robust guidance effect at the medium load for both levels of SOA, 3000 ms and 5000 ms, but failed to observe such effect at high load with a 5000 ms SOA. These results suggest that the disappearance of guidance in all three experiments should be attributed to the load factor as opposed to the SOA factor.

One issue of importance is whether the verbal encoding strategy was employed and responsible for the disappearance of attentional guidance in Experiments 1 and 2? Olivers, Meijer, and Theeuwes (2006) was the first demonstrating the impact of verbal encoding strategy on guidance. They observed robust guidance when using more visual memory materials but failed to do so when using more verbal memory materials. Different from these results, Soto and Humphreys (2007) found that verbal WM, as well as visual WM, can guide visual attention automatically. Such discrepancy was conciliated by a recent study of Dombrowe, Olivers, and Donk (2010) who found that guidance from easily verbalizable WM content decreased with increasing time (e.g., Olivers, Meijer, & Theeuwes, 2006 with an SOA of 3 s), whereas the guidance from visual WM content could sustain as long as 3500 ms. According to Dombrowe, Olivers, and Donk (2010), it was possible that verbal encoding strategy was employed leading to the disappearance of guidance at the 5000 ms SOA in Experiments 1 and 2. But it would be difficult to explain the different results between medium and high load condition with the identical SOA of 5000 ms after controlling for verbal encoding strategy in Experiment 3. Therefore, although the effect of verbal encoding on guidance may be exist, such effect should be separate from that of the load factor. Similarly, SOA may affect guidance (there was a non-significant decline of guidance with increasing SOA at the medium load), such effect should not be used to account for the effect of the load factor.

11. General discussion

The present study examined the role of memory load on attentional guidance from WM representations. The set of three experiments showed clear evidence that visual objects maintained in WM could guide attention to a memory-matching-distractor. This replicates a finding that has been consistently reported in previous studies (Olivers, Meijer, & Theeuwes, 2006; Soto & Humphreys, 2008; Soto, Humphreys, & Heinke, 2006; Soto et al., 2005).

Based on Soto and Humphreys (2008) that higher memory load combined with articulatory suppression could eliminate the guidance effect, we investigated whether, in the absence of articulatory suppression, varying memory load alone can have an effect on attentional guidance. As in Soto and Humphreys (2008), we found that when memory load was increased from one item to two items, there was no sign that the guidance effect was attenuated. However, novel in our results, when load was further increased to four items approaching the limit of WM capacity (Cowan, 2001; Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001), the guidance effect disappeared completely, indicating a clear impact of memory load on attention guidance.

Such results, apparently, are incongruent with the classic conceptualization of load where any increase in WM load would lead to increased interference from distractors (e.g., in de Fockert et al., 2001; Lavie & De Fockert, 2005). They are more in line with a specialized load account recently proposed by Kim and colleagues (Kim, Kim, & Chun, 2005; Park, Kim, & Chun, 2007). By this account, separate mechanisms are involved in processing target and distractors and the effects of WM load on attentional selection depends on whether load-related processing overlaps with processing of targets or distractors. When load-related processing overlaps with target processing, there will be more interference from distractors (e.g., in de Fockert et al., 2001; Lavie & De Fockert, 2005). However, when load-related processing overlaps with distractor processing, there will be less resources allocated to distractor processing and hence reduced interference (e.g., in Kim, Kim, & Chun, 2005; Park, Kim, & Chun, 2007).

This theory can be used to account for the critical finding in the present study as follows. In all three experiments, the items maintained in WM were homogenous and engaged the same type of cognitive resources. When the load was increased, the items in WM would compete for the limited cognitive resources with each other. Therefore, the load engaged processing resources related to the item which was used as a distractor in visual search, leading to shallower processing of the memory-matching distractor. This would produce the disappearance of the guidance effect because when the memory-matching distractor did not receive enough processing in WM, it would not stand out from the other distractors to capture attention.

An alternative explanation of our results is to use the biased-competition model (Desimone & Duncan, 1995; Duncan, Humphreys, & Ward, 1997) that emphasizes top-down signals. Essential to this theory is the proposal that activation of specific memory representations in prefrontal cortex feedback to enhance a visual representation in the temporal cortex, which in turn facilitates the processing of a visual item to gain more attention and win the competition over other items in a visual scene. That is, the memory-driven attentional guidance can be interpreted as the result of the memory-matching-distractor winning the competition from other items in visual search display under the help of the top-to-down feedback loop. In the present study, the items in memory set were homogenous and would therefore compete for resources with each other. Under low or medium load, there could be enough spare resources to sustain the top-down feedback. When the load was high, to ensure successful maintenance, there may not be enough spare resources for the normal operation of the feedback loop, and hence the breakdown of attentional guidance.

There are also supporting evidence to the idea that interference within WM affects attentional guidance. For example, Houtkamp and Roelfsema (2006) asked participants to maintain pre-specified target and another object in WM and then search for the target in a search display. While the target was found to guide attention efficiently, the other memory object did so weakly and only in the absence of target. The results suggest that the target template may be associated with a preferential status in WM and suppress other objects of accessory status in WM. Similar results have been obtained in Peters, Goebel, and Roelfsema (2009) and Zhang et al. (2010).

One implication of the present study is that the top-down guidance of attention from WM is unlikely to be an automatic process. Several previous studies seems to show that the attentional guidance occurred automatically (Soto & Humphreys, 2007, 2009; Soto, Humphreys, & Heinke, 2006; Soto et al., 2005, 2008), because the guidance had been observed under many circumstances, e.g., at early stage of selective attention (Soto et al., 2005) and at the first saccades (Soto, Humphreys, & Heinke, 2006; Soto et al., 2005), within easy visual search (Soto, Humphreys, & Heinke, 2006) and popout search process (Soto, Humphreys, & Heinke, 2006), and under a condition where the WM representations were only distractor-matched (Soto, Humphreys, & Heinke, 2006; Soto et al., 2005). But to judge whether a process is automatized, it should satisfy certain criteria, i.e., draining minimal amounts of energy from attentional capacity and continuing to operate even at high load (Hasher & Zacks, 1979; Shiffrin & Schneider, 1977). Therefore, the present results suggest that the attentional guidance may not be a completely automatic process, given its susceptibility to cognitive resource variations.

12. Conclusion

The present study demonstrates that WM load modulates attentional guidance, independent of the presence of other task manipulation, such as articulatory suppression. This finding implies that the top-down guidance of attention from WM is unlikely to be an automatic process, given its susceptibility to the modulation of cognitive resources.

Acknowledgments

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