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Rehearsal in Spatial Working Memory

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Much of the research concerning spatial working memory has focused on its independence from other working memory systems. For instance, the influential model of working memory introduced by [Baddeley and Hitch \(1974\)](#) emphasizes the separability of visuospatial and verbal storage mechanisms. Consistent with this model, there is now a substantial body of behavioral and neuropsychological evidence supporting a functional dissociation between spatial and verbal working memory systems (for a review, see [Jonides et al., 1996](#)). Although the dissection of verbal working memory into its component processes has been productive (see, e. g. , [Awh et al., 1996](#); [Paulesu, Frith, & Frackowiak, 1993](#)), a description of the specific mechanisms that mediate spatial working memory has been more elusive. Here we present the results of several experiments that identify what appears to be an integral component of spatial working memory—a spatial attentional mechanism that may play the role that verbal rehearsal plays for verbal working memory.

Ours is not the first observation that spatial attention and spatial working memory may be related. [Smyth and Scholey \(1994\)](#) offered evidence that maintenance in visuospatial working memory involves shifts of spatial attention. Their studies measured performance in a version of the Corsi blocks task in which participants memorized the temporal order of stimulus presentation in a predefined array of boxes. Performance on this task declined when the retention interval was filled with concurrent tasks that caused shifts of spatial attention. Although these data suggest a role for spatial attention in the Corsi blocks task, it is still unclear which component of the task was disrupted. For instance, it is possible that the concurrent shifts of

spatial attention interfered with participants' memory of the temporal order of the stimuli, rather than with spatial memory per se. Also, while spatial attention was implicated, its specific role in visuospatial storage was not elucidated. Below we propose an explicit account of how spatial selective attention might mediate rehearsal in spatial working memory, and we test predictions that exploit the known functional characteristics of spatial attention.

A long line of research has demonstrated that allocation of spatial selective attention leads to location-specific improvements in processing efficiency (e. g. , [Posner, 1980](#)). That is, observers can respond with greater speed and accuracy to stimuli that fall in attended rather than unattended regions of space. Furthermore, a growing body of evidence suggests that these enhancements begin at the level of early-sensory processing (see [Mangun, Hansen, & Hillyard, 1987](#)). This model of spatial selective attention, in which there is location-specific modulation of early-sensory processing, is at the core of the hypothesis investigated in this article. We hypothesize that the interaction of spatial selective attention and early-sensory processing mediates the rehearsal of information in spatial working memory.

To be concrete, we propose that the frontal and parietal mechanisms that guide the internal allocation of attention (see [Mesulam, 1981](#)) cause enhanced activation of sites in extrastriate occipital cortex, resulting in heightened activation of location-specific representations. In this way, the allocation of spatial attention during a retention interval facilitates the prolonged activation of spatially specific representations in working memory (much as the rehearsal of verbal representations during a retention interval may cause heightened activation of those representations in a verbal working memory task). There is neuroanatomical evidence in support of this hypothesis. A review of the neural circuitry underlying spatial working memory and spatial selective attention ([Awh & Jonides, in press](#)) has shown that there is considerable overlap in the cortical sites that participate in these tasks. Beyond the sheer overlap in neuroanatomical sites of attention and memory, we draw two direct behavioral predictions from this model:

- If spatial selective attention is directed toward locations held in working memory, then the typical effects of selective attention—enhanced visual processing at attended locations—should be evident at memorized locations.
- If participants are hindered in their ability to attend to memorized locations, they should also be impaired in their ability to remember those locations.

Experiment 1 provides evidence for prediction 1 by measuring visual processing efficiency at memorized and nonmemorized locations. Experiment 2 eliminates key alternative explanations for the results of Experiment 1 by using an identical stimulus display with a nonspatial memory task. Finally, Experiment 3 tests Prediction 2 by comparing the effects of two color-discrimination tasks on the retention of spatial information. Although the discriminations and responses required by the color tasks were similar, only one of them entailed shifts of spatial selective attention away from the memorized location.

[Experiment 1](#)

[Awh, Smith, and Jonides \(1995\)](#) carried out a preliminary behavioral test of Prediction 1. Participants performed a choice reaction time task during the retention interval of a spatial working memory task. On only 25% of the trials (*choice matches*), the position of the choice stimulus matched the memorized location. The key prediction was that there should be faster reaction times to choice matches than to choice stimuli that fell in nonmemorized locations (*choice misses*). The prediction was confirmed; participants were reliably faster to respond to choice matches (598 ms) than to choice misses (615 ms).

Although these results are consistent with the proposed model of spatial working memory, [Awh et al. \(1995\)](#) emphasized that two alternative hypotheses should be considered: (a) The presentation of the memory cue itself may have caused *automatic orienting* of attention ([Jonides, 1981](#)) to the memorized location, regardless of whether this orienting subserved spatial working memory; and (b) participants may have noticed that the memory cue predicted the location of the choice stimulus with 25% validity. Thus, participants may have engaged in *strategic orienting* toward the memorized location in order to facilitate choice performance (i. e. , *not* in the service of memory). We designed Experiments 1 and 2 to address these alternative explanations. The logic is straightforward: Independent groups of participants memorized either spatial or nonspatial aspects of an identical stimulus display. Once again, visual processing efficiency was assessed with a choice reaction time task. The prediction was that the reaction time advantage for choice matches would be observed only when spatial working memory was engaged.

Method

Participants.

Eight University of Michigan students were paid to participate in two 1-hr sessions; an additional participant was eliminated because he did not comply with instructions to maintain gaze in the center of the display. All participants were right-handed men with either normal or corrected-to-normal vision.

Equipment.

Stimulus events and responses were collected with a Macintosh computer with a 14-in. monitor that was used to run Psyscope 1.0.2 (Cohen, MacWhinney, Flatt, & Provost, 1993). Participants were seated approximately 45 cm from the display. Eye movements were monitored with a video camera, the output of which was evaluated by observers after the experimental session was complete. Trials in which eye movements occurred before the completion of the choice response were eliminated from subsequent analyses. Participants made all responses with their right hands using a two-button mouse.

Design and procedure.

The sequence of events in a single trial (depicted in

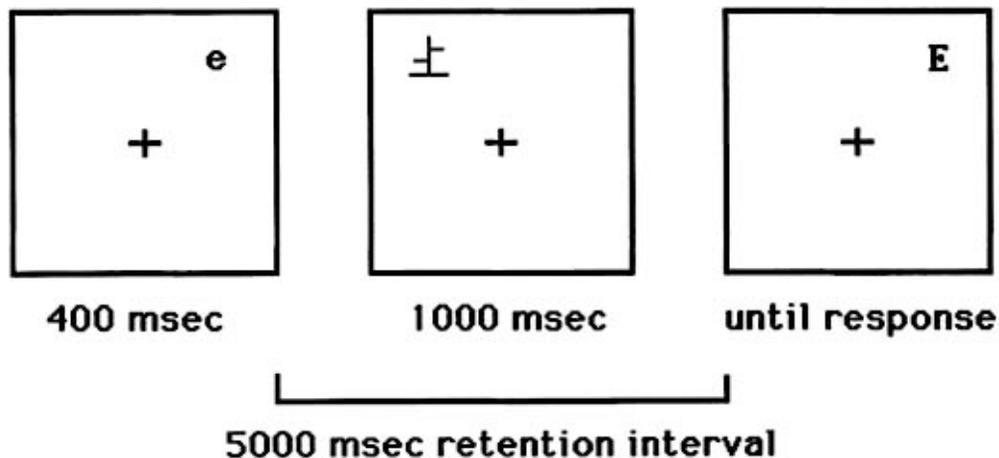


Figure 1 - Sequence of events in a single trial of the spatial and letter dual tasks.

Figure 1) was as follows: (a) The appearance of a central fixation cross and a 50-ms warning tone marked the beginning of each trial. (b) Five hundred milliseconds after the onset of fixation, the *memory stimulus* (a lowercase letter in 24-point bold New York font) was presented for 400 ms. The potential locations of this letter included 36 equally spaced positions on each of three imaginary concentric circles with radii of 4°, 4.8°, and 5.5° of visual angle (the *inner*, *middle*, and *outer* circles, respectively). Thus, there were 108 equally likely positions for the presentation of the memory stimulus. (c) A 5,000-ms retention interval ensued, during which one of two possible choice reaction time stimuli appeared for 1,000 ms (potential locations were the same as those for memory stimuli). The choice stimulus appeared after an interval that varied randomly between 1,500, 2,500, and 3,500 ms after the offset of the memory stimulus. The choice stimulus was one of two letterlike stimuli (see Figure 1). Participants indicated which choice stimulus had appeared by pressing either the right or left key of the mouse. (d) At the end of the retention interval, an uppercase letter in 24-point bold New York font appeared. This letter remained visible until the participant pressed the right or left mouse key to indicate whether or not the letter was in the same location as the original memory stimulus. Participants received auditory feedback (a 50-ms buzz) when they responded incorrectly to either the choice stimulus or the memory probe. There was an intertrial interval of 200 ms.

The position of the memory probes matched the memorized location with probability .5 (*hit trials*). When the probe did not fall in the memorized location (*miss trials*), the distance between the probe and the cross was varied systematically between 0.7°, 2°, and 2.7° of visual angle (Miss 1, Miss 2, and Miss 3, respectively). The identity of the letters used as the memory

stimulus and the memory probe matched with probability .5; this was arranged for the purpose of matching this experiment with Experiment 2 below.

The choice stimulus appeared in the same location as the one held in memory (*choice match*) with probability .25. When the choice stimulus appeared elsewhere (*choice miss*), the distance from the memorized location depended on which of the three possible circles the choice stimulus occupied. Specifically, the choice stimulus appeared either 4.8°, 6.6°, or 8.2° away from the memorized location (on the inner, middle, and outer circles, respectively). The distance of the choice misses from the memorized locations was intentionally confounded with the circle on which the choice stimuli appeared so that reaction times to stimuli at each distance could be compared with choice matches at equivalent retinal eccentricities. That is, choice misses on each circle could be compared with choice matches falling on the same circle. Note that while the eccentricity of the choice miss stimuli was predictive of their distance from the memorized location, there was still a random relationship between the eccentricity of the memory and choice miss stimuli.

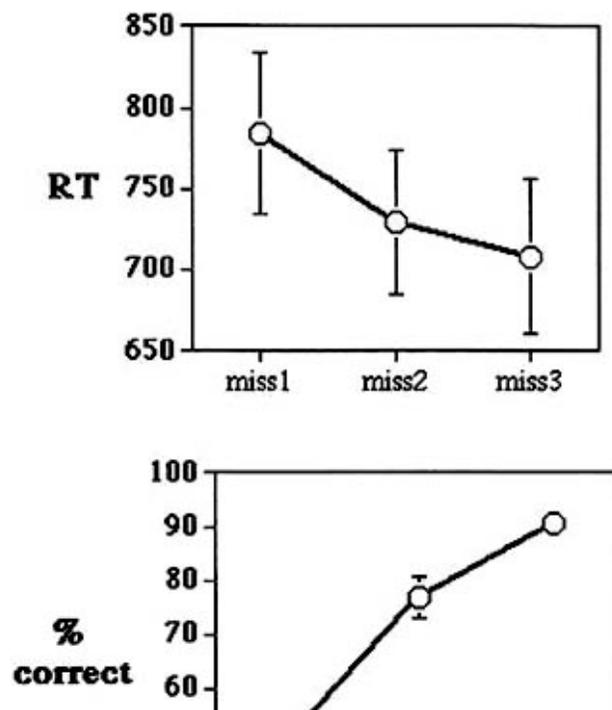
The first session was used to familiarize the participants with the task. To facilitate this goal, we broke the dual task into two separate tasks: *memory-alone* and *choice-alone*. The memory-alone task was identical to the dual task except that no choice stimuli were presented. The choice-alone trials were identical to the dual-task trials with the following modifications: (a) The memory stimuli and memory probes were eliminated, and (b) each trial ended directly after presentation of the choice stimulus. During Session 1, participants practiced four blocks (160 trials) of the memory-alone task, two blocks (80 trials) of the choice-alone task, and two blocks (96 trials) of the dual task. The second session started with one practice block of the memory-alone task, which was followed by six blocks of the dual task (288 trials). The 288 dual-task trials consisted of 216 choice-miss trials (72 on each circle) and 72 choice-match trials (24 on each circle). The order of trials was completely randomized.

Participants were instructed to give *memory accuracy* the highest priority. In addition, they were told to respond quickly, but never at the expense of accuracy. Likewise, participants were instructed to respond to the choice stimuli as quickly as possible without compromising memory accuracy. Finally, participants were told to maintain fixation on the central fixation cross throughout each trial. During the practice session, participants were warned when deviations from fixation were detected.

Results

Memory responses.

Accuracy and reaction time data for correct responses (depicted in



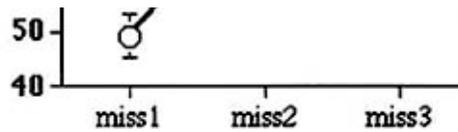


Figure 2 - Mean reaction time (RT, in milliseconds) and accuracy of spatial memory responses during miss trials, as a function of the probe's distance from the memorized location.

Figure 2) for participants' memory responses were orderly. The mean accuracy on the memory task was 77%. Whether the identity of the memory probe matched that of the memory cue had no reliable effect on accuracy (77% and 76% for identity matches and mismatches, respectively), $t(7) = 0.6, p > .05$, or reaction time (720 ms and 723 ms, respectively), $t(7) = 0.35, p > .05$. However, the distance of the memory probe from the memorized location had a strong and reliable effect. The mean accuracy on miss trials was 49%, 77%, and 90% on Miss 1, Miss 2, and Miss 3 trials, respectively, showing a monotonic increase as the distance of the probe from the memorized location increased, $F(2,14) = 39.5, p < .05$. Similarly, correct reaction times to memory probes were 756, 702, and 677 ms for Miss 1, Miss 2, and Miss 3 trials, respectively, showing a monotonic decrease as the distance of the probe from the memorized location increased, $F(2,14) = 29.1, p < .05$. These distance effects provide evidence that participants were using a spatial coding strategy to perform the primary memory task. ¹

Choice responses.

One participant whose eyes moved on more than 50% of the trials was replaced. Across the final 8 participants, an average of 8.3% of trials were eliminated because of eye movements. The procedure used for identifying trials with eye movements was as follows: (a) The onset of the trial was noted by the sound of the warning tone on the videotape, and (b) the stability of the participant's gaze was monitored from trial onset until the observer heard the click of the mouse from the participant's choice response. We assessed the reliability of this procedure by comparing one experimenter's ratings with those of two independent observers. Across selected blocks from 3 different participants, there was a 96% correspondence in eye-movement ratings between the experimenter and each of the independent observers. Only reaction times to correct responses were analyzed; the mean accuracy was 98%.

Table 1
Mean Reaction Times (in Milliseconds) for Choice Responses in the Spatial Dual Task

Condition	Choice match	Choice miss
Choice interval		
1,500 ms	622	631
2,500 ms	598	611
3,500 ms	594	605
Circle		
Inner	602	605
Middle	596	610
Outer	617	632
Grand mean	605	616

Table 1 displays mean correct choice reaction times for choice-miss and choice-match trials.

Reaction times to choice matches were reliably faster than those to choice misses. Mean reaction times were, respectively, 604 and 615 ms for choice matches and choice misses; 603, 604, and 623 ms for the inner, middle, and outer circles; and 626, 605, and 599 ms for the choice intervals of 1,500, 2,500, and 3,500 ms. The total number of trials was not sufficient for analyzing concurrently the effects of cue (choice match vs. choice miss), circle, and choice interval. However, the interactions of cue with circle and cue with choice interval are both of theoretical interest. Thus, two separate analyses of variance (ANOVAs) were carried out: (a) The first ANOVA was a two-way repeated measures analysis of cue and circle. This analysis revealed a main effect of cue, $F(1,7) = 6.8, p < .05$, and circle, $F(2,14) = 5.6, p < .05$. The interaction of cue and circle was not significant, $F(2,14) = 0.79, p > .05$. (b) The second ANOVA was a two-way repeated measures analysis of cue and choice interval. This analysis revealed main

effects of cue, $F(2,7) = 5.6$, $p < .05$, and choice interval, $F(2,14) = 9.1$, $p < .05$. The interaction of cue and choice interval did not approach significance, $F(2,14) = 0.05$, $p > .05$. Accuracy in the choice-match and choice-miss conditions (98.4% and 97.6%, respectively) was not significantly different, $t(7) = 1.4$, $p > .05$, indicating that there was no noticeable speed-accuracy trade-off.

Discussion

The key prediction in this experiment was confirmed. Participants were reliably faster to respond to choice stimuli when they appeared in locations that were currently in working memory. The enhanced processing observed at memorized locations supports the hypothesis that participants allocate spatial selective attention to locations held in working memory. Reaction time benefits associated with spatial attention have been shown to increase as the distance increases between attended and unattended locations ([Downing, 1985](#)). Thus, because the distance between the memorized location and the choice misses was directly correlated with the circle on which they appeared (4.8°, 6.6°, or 8.2° on the inner, middle, and outer circles, respectively), one might predict an interaction of cue and circle in this experiment. This should have presented itself as a larger difference between choice matches and choice misses as the distance increased between the choice misses and the memorized locations. Although the overall means suggest a trend in this direction, the interaction did not reach significance. Nonetheless, there does appear to be an influence of memorized location on attentional allocation.

Experiment 2

There are alternative hypotheses that are not directly addressed by Experiment 1: (a) The abrupt onset of the memory cues may have elicited automatic orienting to the memorized locations, or (b) participants may have engaged in strategic orienting to the memorized locations in the service of the choice task. However, an argument to the contrary is worth noting: The automatic-orienting hypothesis is made less plausible by the fact that there was a minimum 1,500-ms interval between the memory cue and the choice stimulus. This time interval exceeds previously demonstrated durations of automatic orienting. [Mueller and Rabbit \(1989\)](#) studied the time course of this process by observing discrimination accuracy at various time intervals (stimulus onset asynchronies, or SOAs) after the presentation of peripheral cues. They found that the benefits associated with peripheral cues peaked within approximately 175 ms but had dissipated by around 400 ms. The attentional effects observed in Experiment 1 are distinct from those observed by Mueller and Rabbit in two ways: (a) The minimum 1,500-ms choice interval far exceeds the estimated 400-ms duration of automatic orienting, and (b) the size of the choice-match advantage observed in Experiment 1 was unaffected by the length of the choice interval, as evidenced by the lack of an interaction between cue and choice interval. But [Mueller and Rabbit \(1989\)](#) observed a strong interaction between SOA and the effects of peripheral cuing, with benefits decreasing sharply as the SOA increased. Thus, the choice-match advantage observed in Experiment 1 is incompatible with the known characteristics of automatic orienting. Nevertheless, Experiment 2 offers a direct test of these alternative hypotheses.

Participants in Experiment 2 memorized the identity of the initial memory cue rather than its location. The stimuli presented, the probability of choice matches, the interval between the memory cue and the choice stimuli, and the presentation durations used in Experiment 1 were duplicated in this experiment. Thus, any stimulus-driven capture of attention that may have had an effect in Experiment 1 should also have driven the results of Experiment 2. [Tsal and Lavie \(1993\)](#) demonstrated that attention toward the color or shape of a stimulus entails directing attention to its location regardless of whether the location of the stimulus is informative, so there is good reason to believe that identification of the letter memory-cue provides a valid test of the automatic-orienting effects of these memory cues. Furthermore, the location of the memory cues in Experiment 2 was once again a valid predictor of the choice stimulus location on 25% of the trials. Thus, Experiment 2 was also intended to demonstrate the extent to which the contingency between the memory cue and the choice stimulus would cause participants to engage in strategic orienting to the location of the memory cue.

Method

Participants.

A new group of 8 University of Michigan students was paid to participate in two 1-hr sessions.

Two additional participants were tested, but their data were discarded because they did not maintain fixation sufficiently accurately, as described below. All participants were right-handed men with either normal or corrected-to-normal vision.

Design and procedure.

The stimulus display and procedures in this experiment were identical to those in Experiment 1 with the following exceptions: (a) When the memory probe appeared, participants based their decisions on whether it was the same in identity as the memory cue. (b) Because memory for the identity of the memory probe was the relevant feature in this task, the position of memory probes was randomly determined on 75% of the trials. On the remaining trials, the probe fell either 0.7°, 2°, or 2.7° of visual angle away from the location of the initial memory cue (as in the miss trials of Experiment 1). This allowed a comparison of the effect of probe distance on memory performance in the two experiments. (c) Because the letter memory-task was relatively easy, only two blocks of practice trials were given in the memory-alone condition during Session 1. However, the same amount of practice was given on the choice-alone task and the dual task (during which the contingency between the memory cue and the choice stimulus locations might be learned).

Results

Memory responses.

The mean accuracy on the letter memory-task was 95%. The distance of the memory probe from the location of the memory cue did not have a significant effect on accuracy, $F(2,14) = 1.05$, $p > .05$, or reaction time, $F(2,14) = 0.25$, $p > .05$ (see

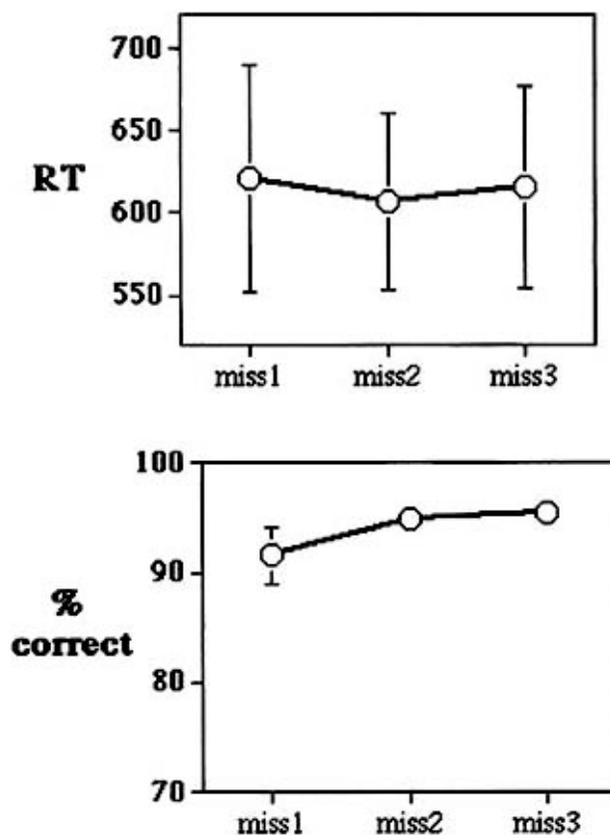


Figure 3 - Mean reaction time (RT, in milliseconds) and accuracy of letter memory responses during miss trials, as a function of the probe's distance from the memorized location.

Figure 3). In order to examine directly the interaction of memory task and probe distance, we carried out a repeated measures ANOVA with probe as a within-subjects variable and task (spatial memory or letter memory—that is, Experiment 1 or Experiment 2) as a between-subjects variable. A significant interaction of task and probe distance was observed for both reaction time,

$F(2,28) = 5.4, p < .05$, and accuracy, $F(2,28) = 22.9, p < .05$. This result suggests that the distance effects observed in Experiment 1 may be diagnostic of the use of a spatial coding strategy.

Choice responses.

Two participants were replaced because of excessive eye movements (over 50% of trials). For the final 8 participants, an average of 5.1% of the trials were eliminated from subsequent analyses because of eye movements that occurred before completion of the choice response. Only correct responses to the choice task were considered; the mean accuracy was 98%.

There was no reaction time advantage for choice-match responses. Mean reaction times were, respectively, 589 and 585 ms for choice matches and choice misses; 579, 585, and 599 ms for inner, middle, and outer circles; and 602, 581, and 580 ms for choice intervals of 1,500, 2,500, and 3,500 ms.

Table 2
Mean Reaction Times (in Milliseconds) for Choice Responses in the Letter Working Memory Dual Task

Condition	Choice match	Choice miss
Choice interval		
1,500 ms	598	604
2,500 ms	583	578
3,500 ms	588	572
Circle		
Inner	581	577
Middle	586	586
Outer	605	592
Grand mean	590	585

2 displays mean reaction times for the correct responses to choice-miss and choice-match trials. As in Experiment 1, two separate analyses were performed with these data: (a) A two-way repeated measures ANOVA with cue and circle as factors revealed no main effect of cue, $F(1,7) = 0.97, p > .05$, and a main effect of circle, $F(2,14) = 4.1, p < .05$. The interaction between cue and circle was not significant, $F(2,14) = 0.68, p > .05$. (b) A two-way repeated measures ANOVA with cue and choice interval as factors revealed no main effect of cue, $F(1,7) = 1.0, p > .05$, and a main effect of choice interval, $F(2,14) = 4.0, p < .05$. In addition, there was a significant interaction of cue and choice interval, $F(2,14) = 4.1, p < .05$; this interaction may be described as an increasing disadvantage for choice matches as the choice interval increased. Accuracy was 98% in both the choice-match and choice-miss conditions, which suggests that there was no strong speed-accuracy trade-off.

In order to examine directly the interaction of memory task and the effect of cue, we carried out a repeated measures ANOVA with cue as a within-subjects variable and task (spatial memory or letter memory—that is, Experiment 1 or Experiment 2) as a between-subjects variable. As predicted, a significant interaction was observed between task and cue, $F(1,14) = 5.2, p < .05$. No main effects were observed for cue, $F(1,14) = 0.43, p > .05$, or task, $F(1,14) = 0.62, p > .05$.

Discussion

When participants memorized the identity of the memory cue rather than the spatial position, they showed no reaction time advantage for choice matches over choice misses. These results argue against the possibility that the reaction time effects found in Experiment 1 were due to stimulus-driven attentional capture. Furthermore, the predictive relationship between the location of the memory cue and the ensuing choice stimulus was identical across experiments. Thus, these results argue against the strategic-orienting hypothesis; participants should have been just as likely to implement such a strategy in Experiment 2, where no reaction time effect was observed. The most compelling remaining explanation is that the act of maintaining information in spatial working memory is the cause of the observed shifts of spatial selective attention.

Letter memory performance was better than spatial memory performance, both in terms of speed and accuracy. However, it is unlikely that this difference influenced the observed interaction of task and cue. There is no reason to suspect that the difficulty level of either memory task influenced the automatic-orienting characteristics of the letter stimuli. Furthermore, it is unclear how a more difficult verbal task would have influenced the degree to which participants might have engaged in strategic orienting. It is possible that the simple fact that spatial information was relevant in Experiment 1 influenced the tendency for participants to notice (and attempt to use) the contingency between the location of the memory cue and the choice stimulus. This possibility is not addressed by Experiment 2. However, Experiment 3 provides additional evidence suggesting that the observed processing advantage at memorized locations is not dependent on any orderly correspondence between the memorized locations and the intervening stimuli.

Experiment 3

Introduction

Experiments 1 and 2 demonstrate the predicted association between spatial working memory and spatial selective attention, but they cannot address the stronger claim that selective attention plays a functional role for spatial working memory. To do this, one needs to show that these shifts of attention are necessary for the accurate maintenance of location-specific information. In line with this reasoning, in Experiment 3 we tested the following prediction: If participants are impaired in their ability to direct attention toward locations in working memory, there should be a corresponding decrease in memory accuracy.

Participants were engaged in color-discrimination tasks during the retention interval of a spatial working memory task. Two types of color stimuli were presented: In one case, the color stimuli occupied discrete randomly selected locations, and accurate discrimination entailed shifts of attention to nonmemorized locations (see [Tsal & Lavie, 1993](#)). Other conditions used color stimuli that occluded all potential memorized locations; as a result, the necessary color information was available everywhere in the display, including within the memorized location, and shifts of spatial attention were not necessary for accurate discrimination. Thus, although the color judgments required by these intervening tasks are virtually identical, only one task entailed shifts of spatial attention. According to the proposed model, shifts of attention to nonmemorized locations should be incompatible with the maintenance of information in spatial working memory because of limited spatial selective attention resources. Therefore, the discrimination task that requires shifts of attention should cause greater decrements in spatial working memory accuracy.

Method

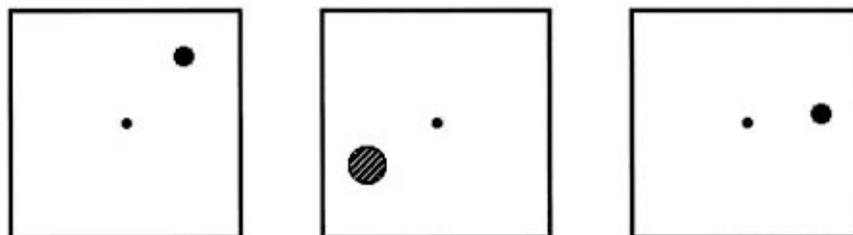
Participants.

Eight University of Michigan students were paid to participate in a single experimental session lasting 2.5 hr. All participants were right-handed men with normal or corrected-to-normal vision.

Design and procedure.

In general, the dual tasks used in Experiment 3 (depicted in

Shifting-Attention Condition



Static-Attention Condition

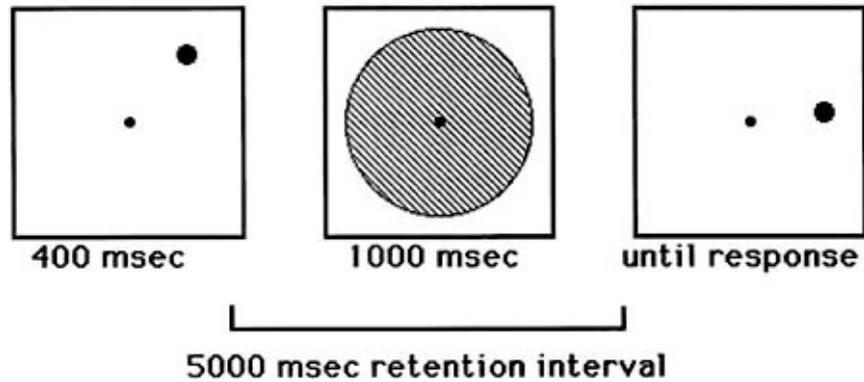


Figure 4 - Sequence of events in a single trial of the shifting-attention and static-attention dual tasks.

Figure 4) were similar to those used in Experiments 1 and 2. Once again, participants performed a spatial working memory task with an intervening choice task during the retention interval. The timing of stimulus presentations and the general features of the stimulus display were identical to those in Experiments 1 and 2 with the following exceptions: Instead of letters, the memory stimuli and the memory probes were black dots that subtended approximately 0.5° of visual angle.

Two types of color stimuli (instead of the choice stimuli used in Experiments 1 and 2) appeared during the retention interval: (a) Half of the stimuli were small colored circles subtending approximately 0.9° of visual angle. The specific colors used for these stimuli were either blue and purple or red and pink.² On each trial, the location of the small color stimulus was randomly selected from the total set of potential memory locations. (b) The other half of the stimuli were large color circles with radii of approximately 8.6° of visual angle. The specific colors used were either two different shades of blue or two different shades of red. All color stimuli were presented for 500 ms. The interstimulus interval between the color stimulus and the memory cue varied randomly among the three values of 1,500, 2,500, and 3,500 ms.

Four separate conditions were run: (a) The *shifting-attention* condition required participants to indicate (by pressing the left or right key on a computer mouse) which of two possible small color stimuli appeared during the retention interval. (b) The *static-attention* condition required participants to indicate (again by pressing the left or right mouse-key) which of two possible large color stimuli had appeared during the retention interval. (c) During the *shifting-control* condition, small color stimuli appeared during the retention interval, but only memory responses were required. (d) Likewise, during the *static-control* condition, large color stimuli appeared during the retention interval, but only memory responses were required. The control conditions were visually identical to their counterparts, and they were included to provide a baseline that accounted for any changes in memory performance caused by simple presentation of the color stimuli. For 4 participants, the blue and purple stimuli appeared in the shifting-attention condition, the blue stimuli appeared in the static-attention condition, and the remaining color pairs were used in the control conditions. The other 4 participants saw the red and pink stimuli during the shifting-attention condition, the red stimuli during the static-attention condition, and the remaining color pairs in the control conditions. Different color pairs were used during the attention and control conditions in order to preclude the possibility that participants might develop a prepotent tendency to respond or attend to the specific colors presented in the shifting- and static-attention conditions.

The experimental session began with practice blocks designed to familiarize participants with the tasks. The dual tasks were broken into separate component tasks for the purpose of facilitating learning and in order to evaluate performance on the color task outside the context of the spatial memory task. The memory-alone task was identical to the one used in Experiments 1 and 2. The *shifting-alone* task was identical to the shifting-attention task with the following modifications: (a) The memory stimuli and memory probes were eliminated, and (b) each trial ended directly after presentation of the color stimulus. Equivalent modifications of the static-attention task created the *static-alone* task.

The session began with three blocks of static-alone practice. Subsequently, a response deadline equal to 1 *SD* above the mean reaction time on Blocks 2 and 3 was imposed, and participants practiced a fourth block of static-alone trials with this deadline. During the fourth block (and throughout the rest of the experiment), participants received auditory feedback if they responded

incorrectly or if they responded after the deadline had passed. An identical practice procedure was applied with the shifting-alone task.

The response deadline procedure was implemented in order to encourage participants to allocate equivalent resources to the color discriminations (i. e. , similar to those applied when the tasks were performed alone) in the shifting- and static-attention conditions. Pilot tests had indicated a greater decline in color-discrimination performance in the shifting-attention condition than in the static-attention condition (relative to the shifting-alone and static-alone performance). These pilot data are compatible with the proposed model in that they suggest the predicted incompatibility between discrimination of small color stimuli and accurate spatial working memory. However, declines in performance on the color-discrimination tasks are contrary to the goal of observing memory performance as the primary dependent variable.

Pilot data were also used to identify colors whose relative discriminability led to approximately equal accuracy on the shifting-alone and static-alone tasks and to faster reaction times to the small color stimuli. We designed the shifting-alone task to be easier than the static-alone task to ensure that general task difficulty could not account for the predicted differences in memory interference. That is, the relative difficulty of the color tasks was biased against our observing the predicted patterns of memory interference.

Practice on the color tasks was followed by two blocks of memory-alone practice and a short break. Dual-task performance data were collected over 12 separate blocks (40 trials each). There were three blocks of each of the four conditions. Each three-block set was preceded by a 20-trial practice run of the ensuing task. The order of block presentation was completely counterbalanced across the 8 participants, taking into account shifting versus static conditions, dual-task versus control-task conditions, and the assignment of color pairs. Participants were encouraged to take short breaks whenever they wished, but all participants were given a mandatory 10-min break after the first six dual-task blocks.

Participants were instructed to give color-discrimination performance the highest priority. That is, they were told to respond to the color stimuli with the same accuracy and reaction time that they had demonstrated during practice trials. Regarding the spatial memory responses, participants were told to give accuracy the highest priority; no emphasis was given to the speed of memory responses. As in Experiments 1 and 2, participants were also instructed to maintain central fixation throughout each trial, and they were reminded of this during practice blocks when eye movements were detected.

Results

Memory responses.

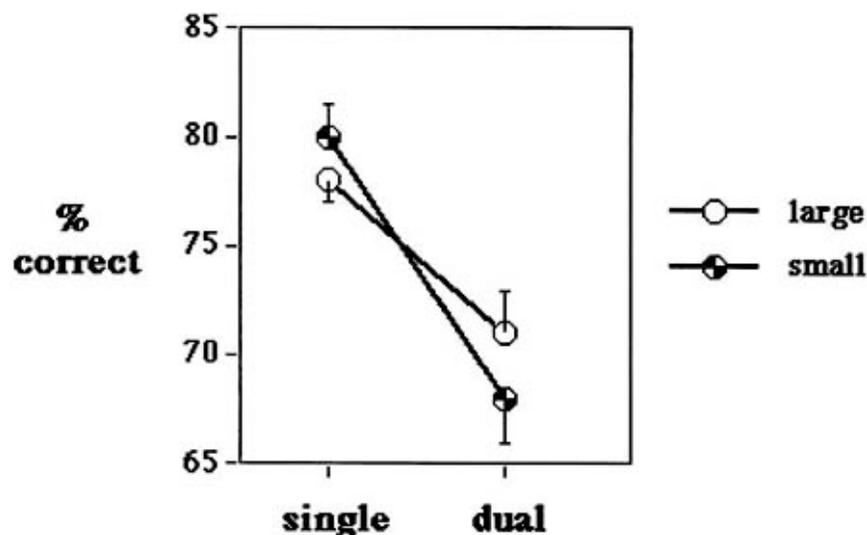


Figure 5 - Spatial memory accuracy as a function of whether participants were responding to the color stimuli and as a function of the size of the color stimuli.

Figure 5 displays a graph of memory accuracy in the four conditions. Memory accuracy was significantly poorer in the shifting-attention condition (68%) than in the static-attention condition

(71%), $t(7) = 2.3$, $p < .05$. Relative to memory performance in the shifting-control condition, responding to the small color stimuli led to a 12% decline in memory accuracy. However, responding to the large color stimuli led to only a 7% decline in spatial memory accuracy (relative to memory performance in the static-control condition). Thus, spatial memory accuracy exhibited a significant crossover interaction between the type of color stimuli that were presented (large vs. small) and whether participants were required to discriminate these colors, $t(7) = 1.8$, $p < .05$, one-tailed. ³

Color responses.

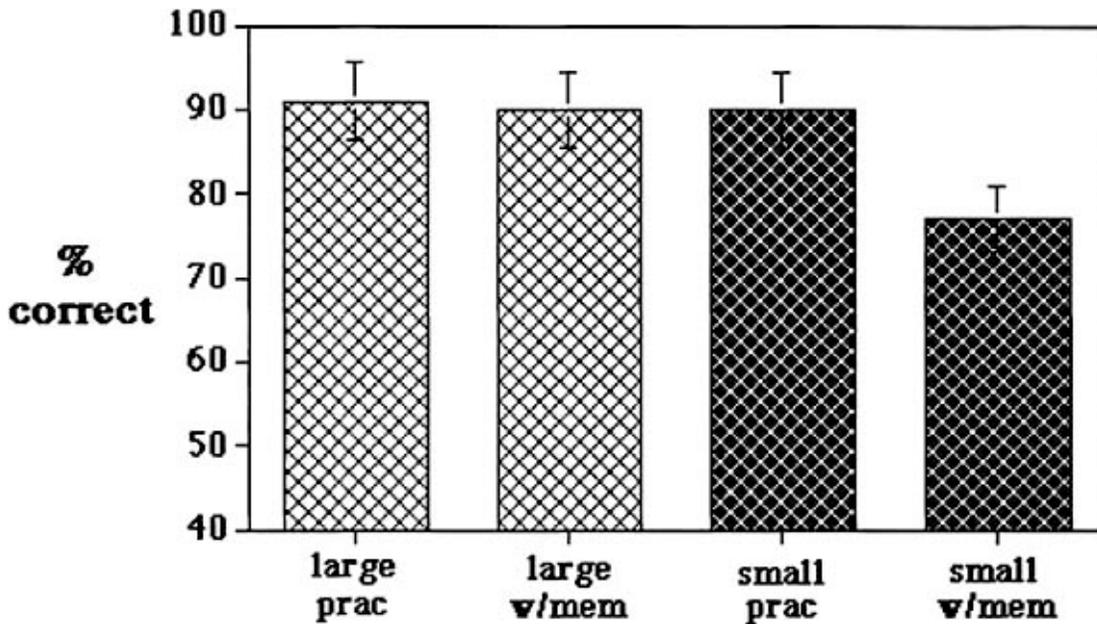


Figure 6 - Color discrimination accuracy for large and small color stimuli during practice (prac) trials (when spatial memory was not engaged) and during dual-task trials (w/mem = with memory task).

Figure 6 displays a graph of color-discrimination accuracy. Consistent with the pilot observations, participants were significantly faster to discriminate the small color stimuli (during the shifting-alone condition) than the large color stimuli (during the static-alone condition), as evidenced by the mean response deadlines imposed on these tasks (592 ms and 649 ms, respectively), $t(7) = 2.6$, $p < .05$. Accuracy was equivalent between the shifting-alone (90%) and static-alone (91%) tasks, $t(7) = 0.14$, $p > .05$. However, in the context of the memory tasks, color discrimination was worse for the small color stimuli (77%) than for the large color stimuli (90%), $t(7) = 3.7$, $p < .05$. Thus, color-discrimination accuracy exhibited a strong interaction between the size of the color stimuli and whether or not spatial working memory was engaged, $t(7) = 3.1$, $p < .05$ (see Footnote 3).

Eye movements.

It was important to verify that the frequency of eye movements in each task was not confounded with the experimental manipulations of interest. A trial-by-trial analysis showed that the shifting-attention and static-attention conditions elicited similar numbers of eye movements (25% and 24% of all trials, respectively), $t(7) = 0.57$, $p > .05$. The shifting-control and static-control conditions were also matched for frequency of eye movements (17% and 16% of all trials, respectively), $t(7) = 1.0$, $p > .05$. However, when the eye-movement count is restricted to the interval before the color response is made, there is a nonsignificant trend toward more eye movements in the shifting-attention condition (13%) than in the static-attention condition (8%), $t(7) = 1.99$, $p = .09$. The period before the color response is of particular interest because only eye movements occurring during this period might be directly attributable to the color-discrimination tasks (though eye movements to the memory cue also occurred during this period). To rule out the possibility that these eye movements might explain the observed patterns in memory accuracy, we reanalyzed these data after removal of all trials with eye movements prior to the color-discrimination response. No qualitative changes in the data were observed. ⁴

Discussion

Spatial working memory accuracy was impaired when an intervening task required shifts of attention to nonmemorized locations. This pattern was revealed by direct comparison of memory accuracy in the shifting- and static-attention conditions, but it was most pronounced when accuracy in each condition was compared with accuracy in the corresponding control condition. These data provide evidence that shifts of spatial selective attention to memorized locations contribute directly to the accurate maintenance of information about location.

Performance on the color-discrimination tasks was also informative. Despite instructions to give highest priority to the color-discrimination task, participants were unable to maintain accuracy on this task during the shifting-attention task. This result cannot be explained in terms of general resource limitations, because participants showed no significant decrease in color task performance during the static-attention condition; this was despite the fact that the static-alone task was, if anything, more difficult than the shifting-alone task. Instead, this result underscores the fundamental incompatibility between the color-discrimination task used in the shifting-attention condition and the accurate maintenance of information in spatial working memory. Notice that this result converges nicely with the results of Experiment 1. Although the first experiment demonstrated enhanced visual processing at memorized locations, the problems with color discrimination during the shifting-attention condition suggest impaired processing at nonmemorized locations. ⁵ Furthermore, because the locations of the color stimuli bore no orderly relationship to the memorized locations, the possibility of strategic orienting (in service of the color task) cannot explain these data.

Although the memory impairments demonstrated in Experiment 3 are consistent with the notion of attention-based rehearsal, an alternative hypothesis should be considered. The small color stimuli caused shifts of spatial attention, but they also involved the presentation of a new location to participants. One possibility is that the location of the color stimulus was automatically encoded and created a new representation that interfered with the original memorized one. ⁶ In this case, the data could reflect interference between similar representations rather than a disruption of attention-based rehearsal. The memory data do not rule out this interpretation. However, this kind of content-based interference cannot explain the color task data. The memory task disrupted color responses only in the shifting-attention condition, but location was irrelevant to the color discriminations. Instead we argue that there was a conflict between participants' prior focus of attention on the memorized location and the need to shift attention to the small color stimuli. Finally, a similar argument applies to the results of Experiment 1. That is, content-based interference cannot explain the improved choice responses at memorized locations, but attention-based rehearsal can.

It should be emphasized that the design of Experiment 3 is biased against our observing the predicted findings. As noted earlier, the static-alone task was more difficult than the shifting-alone task, as shown by the reliably longer response latencies for static-alone stimuli. The greater difficulty of the large color stimuli discrimination task clarifies the interpretation of these results by ruling out alternative explanations having to do with general resource limitations. However, to the extent that any challenging task would impair memory performance, it is likely that the greater difficulty of the static-attention color task led to an underestimation of the deleterious effects of the color task used in the shifting-attention condition. A similar (though more speculative) argument can be drawn from the impairments in color discrimination observed in the shifting-attention condition. Given that participants were instructed to place primary emphasis on color task accuracy, it is unclear why participants would have been unable to maintain their initial levels of performance. A plausible explanation of these data is that participants were reacting to auditory error feedback they received for each memory response. Despite the explicit instructions to emphasize color performance, they may have diverted selective attention resources from the color task to the memory task in order to maintain a comfortable level of memory performance. This strategy would work directly against the observation of the predicted memory effects.

General Discussion

Summary

We proposed a specific hypothesis regarding the subcomponents of spatial working memory in which the on-line maintenance of spatial information is mediated by discrete shifts of spatial selective attention. Two forms of behavioral evidence converge to support this model of spatial

working memory: (a) Enhanced processing attributable to shifts of selective attention is observed at locations that are currently stored in spatial working memory (Experiment 1); these reaction time patterns are not attributable to stimulus-driven attentional shifts or to strategic orienting on the part of participants (Experiment 2). Experiment 3 provides converging evidence for these attentional effects by demonstrating that participants are impaired in their ability to discriminate colors at nonmemorized locations. (b) Experiment 3 shows that when participants are hindered in their ability to direct selective attention to memorized locations, spatial working memory accuracy is impaired. This result suggests that the observed shifts of spatial selective attention play a functional role in the accurate maintenance of spatial information, not just an epiphenomenal role.

The Oculomotor Rehearsal Hypothesis

One of the first explicit hypotheses about the subprocesses that mediate spatial working memory was offered by [Baddeley \(1986\)](#). He suggested that working memory for locations might be mediated by implicit eye-movement programs (in the same way that covert articulation mediates rehearsal in verbal working memory). Can this oculomotor hypothesis accommodate the evidence cited in support of attention-based rehearsal?

The decreased reaction times observed at memorized locations pose an interpretational problem for the oculomotor hypothesis. Why should the programming of an eye movement facilitate visual processing at a targeted location? However, a modification of an oculomotor hypothesis might account for this result. If one assumes that eye movements—whether implicit or overt—are habitually preceded by shifts of attention to the target locations, then the oculomotor hypothesis might be reconciled with evidence of covert orienting during storage in spatial working memory. But in this case, the observed covert orienting might reveal only a correlation of spatial working memory and attention (secondary to the rehearsal role of oculomotor programming) rather than a functional role for spatial selective attention.

The relationship between eye movements and attention has been explicitly investigated; in fact, it has even been hypothesized that both processes could be mediated by a single system that mediates oculomotor programming ([Klein, 1980](#); [Rizzolatti, 1983](#)). Whereas some studies have shown a relationship between oculomotor and attentional mechanisms (e. g. , [Sheliga, Riggio, Craighero, & Rizzolatti, 1995](#)), others have found that these mechanisms can be dissociated (e. g. , [Klein, 1980](#); [Rafal, Calabresi, Brennan, & Sciolto, 1989](#); [Reuter-Lorenz & Fendrich, 1992](#)). Thus, while some experimental situations reveal interdependence between oculomotor programming and shifts of spatial attention, the latter studies suggest that this relationship is not obligatory.

The data of Experiments 1 and 2 are not diagnostic about whether this kind of relationship between oculomotor programming and attention is responsible for the observed shifts of spatial attention. However, the impaired color discrimination at nonmemorized locations (in the shifting-attention condition of Experiment 3) does not yield as easily to this explanation. Given the evidence against an obligatory relationship between oculomotor programs and attentional shifts, a reasonable prediction from the modified oculomotor hypothesis would be that although participants retained the memorized location through oculomotor rehearsal, they should still be free to make the attentional shifts necessary for accurate color discrimination. The fact that participants were unable to maintain color discrimination performance during the shifting-attention condition argues that participants did not have this option. These data suggest that the accurate maintenance of spatial information necessitated the use of spatial selective attention resources and caused the observed decrements in color-discrimination performance.

Conclusions

Two types of behavioral evidence converge to support one of the first detailed models of the subcomponents of spatial working memory, one in which direct shifts of spatial selective attention constitute an active rehearsal mechanism for the on-line maintenance of location information. Interesting directions for future research include developing a better understanding of how far the correspondence between spatial selective attention and spatial working memory extends. Are these mechanisms identical or just highly integrated? Finally, the interaction of spatial selective attention and early visual processing that is at the core of the present model of spatial working memory is echoed in other processing modalities. For instance, there is direct evidence that the response of inferotemporal neurons (known to respond selectively to nonspatial stimulus information such as color) can be enhanced when the property for which they are tuned is behaviorally relevant ([Fuster, 1995](#)). On the basis of this demonstration and similar ones in other

sensory modalities, [Fuster \(1995\)](#) suggested that sensory attention might be generally described as the selective activation of the areas of cortex that specialize in the attended modality of information. This intuitively pleasing description leaves open the possibility that other modalities of working memory may be fruitfully examined with models analogous to the one we have proposed for spatial information.

Footnotes

1

A straightforward prediction regarding memory performance is that accuracy should be higher during choice-match trials. Unlike the choice-miss trials, the choice-match trials do not require participants to orient attention away from the memorized location. Accordingly, spatial memory performance shows a trend toward better accuracy during choice-match trials (78% vs. 76%), $t(7) = 2.1$, $p = .07$. However, these data are not diagnostic because they fail to eliminate a simple alternative explanation: When only the memorized position is restimulated during the retention interval, memory performance is better. The design of Experiment 3 is more appropriate for exploring the effects of orienting to nonmemorized locations.

2

The precise colors used in Experiment 3 can be specified by the parameters displayed in the color controls panels of the applications that were used to create these stimuli: Adobe Photoshop 2.0.1 was used to create the large color stimuli. The two shades of blue were defined by the following sets of color parameters: (a) red—0, green—0, blue—255, hue angle—240, saturation—100, brightness—100; (b) red—51, green—0, blue—255, hue angle—252, saturation—100, brightness—100. The two shades of red were defined by one of the following sets of color parameters: (a) red—255, green—32, blue—0, hue angle—8, saturation—100, brightness—100; (b) red—255, green—0, blue—58, hue angle—346, saturation—100, brightness—100. The small color stimuli were created from within Psyscope 1.0.2. The following sets of color parameters were used: (a) for red stimuli, red—100, green—0, blue—0, hue angle—0, saturation—100, brightness—50; (b) for pink stimuli, red—100, green—0, blue—100, hue angle—300, saturation—100, brightness—50; (c) for blue stimuli, red—11, green—9, blue—100, hue angle—241, saturation—100, brightness—55; (d) for purple stimuli, red—100, green—0, blue—65, hue angle—279, saturation—100, brightness—50.

3

The memory reaction times for this experiment are less informative because participants were urged to emphasize only the accuracy of their responses. However, we analyzed these data in order to examine the possibility of speed-accuracy trade-offs. There were no significant differences between memory reaction times in the static-control (782 ms) and the shifting control (798 ms) conditions, $t(7) = 0.48$, $p > .05$. Likewise, there was no significant difference between memory reaction times in the static-attention (717 ms) and shifting-attention (664 ms) conditions, $t(7) = 1.5$, $p > .05$. Finally, there was no reliable interaction between the type of color stimuli presented (large vs. small) and whether participants were required to discriminate those stimuli, $t(7) = 1.36$, $p > .05$.

4

All previously significant effects remained significant at $p < .05$ with the exception of the direct comparison between memory accuracy in the static-attention and shifting-attention conditions. But even here, memory performance was better in the static-attention condition, $t(7) = 2.2$, $p < .06$.

5

Comparing discrimination performance in response to small color stimuli that fell near the memorized location with performance when those stimuli fell farther away might yield a direct test of this interpretation. We attempted to carry out such a post hoc analysis. For a given memorandum, close was defined as any stimulus that fell within the same 40° slice (centered on the memorandum) of the imaginary circles that defined the potential memory locations. Unfortunately, this procedure yielded, on average, only 13 correct responses in the near category. (Recall that the small color stimuli were randomly positioned). Thus, there was not adequate power to make this comparison.

6

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