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Spatial working memory maintenance: Does attention play a role? A visual search study

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A B S T R A C T

Recent studies have proposed that a common mechanism may underlie spatial attention and spatial working memory. One proposal is that spatial working memory is maintained by attention-based rehearsal [Awh, E., Jonides, J., & Reuter-Lorenz, P. A. (1998). Rehearsal in spatial working memory. *Journal of Experimental Psychology: Human Perception and Performance, 24*(3), 780–790], and so a spatial attention shift during the retention interval of a spatial location should impair its memory performance. In the present study, participants engaged in single-item, parallel or serial search tasks while remembering a spatial location. Although memory tended to bias all searches, the need for an attentional shift during the retention interval impaired memory performance only in single-item search, but not in other searches. These findings suggest that previous evidence for the attention-based rehearsal account does not generalize to visual search. Results are discussed with regard to the relationship between spatial attention and spatial working memory.

1. Introduction

Attention and memory are two important cognitive abilities. Whereas selective attention determines how limited mental resources are allocated to the most important piece of information in the environment, memory maintains this information in order to allow past experience to guide future behaviors. Although the two abilities appear to occur at different stages of information processing, and so each of them has their own research tradition, recent research has shown that they may be more intertwined than has been previously considered.

With regard to the relationship between attention and memory, earlier research has shown that memory content may influence the way that visual spatial attention is allocated. The inhibition of return effect (IOR; Posner & Cohen, 1984) is observed when memory of previously visited locations prevents attention from visiting these locations again. This inhibitory tagging memory mechanism appears to improve serial visual search efficiency, suggesting that memory plays a role in attentional allocation (Klein, 1988; Müller & von Mühlenen, 2000; but see Takeda & Yagi, 2000; Horowitz & Wolfe, 2003). In addition to inhibitory tagging, visual working memory also influences allocation of attention and biases attention towards a location that contains a memorized visual item (Downing, 2000; Soto, Heinke, Humphreys, & Blanco, 2005; Olivers, Meijer, & Theeuwes, 2006; but see Downing & Dodds, 2004; Woodman & Luck, 2007).

The relationship between visual attention and working memory has also been examined by looking at whether working memory is important for attentional tasks. One way to achieve this is to observe whether an attentional task is impaired by filling up working memory to its capacity. Reduction in efficiency of attentional allocation here would mean that working memory is required for the attentional task, and attentional efficiency can be measured by the visual search paradigm. In a visual search task, participants discern the presence or the identity of a predefined target among a number of distractors. In a serial search, in which focused attention is required to distinguish a target from a distractor, reaction time typically increases linearly with the number of total search items. This search slope is a measure of visual search efficiency. By comparing serial search efficiency during the retention interval of a working memory task with a situation with no memory burden, it was found that visual search does not require visual working memory (Woodman, Vogel, & Luck, 2001) or verbal working memory (Han & Kim, 2004). However, visual search efficiency is impaired by executive working memory load (Han & Kim, 2004) and spatial working memory load (Oh & Kim, 2004; Woodman & Luck, 2004), suggesting that executive working memory and spatial working memory are important for allocation of attention.

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The suggestion that visual search requires spatial working memory is closely linked to a suggestion that visual attention plays a crucial role in spatial working memory maintenance (Awh, Jonides, & Reuter-Lorenz, 1998). According to Awh et al.'s attention-based rehearsal hypothesis, remembering a spatial location is achieved by focusing attention at that position. This conjecture could potentially explain why remembering spatial locations impaired visual search in Oh and Kim's (2004) and Woodman and Luck's (2004) studies. For instance, if remembering spatial locations required fixating attention, it would severely interfere with the visual search operation in which shifts of focused attention are required.

Although Oh and Kim (2004) and Woodman and Luck (2004) showed that spatial working memory is engaged in visual search, it is not clear whether the relationship between spatial working memory and spatial attention is as what Awh et al. (1998) had described. To justify their attention-based rehearsal account, evidence is needed to show that attention is crucial for maintaining spatial working memory. In Awh et al.'s study, this point was demonstrated by testing whether an attentional shift during the retention interval of a spatial location memory task would impair memory performance. The rationale was that, if a shift of attention impaired memory performance, it would mean that fixating attention at a location (presumably the memory location) was crucial for maintaining spatial memory.

Therefore, in their Experiment 3, they compared spatial working memory performance in two conditions. In the shifting-attention condition, performance was compared between (i) a dual-task condition in which a color judgment task requiring a shift of attention was inserted into the retention interval of a spatial working memory task, and (ii) a passive-viewing condition in which participants only needed to passively view an identical stimulus during the retention interval. As a result, they found that memory performance was worse in the dual-task condition than in the passive-viewing condition. Assuming the color judgment task required a shift of attention, this finding was taken to argue that such an attentional shift disrupted the maintenance of spatial memory. To rule out the possibility that the effect was simply a general dual-task disadvantage, Awh et al. included a static-attention condition in which a large color disc replaced the original color probe. Because the color disc was large enough to cover all possible memory positions, shifting of attention was not required for judging the color of the disc. Therefore, a comparison between the dual-task and passive-viewing conditions using this stimulus provided a baseline measure of a general dual-task disadvantage. A comparison between the dual-task costs measured in the shifting-attention and static-attention conditions revealed a net cost to memory performance by a shift of attention. Awh et al. concluded that attentional shifts could disrupt the maintenance of spatial working memory.

One potential problem with Awh et al.'s (1998) study is that their cross-condition comparison of dual-task cost may not justify their conclusion. Although the dual-task cost of the shifting-attention condition was indeed larger than the static-attention condition, the fact that a dual-task cost existed for the static-attention condition implies that a dual-task cost can exist without an attentional shift. It is unclear what factors determined the size of this dual-task cost. Therefore, it is not clear whether the larger the dual-task cost in the shifting-attention condition was due to greater memory impairment caused by attentional shifts, or was due to other differences between the shifting- and the static-attention condition. The latter possibility is worth considering because the two conditions in Awh et al.'s study were quite different from each other in terms of stimuli sizes and color choices. Furthermore, the difference of the dual-task costs was relatively small (7% drop versus 12% drop). Taken together, there is a need to evaluate the attention-based rehearsal account more carefully.

The present study has two main purposes. The first purpose is to investigate whether attention plays any role in remembering a spatial location. The second purpose is to obtain more evidence with regard to the role of working memory in influencing the allocation of spatial attention. In Experiment 1, we tested a simplified version of Awh et al.'s (1998) experimental design. In Experiments 2–4, we generalized our investigation to a visual search paradigm.

2. Experiment 1

In Experiment 1, we used a single-item search task that required a spatial relation judgment instead of Awh et al.'s (1998) color judgment task. A spatial relation judgment requires focal attention (e.g., Treisman & Gelade, 1980), and this choice would better guarantee a need for focal attention than a color judgment task (e.g., Chan & Hayward, 2009). With this task, we compared working memory performance when participants identified a target appearing at or away from the memory location (static-attention and shifting-attention conditions, respectively) during the retention interval. In this case whether or not attention was shifted was manipulated within the same task, and thus across-task differences did not confound effects from the attentional shift. Therefore, in our task, participants first remembered the location of a cue (400 ms). After a blank period (1600 ms), the target for the search task appeared (200 ms), and participants had to discern whether the target was a "i" or a "!" shape (30° tilted anticlockwise) by pressing one of two buttons. 2000 ms after the onset of the target, two location probes were presented and participants judged which probe appeared at the memory location by pressing one of two buttons. The location cue and the target appeared at the same position in 16.7% of test trials. Fig. 1 gives an illustration of the method of the experiment.

There are two main focuses in the analysis of this experiment. First, whether or not search performance was better in the static-attention condition than in the shifting-attention condition would indicate whether spatial working memory biased attention towards the memory location. Second, whether memory performance was worse in the shifting-attention condition would indicate whether focusing attention to the memory location was essential for remembering that location. For instance, if fixating attention is not crucial for retaining a location, there should be little reason for shifting attention towards a distant target to impair working memory performance.

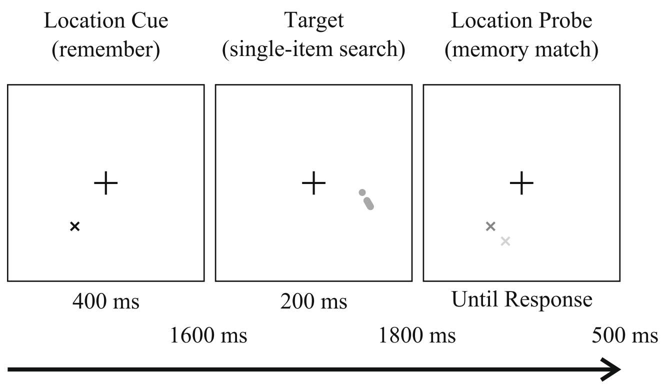

Fig. 1. Illustration of a test trial in Experiment 1. The participants were instructed to memorize the location of a location cue. Then, they reported whether the target was an upright or an inverted "i" shape. After that, they judged which location probe matched the memory location.

1.1. Method

1.1.1. Participants

Fourteen students from the University of Hong Kong participated in the experiment. Data from four of them were discarded due to excessive eye movement (measured by a catch task, see *Design and Procedure* for detail). All had normal or corrected-to-normal vision. They were paid HK$30 for a 30 min session.

1.1.2. Apparatus and stimuli

The stimuli were presented on a 17″ Apple eMac computer. With a viewing distance of approximately 57 cm, the viewing dimensions were about 32° × 24°. Vertical refresh rate was 60 Hz. On a dark background, the fixation cross was a white "+" shape composed of two 0.8° long, 0.08° thick, vertical and horizontal lines. The location cue was a white "×" shape composed of two 0.4° long, 0.08° thick, 45° and −45° rotated diagonal lines. The target had a shape resembling a letter "i", which was composed by a short and a long vertically aligned line. The short line was 0.24° thick, 0.24° long, and the long line was 0.24° thick, 0.48° long (both lines had round endings). The total height of the target was 0.8°. The target was 50% grey in color, and was rotated clockwise by either −30° or 150°. The location probes had the same shape and size as the location cue but were either red or green.

The search target appeared randomly in one of six invisible cells, with the constraint that the target center was never closer than 0.52° from the closest edge of its cell. The cells were defined by the following criteria: two connected, non-overlapping concentric rings of 2.4° thick, the closer ring had an inner radius of 3° and the outer ring had an inner radius of 5.4° and an outer radius of 7.8°. Each ring was divided into three equally sized and shaped cells by lines penetrating the origin. This cell setting was also used in the visual search screen of the subsequent experiments. In 16.7% of test trials, the location cue appeared at the same location as the target; in other trials, the location cue was positioned in a non-target cell. For all trials, one of the location probes would appear at the location cue position, and the other probe would appear at 2.4° away from the cue position, along a randomly chosen direction.

1.1.3. Design and procedure

There were two types of trials in this experiment, test trials and catch trials. On a test trial, the fixation cross first appeared and remained visible throughout the trial except during the inter-trial interval (ITI). After 1000 ms since the onset of the fixation cross, the location cue then appeared for 400 ms. After an inter-stimulus interval (ISI) of 1600 ms, the target appeared for 200 ms. Within 2000 ms of target onset, participants had to make a speeded judgment of whether the target was a -30° rotated item ("i") or was a 150° rotated item ("!"). If the response was incorrect or no response was recorded in time, a 1000 Hz sine tone played for 200 ms.[1] At 2000 ms after the onset of the target, a red and a green location probe appeared, and participants made an unspeeded judgment of which probe appeared at the location cue position, by pressing one of two keyboard buttons (left-shift button for red and right-shift button for green). The colors were mapped to the probes randomly. The probe screen lasted until response. A 500 ms ITI occurred afterwards. Test trials occupied 75% of all trials.

On a catch trial, the fixation cross appeared for 1000 ms, the location cue then appeared together with the fixation cross for 400 ms, as in a test trial. After an ISI of 1600 ms, either a 3 × 1 or 1 × 3 pixels white line (0.04° × 0.12°) appeared at the center of the display for 200 ms, and participants had to make an unspeeded judgment of whether a vertical line or a horizontal line appeared by pressing a keyboard button (left-shift button or right-shift button, respectively). A 500 ms ITI occurred after a response. Since this line was very small, it was assumed that the task would be very difficult and performance would be inaccurate if eye fixation was located to any potential target regions, which were at least 3.5° away from the fixation position. 25% of all trials were catch trials. The purpose of catch trials was for assessing whether participants fixated their eyes to the fixation cross prior to search. Making sure the search was started with a proper fixation was necessary; otherwise any advantage in the static-attention condition in terms of search performance could have been due to fixation at the memory location.

In the beginning of the experiment, participants were instructed about the task, with the importance of eye fixation being stressed, along with the importance of achieving very high accuracy in the catch task. The experiment started with a practice block of 32 trials, followed by two blocks of 112 trials.

2.2. Results

2.2.1. Catch trials

Only data from participants with higher than 92% accuracy on the catch trials were analyzed. For the analyzed data, the average accuracy of the catch trials was 97.1%, reflecting very good fixation performance.

2.2.2. Single-item search performance

Responses faster than 200 ms or slower than 1800 ms were not analyzed, which accounted for 1.4% of all trials. Results are shown in Fig. 2, right panel. Paired *t*-tests were conducted to analyze the results. Responses were reliably more accurate in the static-attention condition (i.e., when the target appeared at the memory location) than in the shifting-attention condition (i.e., when the target appeared somewhere else), 97.8% versus 95.9%, $t(9) = 2.40$, $p < .05$. This result strengthens previous findings that attention tends to be biased towards a location retained in working memory (Awh et al., 1998, Experiments 1 and 2), and as such provides accumulative evidence for a significant role being played by spatial working memory in the operation of attentional allocation. In line with the accuracy results, correct response times (RTs) were faster in the static-attention condition, although this result was not statistically reliable, 811 ms versus 819 ms, $t(9) = 1.03$, $p > .3$.

2.2.3. Spatial working memory performance

Only trials with correct search responses made between 200 and 1800 ms were analyzed. A paired *t*-test showed that memory performance was more accurate in the static-attention condition, 92.6% versus 87.3%, $t(9) = 2.80$, $p < .03$ (Fig. 2, left panel). RTs were not analyzed as responses were unspeeded.

2.3. Discussion

The present findings are consistent with the attention-based rehearsal proposal. We found better attentional performance at the memory location (measured by the single-item search task), suggesting that attention was biased towards the memory location; and we found better memory performance when no shift of attention was required by the intervening focused attention task. Both findings were consistent with the idea that maintenance of a

[1] Due to a programming error, the experiment program actually waited for input for 2200 ms rather than 2000 ms after target onset if a response was not recorded within 2000 ms of target onset. This error should not affect our results because any response that was made 2000 ms after target onset was regarded as a miss response. Regardless of their correctness, miss responses and memory responses that followed a miss were not analyzed.

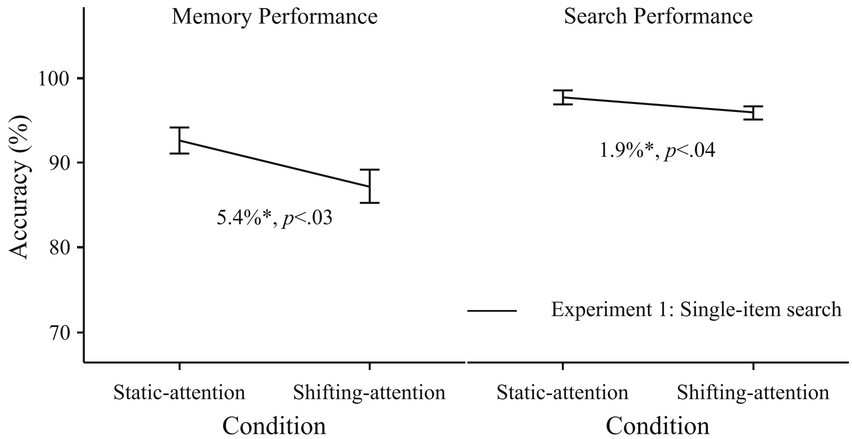

Fig. 2. Results of Experiment 1. The left panel shows that spatial working memory was more accurate in the static-attention condition. The right panel shows that search was more accurate in the static-attention condition. Error bars show 1 standard error of mean.

spatial location in working memory is achieved by focusing attention at that location.

Before we can accept this conclusion we have to address a potential confound. The issue is that in the static-attention condition of the present experiment, as the target location coincided with the memory location, the mere presence of a visual item at the memory location may have refreshed the memory representation and improved spatial working memory performance; in the shifting-attention condition, there was no visual item at the memory location. It has previously been documented that the presence of a visual item could improve spatial working memory (Belopolsky & Theeuwes, 2009). Here, the better working memory performance associated with the static-attention condition may not be necessarily due to the lack of an attentional shift.

To address this point, Experiment 2 was based on Experiment 1, but the single-item search task became a parallel *compound search task*. In a compound search task, participants first searched for a predefined target among several distractors, and then responded to the target identity. In the present experiment, this means that some vertical distractors (0° and 180° rotated "i" shape) were introduced along with the original oblique target. Under these conditions, by assigning either a target or a distractor to appear at the memory location in each trial, the memory location would always be refreshed. In this case, if working memory performance is still better when the target appeared at the memory location, converging evidence would be established for the attention-based rehearsal hypothesis; otherwise, if memory performance is not better for the static-attention condition, this would cast doubt on the notion that memory is retained by fixating spatial attention at the memory location.

3. Experiment 2

3.1. Method

3.1.1. Participants

Sixteen students in the University of Hong Kong participated in the experiment. Data from six of them were discarded due to excessive eye movement as measured by the catch task. All had normal or corrected-to-normal vision. They were paid HK$30 for a 30 min session.

3.1.2. Apparatus and stimuli

The same apparatus as in Experiment 1 were used. The stimuli were constructed as specified in Experiment 1. In the parallel search task, the targets were either −30° or 150° rotated clockwise, and the distractors were either 0° or 180° rotated.

The search target appeared randomly in one of the six cells, and a distractor item appeared in each of the other five cells. These cells were defined as in Experiment 1. If it was a static-attention trial, the memory location coincided with the target; if it was a shifting-attention trial, the memory location coincided with one of the distractors. 16.7% of test trials were static-attention trials. In each search display, half of the visual items were "i"s and half of them were "!"s, distributed randomly.

3.1.3. Design and procedure

All aspects of the design and procedure were identical to Experiment 1, except that the single-item search task was replaced by the parallel search task. See Fig. 3 for an illustration.

3.2. Results

3.2.1. Catch trials

Only data from participants with higher than 92% accuracy on the catch trials were analyzed. For the analyzed data, the average accuracy of the catch trials was 99.6%, reflecting very good fixation performance.

3.2.2. Parallel search performance

Data were screened in the same way as for Experiment 1, which accounted for 1.8% of all trials. Results are shown in Fig. 5, right panel. Paired *t*-tests were conducted to analyze the results. Responses were reliably more accurate in the static-attention condition than

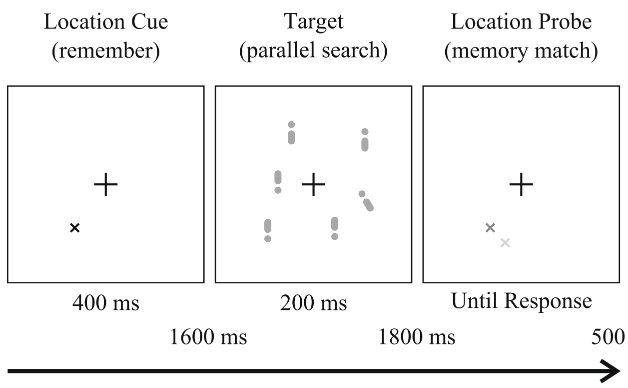

Fig. 3. Illustration of a test trial in Experiment 2. The participants were instructed to memorize the location of a location cue. Then, they searched for a tilted target among vertical items and judged whether the target was an upright or an inverted "i" shape. After that, they judged which location probe matched the memory location.

in the shifting-attention condition, 92.7% versus 85.5%, $t(9) = 3.83$, $p < .01$. As in Experiment 1, this shows that attention tended to be biased towards a location retained in working memory, and provides accumulative evidence for a role played by spatial working memory in attentional allocation. In line with the accuracy results, correct RTs were faster in the static-attention condition, although this result was not statistically reliable, 917 ms versus 922 ms, $t(9) = .282$, $p > .7$.

3.2.3. Spatial working memory performance

Data were screened in the same way as for Experiment 1. Contrary to Experiment 1, a paired *t*-test revealed no difference in terms of accuracy between the static-attention and shifting-attention conditions, 90.2% versus 88.3%, respectively, $t(9) = .66$, $p > .5$ (Fig. 5, left panel). This shows that shifting attention to a distant target did not impair working memory performance. RTs were not analyzed as responses were unspeeded.

3.3. Discussion

The present findings are consistent with the previous suggestion that spatial working memory influences attentional prioritization and biases attention towards a memorized location. On the other hand, these findings question whether focusing attention is indeed crucial for the maintenance of spatial working memory (Awh et al., 1998). With respect to the present experiment, the non-significant advantage for the static-attention condition was only 1.9% in terms of memory accuracy. Thus, even though it may not completely rule out a role for attention in spatial working memory, such a role appears not as important as previously considered.

One potential problem with this experiment is that the search process for an oblique target among vertical distractors is known to occur in parallel (e.g., Treisman & Gelade, 1980). In parallel search a target could be found easily, and attention could be allocated efficiently. One possibility is that focused attention may shift towards the target and shift back to the memory location very quickly, with the associated impairment to memory maintenance being too small to be detected. In Experiment 3, we tried to generalize our results to a serial search paradigm. In serial search, there should be a stronger need for attention to shift around the search array than in parallel search when preattentive information does not guide attention. In a shifting-attention condition, attention moves around the display to facilitate localization of the target, and this should require a few attentional fixations at multiple positions on the display. This operation should severely interfere with any attention-based memory maintenance process. In a static-attention condition, however, because the target and the memory location coincide, target detection should be easy since an attention shift is not necessary. This is especially true given the common findings that search tends to start at the memory location (e.g., search performance was better in the static-attention conditions in both Experiments 1 and 2). If spatial memory maintenance is indeed attention-based, any effect of an attentional shift on memory performance should be enlarged and detectable by Experiment 3.

4. Experiment 3

4.1. Method

4.1.1. Participants

Twelve students from the University of Hong Kong participated in the experiment. Data from two of them were discarded due to excessive eye movements as measured by the catch task. All had normal or corrected-to-normal vision. They were paid HK$30 for a 30 min session.

4.1.2. Apparatus and stimuli

The stimuli were based upon those used in Experiment 1 except for the following changes. In the serial search task, the search items were "Π" shapes composed of three 0.6° long, 0.2° thick, round ended lines (Fig. 4 gives an illustration). A target had a missing edge on either the left or right side, and a distractor had a missing edge on either the top or bottom side. The target and distractors were positioned as in Experiment 2.

4.1.3. Design and procedure

All aspects of the design and procedure were identical to Experiment 2. With regard to the change of target stimuli, participants pressed the left-shift button for a left-edge-missing target and the right-shift button for a right-edge-missing target (see Fig. 4 for an illustration).

4.2. Results

4.2.1. Catch trials

Only data from participants with higher than 92% accuracy on the catch trials were analyzed. For the analyzed data, the average accuracy of the catch trials was 96.8%, reflecting very good fixation performance.

4.2.2. Serial search performance

Data were screened in the same way as for Experiment 1, which accounted for 4.4% of all trials. Results are shown in Fig. 5, right panel. Paired *t*-tests were conducted to analyze the results. Responses were reliably more accurate in the static-attention condition than in the shifting-attention condition, 88.1% versus 83.7%, $t(9) = 2.48$, $p < .04$. This result basically replicates the pattern of Experiments 1 and 2, suggesting that attention tended to be biased towards a location retained in working memory. In line with the accuracy results, correct RTs were faster in the static-attention condition, although it was not statistically reliable, 925 ms versus 959 ms, $t(9) = 1.53$, $p > .1$.

4.2.3. Spatial working memory performance

Data were screened in the same way as for Experiment 1. Similar to Experiment 2, a paired *t*-test showed no difference in terms of accuracy between the static-attention and shifting-attention conditions, 90.9% versus 89.6%, respectively, $t(9) = .71$, $p > .4$ (Fig. 5, left panel). Again, this shows that shifting attention to a dis-

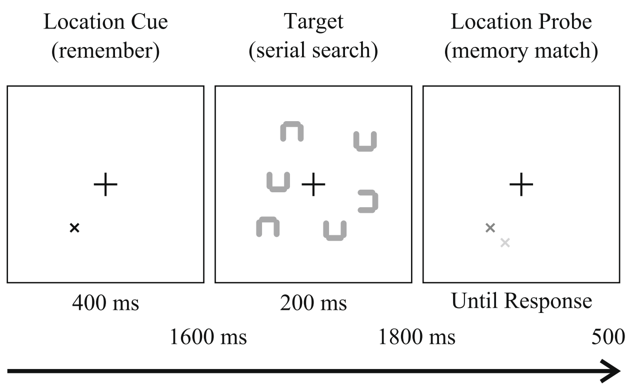

Fig. 4. Illustration of a test trial in Experiment 3. The participants were instructed to memorize the location of a location cue. Then, they searched for a target with either a left or right missing edge among items with either a top or bottom missing edge and judged which edge was missing. After that, they judged which location probe matched the memory location.

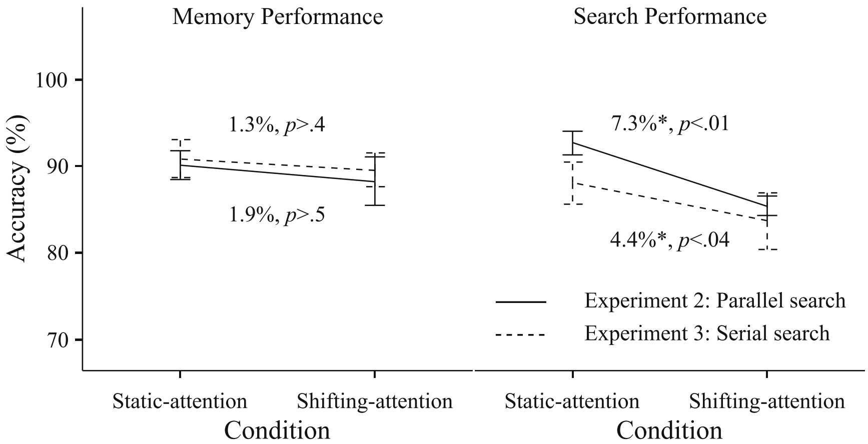

Fig. 5. Results of Experiments 2 and 3. The left panel shows that in both experiments participants performed equally well in the spatial working memory task in both conditions. The right panel shows that in both experiments search was more accurate in the static-attention condition. Error bars show 1 standard error of mean.

tant target in a serial search did not impair working memory performance. RTs were not analyzed as responses were unspeeded.

4.3. Discussion

The present findings are consistent with those of Experiment 2. The findings suggest that attention is biased towards the memory location, and question whether focusing of attention is indeed crucial for the maintenance of spatial working memory. According to the attention-based rehearsal hypothesis, the serial search process should severely disrupt any attention-based rehearsal process that is needed to retain a spatial location in memory. However, this disruption was not observed. This result questions Awh et al.'s (1998) attention-based rehearsal hypothesis.

Experiment 4 was conducted to address two potential issues associated with the conclusions of Experiments 2 and 3. The first issue was that although eye-fixation performance was assessed using a catch task, it remained possible that the catch stimuli were identifiable using parafoveal vision. To evaluate this problem, we tested the performance of the catch task while asking participants to fixate at the memory cue instead of at the center ($N = 3$). We found that performance was much lower (80.3%) than what we observed in our earlier experiments even when the memory cue occurred at its nearest possible distance from the center (3.5°). However, a reasonable concern is that fixation might not have been maintained in some of the trials. Another potential issue is that the use of a visual search display could induce a broadening of the attentional window, and this may have produced an effect similar to a shift of attention.[2] If attentional broadening impaired memory performance, occurring in both the static-attention and shifting-attention conditions, similar memory performance between the two conditions would have been expected. In this case, the present findings may be consistent with the attention-based rehearsal hypothesis.

5. Experiment 4

Experiment 4 was conducted to address these two issues. First, we inserted two flankers on each side of the catch task stimulus. The flanker stimulus is a 3-pixel wide, 1-pixel thick "+" symbol. These flankers should produce a perceptual crowding effect (Bouma, 1970), and profoundly impair parafoveal recognition of the catch stimulus. A pilot experiment ($N = 3$) showed that when fixating at a memory cue 3.5° away from the center, identification accuracy for the catch stimulus was 61.7%. Identification accuracy was 98.3% if participants fixated at the center.[3] With these measures, we were able to better evaluate fixation performance. Second, we added an *empty-space condition* in which neither a target nor a distractor appeared at the memory location. On one hand, we would expect worse memory performance in this condition due to a lack of a stimulus refreshing the memory representation. On the other hand, we would expect that attentional broadening would produce similar performance across all conditions, given that the onset of the visual search display should equally disrupt spatial working memory.

5.1. Method

5.1.1. Participants

Eighteen students from the University of Hong Kong participated in the experiment. Data from three of them were discarded due to excessive eye movements as measured by the catch task. All had normal or corrected-to-normal vision. They were paid HK$30 for a 30 min session.

5.1.2. Apparatus and stimuli

The stimuli were based upon those used in Experiment 3 except that the set size of the serial search was reduced to five. Therefore, in every search display, five of the six cells each contained a search item, and one of the six cells was empty. In 16.7% of trials, the memory location would coincide with an empty cell. These constituted trials for the empty-space condition.

5.1.3. Design and procedure

An empty-space condition in which no visual search item occurred at the memory location was added alongside the static-attention and shifting-attention conditions. The empty-space, static-attention and shifting-attention conditions constituted 16.7%, 16.7% and 66.7% of test trials, respectively. All other aspects of the design and procedure were identical to Experiment 3.

[2] We thank Todd Horowitz for suggesting this possibility.

[3] We tested recognition performance of the catch stimulus at four eccentricities, namely 0°, 1.8°, 3.5° and 5.3°. The identification accuracies were 98.3%, 69.2%, 61.7% and 54.2%, respectively. Data from the 3.5° and 5.3° conditions were most relevant to the present study as they were the closest and average eccentricities of the location cue used in Experiment 4.

5.2. Results

5.2.1. Catch trials

Only data from participants with higher than 92% accuracy on the catch trials were analyzed. For the analyzed data, the average accuracy of the catch trials was 97.5%, reflecting very good fixation performance.

5.2.2. Serial search performance

Data were screened in the same way as for Experiment 1, which accounted for 1.7% of all trials. Results are shown in Fig. 6, right panel. A paired t-test was conducted to analyze the results. Correct RTs were reliably faster in the static-attention condition than in the shifting-attention condition, 894 ms versus 951 ms, $t(14) = 3.18$, $p < .01$. Consistent with previous experiments, this finding suggests that attention tended to be biased towards a location retained in working memory. However, correct RTs were faster in the empty-space condition, 910 ms, than in the shifting-attention condition, $t(14) = 4.32$, $p < .001$. This difference is discussed in the *Discussion* section below. The difference between the empty-space and static-attention condition was not significant, $t(14) = .90$, $p > .3$. A one-way repeated-measures analysis of variance revealed no effect between these conditions in terms of accuracy, 92.6%, 92.0% and 93.7%, $F(2,28) = .644$, $p > .5$.

5.2.3. Spatial working memory performance

Data were screened in the same way as for Experiment 1. Results are shown in Fig. 6, left panel. Consistent with Experiments 2 and 3, a paired t-test showed no accuracy difference between the static-attention and shifting-attention conditions, 91.9% versus 90.1%, respectively, $t(14) = 1.29$, $p > .2$. Responses were less accurate in the empty-space condition (86%) than in the static-attention condition, $t(14) = 2.77$, $p < .02$, or in the shifting-attention condition, $t(14) = 2.34$, $p < .04$. This indicates that the presence of a visual item at the memory location improved memory performance, and is not consistent with the proposal that a visual search display triggers an attentional broadening process that interferes with memory maintenance. RTs were not analyzed as responses were unspeeded.

5.3. Discussion

The results of the search and memory tasks from this experiment are consistent with those obtained from Experiments 2 and 3. Search performance was better in the static-attention condition than in the shifting-attention condition, showing that spatial working memory tends to bias attentional prioritization towards a memorized location. However, no difference in memory performance was observed between the static-attention and the shifting-attention conditions. This lack of difference, consistent with the results of Experiments 2 and 3, leads us to question whether focusing of attention at a memorized location is crucial for spatial working memory maintenance.

By including an empty-space condition, it was also possible to address a potential confound, namely that the onset of a visual search display induces broadening of attentional focus, which in turn interferes with attention-based rehearsal. If this effect had occurred, similar memory performance across all conditions should have been observed, because similar search displays were involved in all conditions. However, worse memory performance was observed in the empty-space condition relative to the static-attention and shifting-attention conditions. This result is consistent with the suggestion that the presence of a visual stimulus at the memory location refreshes memory representation and improves memory. This result is inconsistent with the attentional broadening account of the results in our earlier experiments. In addition, this result is consistent with the results of Experiment 1, and also with the results of Belopolsky and Theeuwes (2009).

With regard to the visual search task, one may notice that performance differences were observed in terms of RT instead of accuracy. We do not have an explanation as to why sometimes effects occur for accuracy and other times for RT. Probably, participants in this experiment favored accuracy to speed, since the RTs are similar to Experiment 3, whereas fewer items were used, and accuracies improved. Whatever the reason, since both measures legitimately reflect search performance, we do not consider how participants trade off accuracy with speed to be a critical issue. Another unexpected observation is that RTs were faster in the empty-space condition than in the shifting-attention condition. This was not expected as the target had not appeared at the memory location in either conditions, and so the serial search should have been similarly slow in both. A potential reason for this RT difference is that in the shifting-attention condition, but not in the empty-space condition, a distractor appeared at the memory location. Here, disengaging attention from an object (i.e., the distractor) may be slower than disengaging attention from an empty space (e.g., Brown & Denney, 2007; Theeuwes, 1991). This may have rendered a delay of search in the shifting-attention condition relative to the empty-space condition.

6. General discussion

In four experiments, participants judged the identity of a search target while retaining a spatial location in working memory. In

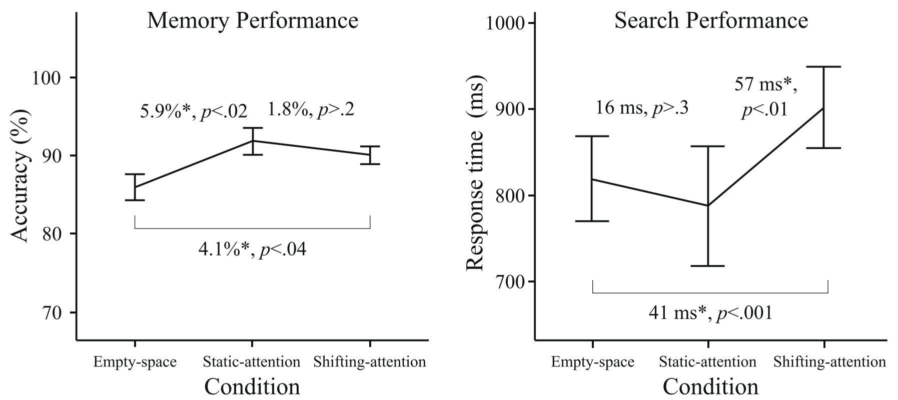

Fig. 6. Results of Experiment 4. The left panel shows that participants performed equally well in the spatial working memory task in the static-attention and shifting-attention conditions, but worse in the empty-space condition. The right panel shows that search was faster in the static-attention and empty-space conditions than in the shifting-attention condition. Please see text for details. Error bars show 1 standard error of mean.

Experiment 1, the search target was the only visual item in the display; in Experiment 2, the search target was the only oblique item, among a number of vertical items, and localization of the target was efficient; in Experiments 3 and 4, the search target was localized only by effortful serial search. In these experiments, we demonstrated a consistent trend that whenever a spatial location was kept in working memory, attention prioritization was biased towards this location. This was reflected by better search performance when the search target occurred at the memory location, compared to when the target occurred away from the memory location. On the other hand, in Experiments 2, 3 and 4, our findings are inconsistent with the previous observation that spatial working memory performance is impaired by tasks that require an attentional shift (Awh et al., 1998; Oh & Kim, 2004; Woodman & Luck, 2004). In our experiments, we failed to observe any impairment to working memory performance when attention shifted. Findings of Experiment 4 ruled out the possibility that the onset of a visual search display may interfere with and mask any effects from an attention-based rehearsal process. Taken together, the present findings confirm the conclusion that remembering a spatial location influences attentional allocation; however, the findings question the previous proposal that working memory for a spatial location may be maintained by attention-based rehearsal.

Why was there a discrepancy in the disrupting effect of making an attentional shift in spatial working memory performance between previous reports and the present study? Previous studies that reported memory impairment by attentional shifts relied on a comparison between a memory-only, single-task condition and a memory-and-search, dual-task condition. Oh and Kim (2004) and Woodman and Luck (2004) measured memory impairment in visual search tasks. In their memory-only condition, a blank period replaced the visual search task. Both studies reported that memory performance was impaired by the insertion of the search tasks, at least when the search had a large set size. In Awh et al.'s (1998) study, similarly, memory impairment was measured by comparing between a passive-viewing, memory-only condition and a memory-and-choice dual-task condition. In the memory-only condition, participants passively viewed the choice stimulus without needing to work on the task. In the memory-and-choice condition, the choice stimulus never appeared at the memory location. They also reported an impairment of memory performance by the insertion of the choice task.

As mentioned in the introduction, a problem associated with measuring working memory impairment by comparing dual- and single-task conditions is that the presence of the search task itself, rather than the actual need for an attentional shift, may be sufficient to reduce working memory performance. This point was demonstrated by the static-attention condition of Awh et al. (1998), in which they made use of a choice stimulus (a color disc) which was large enough to cover all possible memory locations so that an attentional shift was not needed; however, they still observed a drop in memory performance by the insertion of this control choice task. Although Awh et al. drew their conclusion on the basis of a larger dual-task cost associated with a condition requiring an attentional shift, it was difficult to determine whether this difference was due to the additional need for attentional processing or was instead due to subtle between-task differences.

It was not difficult to imagine that this kind of dual-task cost was easily influenced by extraneous factors. In Oh and Kim's (2004) Experiment 1, the dual-task cost was absent at a small set size of four despite being a serial search; in Woodman and Luck's (2004) Experiment 1, the dual-task cost was more obvious at the same set size. After all, in both cases, attentional shifts were necessary in their serial search tasks; however, the dual-task cost was not always present. Here, it demonstrates that dual-task costs are not an extremely stable measure that allows for cross-experiment comparisons.

In the present study, however, we investigated the cost to working memory performance of a need for a shift of attention within the same task. By using a visual search display, we controlled for extraneous factors including masking and priming. We found that in three experiments, the need for shifting attentional focus was not associated with any cost to working memory performance. In each of these experiments there was a very small observed cost; however, this non-significant cost was less than 2% drop in accuracy in each case. This small difference does not appear to us to constitute any support for a notion that focusing attention on a location is the primary mechanism for maintaining that location in spatial working memory.

Consistent with the present findings, Belopolsky and Theeuwes (2009) also failed to find any cost to working memory performance when a shift of attention was manipulated within the same task (using methods similar to the present Experiment 1 and the Experiment 1 of Awh et al., 1998). In their Experiment 5B, better target identification performance was associated with the static-attention condition, showing that attention was paid to the memory location. Yet, no memory improvement was observed when compared to a shifting-attention condition. Their results strengthen our conclusion that focusing attention at the memory location does not seem to be the mechanism for working memory maintenance.

Although the present findings cast strong doubt on the attention-based rehearsal hypothesis (Awh et al., 1998), given that a shift of attention does not seem to correlate with a reduction in memory performance, it is a separate issue whether spatial working memory can influence attentional allocation. The present results as well as findings by Awh et al. (1998) suggest that maintaining a spatial location in working memory does bias attentional prioritization in search. Contrary to these findings is that in four out of five experiments Belopolsky and Theeuwes (2009) found that attentional processing at a memorized location was inhibited, rather than facilitated, in a target identification task embedded in a spatial working memory task. What do these apparently conflicting results suggest?

If the inhibition observed in Belopolsky and Theeuwes' (2009) study was viewed as IOR, this would mean that spatial attention had been paid at the memory location before the search. Support for this possibility follows from their observation that inhibition tends to occur at longer memory-to-search intervals, given an apparent trend of memory-driven facilitation at shorter memory-to-search intervals. If we accepted that the inhibition observed in their study was due to IOR, we could conclude that Awh et al. (1998), Belopolsky and Theeuwes (2009), and the present study are all consistent in observing direct or indirect evidence that spatial attention is paid to the memory location (because one has to first attend to a location in order to produce an IOR at that location). The only difference among these results is when did participants start to shift attention away from the memory cue. However, this discrepancy is not a central issue to the current investigation. The more important findings are that attention was paid to the memory location, and that shifts of attention during the retention interval, no matter before or during search, had no effect on memory performance. These two points taken together lead us to speculate that attending to the memory position may be necessary for *encoding* a spatial location into spatial working memory.

The conclusion of the present study is that whereas we showed evidence for attentional allocation being influenced by spatial working memory, this impact appears to be a one-way relationship. We were not able to find evidence for any influence from the shifting of attention to spatial working memory. Of course, we cannot preclude the possibility that fixating spatial attention at a location can be used as a deliberate strategy to facilitate spatial working memory performance. However, the present findings suggest that this strategy is not the generic mechanism of working memory maintenance. Finally, we speculate that the encoding of a spatial working memory may require focused attention, which would explain why working memory captures attention. Overall, we have shown that there exist clear links between spatial working memory and spatial attention, but the way in which they are connected does not seem to be sufficiently described by previous proposals; more future research is required to clarify this issue.

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