The effects of eye and limb movements on working memory

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Three experiments examined the role of eye and limb movements in the maintenance of information in spatial working memory. In Experiment 1, reflexive saccades interfered with memory span for spatial locations but did not interfere with memory span for letters. In Experiment 2, three different types of eye movements (reflexive saccades, pro-saccades, and anti-saccades) interfered with working memory to the same extent. In all three cases, spatial working memory was much more affected than verbal working memory. The results of these two experiments suggest that eye movements interfere with spatial working memory primarily by disrupting processes localised in the visuospatial sketchpad. In Experiment 3, limb movements performed while maintaining fixation produced as much interference with spatial working memory as reflexive saccades. These results suggest that the interference produced by eye movements is not the result of their visual consequences. Rather, all spatially directed movements appear to have similar effects on visuospatial working memory.

Working memory is a cognitive system involved in the temporary maintenance and manipulation of information (Baddeley, 1986; Baddeley & Logie, 1999). According to Baddeley (1986), the cognitive architecture of working memory consists of a central executive, an articulatory loop, and a visuospatial sketchpad. The central executive is an attentional control mechanism that is responsible for selecting information for temporary maintenance and for delegating resources within the working memory system. The articulatory loop and the visuospatial sketchpad subsystems are responsible for the temporary maintenance of verbal and visuospatial information, respectively. Both subsystems are commonly thought to include a passive perceptual store and an active rehearsal mechanism for maintaining the contents of the store, and researchers have been interested in determining the processes underlying the maintenance of information in the two subsystems. In the verbal working memory subsystem, a subvocal rehearsal process is thought to underlie the maintenance of information in the passive store (i.e., Awh et al., 1996; Baddeley, Lewis, & Vallar, 1984; Salame & Baddeley, 1982). In the spatial working memory subsystem, a rehearsal process involving eye movements or the covert analogue of eye movements has been proposed (Baddeley, 1986), but the effects of such movements have not been systematically examined.

The results of an unpublished experiment by Idziowski, Baddeley, Dimbleby, and Park (cited in Baddeley, 1986) support an eye-movement-based rehearsal process. In this experiment, subjects were required to detect changes in the form of a visual stimulus while simultaneously maintaining the locations of digits in working memory. The stimulus was either stationary (requiring no eye movements) or moving (requiring pursuit eye movements), and results revealed that pursuit eye

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movements interfered with the maintenance of spatial locations. Related findings were reported by Hale et al. (1996, Experiment 3). In their experiment, subjects were required to remember a series of visually cued locations. Following presentation of each cued location, subjects were required to execute an eye movement to a visual target, and these eye movements interfered with the maintenance of spatial information in working memory.

Although the results of the Idzihowski et al. and Hale et al. (1996) experiments are consistent with an eye-movement-based rehearsal process, important limitations characterise these experiments, and an understanding of the relationship between eye movements and spatial working memory has yet to emerge. Specifically, because neither of the experiments examined the effect of eye movements on verbal working memory, it is possible that eye movements interfere with working memory in general (i.e., the central executive) and not spatial working memory (i.e., the visuospatial sketchpad) in particular. In addition, because Idzihowski et al. required smooth pursuit eye movements and because Hale et al. did not precisely measure eye movements, it is unclear whether saccadic eye movements interfere with the maintenance of information in spatial working memory.

Furthermore, if saccadic eye movements interfere with spatial working memory, it is unclear whether or not this interference effect is dependent on the type of saccadic eye movement executed, or even whether interference will result from any type of spatially directed movement, regardless of whether it is an eye movement or a limb movement. This is an important issue because a comparison of the effects of different types of eye and limb movements might help to localise the source of the interference produced by eye movements. One possibility is that all types of eye movements interfere equally, perhaps because of the resulting shift in spatial coordinates or because of accompanying shifts of attention (e.g., Shepherd, Findlay, & Hockey, 1986). Another possibility is that certain types of eye movements interfere more than others. For example, if anti-saccades (i.e., eye movements executed away from a spatial cue) interfere to a greater degree than other types of eye movements, it would suggest that central executive processes play an important role in eye-movement interference. This is because anti-saccades involve not only programming a movement away from the cue, but also inhibition (presumably an executive function) of a reflexive saccade in the direction of the cue. A final possibility is that any type of spatially directed movement will interfere. Although simultaneous eye and limb movements have been shown to interfere with spatial working memory (Hale et al., 1996; Smyth & Scholey, 1994), the effects of limb movements executed in the absence of eye movements have not been studied.

Accordingly, the present study compared the effects of different types of spatially directed movements (i.e., reflexive saccades, symbolically cued pro-saccades, anti-saccades, and limb movements) on working memory. First, however, we sought to establish whether eye movements had differential effects on spatial and verbal working memory. Interference common to both types of working memory would suggest that eye movements interfere with central executive processes, whereas interference specific to one domain would suggest that processes associated with that particular subsystem were being affected. In addition, the effects of peripheral flashes while subjects were required to maintain fixation, which presumably required inhibition of reflexive saccades, were also assessed.

**EXPERIMENT 1**

The purpose of this experiment was to determine if eye movements selectively interfere with the maintenance of information in spatial working memory. The working memory tasks required subjects to remember either a series of letters or a series of spatial locations. In between presentation of the memory items, subjects performed one of three secondary tasks. In the baseline condition, the secondary task was simply to maintain fixation. The present experiment also included two other secondary task conditions in which subjects saw a peripheral flash. In one of these conditions, subjects were required to maintain fixation, whereas in the other condition, subjects executed an eye movement to the location where the flash occurred. The latter two secondary tasks both presumably elicited a shift of attention (e.g., Muller & Rabbitt, 1989; Theeuwes, 1992; Yantis, 1993, but see Yantis & Jonides, 1990), but only one of them required the execution of an eye movement whereas the other required the inhibition of an eye movement. If either of the latter two conditions affected memory for both digits and locations, they would presumably do so by
affecting executive processes that were not specific to one domain, whereas domain-specific effects would provide evidence of selective disruption of either the verbal or visuospatial subsystems (Baddeley, 1986).

**Method**

**Subjects.** A total of 24 undergraduate students from Washington University completed the experiment in a 2-hour session for course credit.

**Apparatus and procedure.** Subjects were seated in a dimly lit room with their chins supported by a chin rest in order to maintain stable head position and keep their eyes a constant distance (55 cm) from the video monitor. Subjects performed verbal and spatial working memory tasks similar to those used in Hale et al. (1996, Experiment 1). These primary tasks were accompanied by a secondary task requiring fixation, a secondary task requiring a shift of attention but no eye movement, or a secondary task involving a reflexive saccade. The corresponding three secondary task conditions were termed fixate, fixate plus, and reflexive. The timing and sequences of events are presented in Figure 1.

The spatial working memory task consisted of a series of yellow Xs (1.5° × 1.5°) each presented for 1250 ms in one of 16 cells of a 4 × 4 grid (6.2° × 6.2°) located in the centre of the screen. The locations of the Xs were selected randomly without replacement for each series such that no location occurred more than once in a series. Two rectangles (0.5° × 0.6°) were presented concurrently with the grid, one located 6.5° to the left of screen centre and one located 6.5° to the right of screen centre. Subjects were instructed to remember the locations of the Xs because they would be asked to indicate the locations of the Xs on the monitor with an erasable pen. At the end of each series, an empty grid signalled subjects to recall the locations of the memory items.

The verbal working memory task consisted of a series of yellow letters (0.5° × 0.6°), each presented for 1250 ms in a box located in the centre of the display. The letters were selected from the following set (B, D, F, G, H, K, L, M, N, Q, R, S, T, W, and X) randomly without replacement for each series such that no letter occurred more than once in a series. Two rectangles (0.5° × 0.6°) were presented simultaneously with the letter, one located 6.5° to the left of screen centre and one located 6.5° to the right of screen centre.

Figure 1. Procedure and sample stimuli (for a series length of one item) for the spatial and verbal secondary task conditions of Experiment 1. When the series length was more than one item, the same procedure (with a different location or letter) was repeated (without the final recall stimulus) for each item. The recall stimulus (the cue for the participant to either mark the spatial locations that appeared previously or recite the letters that appeared previously) was presented once per trial after all of the items had been presented. The fixate plus and reflexive saccade conditions differed only in instruction to the subject (see Method section).
located 6.5° to the right of screen centre. Subjects were instructed to remember the identity and temporal order of the letters because they would be asked to recall the letters at the end of a series. At the end of each series, an empty purple box appeared to signal subjects to recall the memory items in the correct order.

The secondary tasks were interleaved between the presentation of the primary (working memory) task items (Xs or letters) so that completion of the secondary task would not interfere with encoding of the primary task items. In all conditions, the secondary task stimulus consisted of a white central crosshair (0.3° × 0.3°) which appeared simultaneously along with rectangles presented 6.5° to the left and to the right of the centre of the screen. In the fixate condition, the stimulus events consisted of a crosshair and rectangles presented for 2300 ms, and subjects were required to maintain fixation on the crosshair. In the fixate plus condition, the stimulus events consisted of a crosshair and rectangles presented for 1000 ms after which one of the rectangles was cued by filling it in completely with white for 300 ms. This was followed by a crosshair and rectangles presented for 1000 ms. Subjects were required to maintain fixation on the crosshair throughout. Each rectangle had a 0.5 probability of being the one that was filled. In the reflexive condition, the stimulus events were the same as in the fixate plus condition, but subjects were required to execute an eye movement to the filled box. In all conditions, the background colour was dark grey, and the borders of the rectangles and of the box surrounding the letters were white, as were the lines of the grid.

The number of memory items (i.e., series length) was determined by a psychophysical staircase procedure (Levitt, 1970). Each condition began with a series of three letters or Xs. Initially, if the response to the series was correct (i.e., all items were correctly recalled), the number of items in the next series was increased by two. This procedure was followed until the first incorrect response (i.e., one or more items incorrectly recalled), after which the number of items in the next series was decreased by one. Subsequently, the number of items in a series was increased or decreased by one depending on whether the response to the previous series had been correct or incorrect, respectively. Each condition was terminated after the third reversal (i.e., a series with an incorrect response followed immediately by a series with a correct response).

Subjects received three practice series prior to each condition.

Eye movement monitoring. Stimulus presentation was computer-controlled as was the acquisition of eye movement data. Eye position was monitored using an ISCAN (Cambridge, MA) RK426pc video-based eye movement monitor. The eye movement monitor was calibrated at the beginning of each experimental condition by presenting five evenly spaced points across the display which subjects were required to fixate.

Eye position was recorded at a rate of 60 Hz for 2000 milliseconds beginning after the offset of each memory item. In order to identify saccades, the eye position signal was filtered and differentiated so that a smooth velocity record was obtained. The beginning of an eye movement was defined as the first moment in time when the velocity exceeded 10°/s for at least 32 ms with the constraint that velocity subsequently exceeded 30°/s. In the fixate and fixate plus conditions, an error message was presented if an eye movement was made between memory items when subjects were supposed to be fixating the crosshair. In the reflexive condition, an error message was presented if the eye movement was too fast (latency less than 80 ms), too slow (latency greater than 2000 ms), or in the wrong direction from that cued by the filled rectangle. If an eye movement error occurred, the series was aborted and immediately rerun at the same series length but with different memory items.

Design. The two primary working memory tasks (verbal and spatial) were crossed with the three secondary task conditions (fixate, fixate plus, reflexive) to produce a total of six experimental conditions. All subjects participated in all six conditions. Half of the subjects performed the spatial working memory task conditions first, and half performed the verbal working memory task conditions first. The order of secondary task conditions was completely counterbalanced across subjects.

Results

Analysis of the eye movement latencies revealed that there was no significant difference between the latencies from the reflexive conditions of the spatial ($M = 233.0$ ms) and verbal ($M = 231.8$ ms)
working memory tasks, \( t(23) < 1 \). For these conditions, only data from those series in which saccades towards the appropriate target occurred were included in the analyses of the memory data. For the fixate and fixate plus conditions, only data from series in which no eye movements occurred were included in the analyses.

Verbal and spatial memory spans were determined for each subject in each of the secondary task conditions. As in experiments previously conducted in our laboratory (Jenkins, Myerson, Joerding, & Hale, 2000), span was defined as the amount of information (i.e., the number of items) for which the probability of all items being maintained accurately in memory is 0.5 (i.e., the series length that could be correctly recalled 50% of the time). The method by which spans were determined is analogous to a procedure used to estimate psychometric functions. More specifically, the probability of recalling an entire series was determined for each series length that a subject encountered within a particular condition, and then these probabilities were plotted as a function of series length. Linear interpolation was performed on the data from all series lengths ranging from the longest series for which a subject had 100% accuracy to the longest series encountered by that subject. For example, if a subject had 100% correct at series lengths 3, 4, and 5, and the longest series presented according to the staircase procedure was 8, the probabilities for series lengths 5 to 8 were used in the regression analysis. The series length at which the regression equation predicted a probability of .5 was used as an index of the individual's memory span.

Mean verbal and spatial spans in each secondary task condition are presented in Figure 2. As may be seen, eye movements and peripheral flashes produced large decreases in spatial but not verbal spans. A 2 (primary task: spatial and verbal) \( \times \) 3 (secondary task: fixate, fixate plus, reflexive) repeated measures analysis of variance (ANOVA) on memory spans revealed a significant main effect of secondary task, \( F(2,46) = 20.37, p < .001 \), and a significant primary task \( \times \) secondary task interaction, \( F(2,46) = 12.98, p < .001 \). Although verbal spans tended to be larger than spatial spans, the difference did not reach statistical significance, \( F(1,23) = 3.93, p = .06 \). Planned comparisons in the verbal domain revealed no significant difference between the fixate and the fixate plus conditions, \( F(1,23) = 2.85, p > .10 \), or between the fixate and reflexive conditions, \( F(1,23) = 1.62, p > .20 \). Planned comparisons in the spatial domain revealed no significant difference between the fixate and the fixate plus conditions, \( F(1,23) < 1 \). However, memory spans were significantly smaller in the reflexive condition than in the fixate condition, \( F(1,23) = 40.90, p < .001 \).

**Discussion**

In the current experiment, reflexive eye movements significantly interfered with spatial, but not verbal, working memory. In contrast, peripheral flashes in the absence of eye movements did not interfere with the maintenance of either spatial or verbal information in working memory, suggesting that the inhibition of a saccade does not interfere with the maintenance of information in working memory.
The present finding that saccadic eye movements selectively interfere with spatial working memory is consistent with the findings of Hale et al. (1996). Hale et al. found that eye movements alone were sufficient to interfere with spatial working memory, although they did not monitor eye movements precisely or examine the effects of eye movements on verbal working memory. Notably, the results of the present experiment demonstrate that saccadic eye movements selectively interfere with the maintenance of information in spatial working memory.

**EXPERIMENT 2**

The results of Experiment 1 suggest that eye movements selectively interfere with spatial, but not verbal, working memory. It is possible, however, that this interference may be dependent on the type of eye movement executed in that experiment. In Experiment 1, eye movements were summoned by peripheral cues. Eye movements can also be voluntarily generated in response to a central, symbolic cue in the absence of any peripheral stimulus events. Furthermore, eye movements can be executed in a direction away from a peripheral event. Such eye movements are known as anti-saccades and involve the inhibition of a reflexive saccade and the execution of a pro-saccade (Guitton, Buchtel, & Douglas, 1985).

Moreover, reflexive saccades, pro-saccades, and anti-saccades are thought to be mediated by neurobiologically distinct networks (Pierrot-Deseilligny et al., 1995). For example, the parietal eye fields are believed to be responsible for the triggering of reflexive saccades, whereas the frontal eye fields are thought to be responsible for the production of pro-saccades. Furthermore, the prefrontal cortex is thought to be responsible for the inhibition of reflexive saccades in the anti-saccade paradigm. The involvement of prefrontal cortex is especially relevant because it is frequently associated with executive processes as well as with working memory (e.g., Goldman-Rakic, 1996; Roberts, Hager, & Heron, 1994). Because of the various differences in the mechanisms involved in the different types of eye movements, it is possible that the pattern of interference effects in spatial working memory may be dependent on the type of eye movement executed. The purpose of Experiment 2 was to address this possibility. The procedure used in Experiment 2 was similar to that used in Experiment 1 with the addition of secondary tasks requiring pro-saccades and anti-saccades.

**Method**

**Subjects.** A total of 20 undergraduate students were obtained from a subject pool maintained by the Department of Psychology at Washington University. Subjects were paid $15 upon completion of two 1½ hour sessions.

**Apparatus and procedure.** The equipment was the same as that used in Experiment 1. The procedure was similar to that in Experiment 1 except that two secondary tasks were added, one involving a pro-saccade and one involving an anti-saccade. In the pro-saccade condition, the central fixation cross was replaced by an arrow that pointed to either the right or left rectangle, to which subjects executed a saccade. The stimulus events in the anti-saccade condition were the same as in the reflexive saccade and fixate plus condition. That is, either the right or left rectangle was randomly filled. In the anti-saccade condition, subjects then executed a saccade to the rectangle that was not filled, whereas in the reflexive saccade condition, subjects executed a saccade towards the filled rectangle.

The timing for the fixate plus and reflexive saccade conditions was the same as in Experiment 1. For the pro-saccade condition, the fixation cross appeared for 500 ms, and then was replaced by either a left- or right-pointing arrow which was present for 800 ms. The duration of the fixation cross in the fixate condition was 800 ms, similar to the amount of time that subjects fixated prior to executing a pro-saccade (duration of the fixation cross plus saccade latency). The experiment consisted of two separate sessions conducted on separate days. Half of the subjects completed the spatial working memory conditions in the first session, and half of the subjects completed the verbal working memory conditions in the first session.

**Design.** The two primary working memory tasks (verbal and spatial) were crossed with the five secondary task conditions (fixate, fixate plus, reflexive saccade, pro-saccade, and anti-saccade) to produce a total of ten experimental conditions. All subjects participated in all conditions. Half of the subjects performed the spatial working mem-
memory task conditions first and half performed the verbal working memory task conditions first. The order of secondary task conditions was completely counterbalanced across subjects.

Results

The mean eye movement latencies for each secondary task condition are shown in Table 1. A 2 (primary task: spatial and verbal) × 3 (secondary task: reflexive-saccade, prosaccade, and anti-saccade) repeated measures ANOVA on the eye movement latencies revealed no main effect of primary task, $F(1,19)<1$. However, there was a main effect of secondary task, $F(2,38)=15.46$, $p<.001$, reflecting the fact that the latencies of prosaccades and anti-saccades were slower than those of reflexive saccades. There was no primary task × secondary task interaction, $F(2,38)=1.42$, $p>.20$.

Verbal and spatial memory spans were determined for each subject in each condition in the same manner as in Experiment 1. For the fixate and fixate plus conditions, only data from series in which no eye movements occurred were included in the analyses. For the reflexive, pro-saccade, and anti-saccade conditions, only data from series in which saccades towards the appropriate target occurred were included in the analyses.

Mean verbal and spatial spans in each secondary task condition are represented in Figure 3. As may be seen, eye movements and peripheral flashes produced larger decreases in spatial spans than in verbal spans, and the three different types of eye movements all had very similar effects. A 2 (primary task: spatial and verbal) × 5 (secondary task: fixate, fixate plus, reflexive saccade, pro-saccade, and anti-saccade) repeated measures ANOVA revealed a main effect of secondary task, $F(4,76)=4.41$, $p<.01$, and a primary task × secondary task interaction, $F(4,76)=4.41$, $p<.01$. There was no main effect of primary task on memory span, $F(1,19)<1$.

Planned comparisons of the fixate and fixate plus conditions revealed no significant differences in either domain [for spatial working memory, $F(1,19)=1.19$, ns; for verbal working memory, $F(1,19)=3.11$, ns]. Planned comparisons of the three eye movement conditions within each domain also revealed no significant differences in either domain (all $Fs<1$). Accordingly, for each domain, the data from the fixate and fixate plus conditions (i.e., no eye movement) were collapsed as were the data from the three eye movement conditions (i.e., eye movement). Comparisons of the no-eye-movement and eye-movement conditions within each domain revealed that eye movements significantly interfered with both verbal and spatial working memory; $t(19)=4.40$, $p<.001$, and $t(19)=6.25$, $p<.001$, respectively.

**TABLE 1**

Eye movement (EM) mean latencies and standard errors from Experiment 2

<table>
<thead>
<tr>
<th>EM</th>
<th>Spatial Mean (SE)</th>
<th>Verbal Mean (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflexive</td>
<td>297.6 (19.6)</td>
<td>280.8 (15.2)</td>
</tr>
<tr>
<td>Pro-saccade</td>
<td>364.8 (14.7)</td>
<td>355.3 (11.9)</td>
</tr>
<tr>
<td>Anti-saccade</td>
<td>342.1 (22.5)</td>
<td>346.4 (19.1)</td>
</tr>
</tbody>
</table>
As a result, the collapsed data were then subjected to a 2 (primary task: spatial and verbal) × 2 (secondary task: eye movement and no eye movement) repeated measures ANOVA in order to compare the magnitude of interference effects in the two domains. Analysis revealed no main effect of primary task, \( F(1,19) < 1 \), a main effect of secondary task, \( F(1,19) = 45.84, p < .001 \), and a significant interaction between primary and secondary task, \( F(1,19) = 18.36, p < .001 \), reflecting the fact that the magnitude of the interference effect for spatial working memory was greater than that for verbal working memory. As can be seen in Figure 4, the decrease in memory span due to eye movements was actually three times as large for spatial working memory (\( M = 1.8 \) items lost) as for verbal working memory (\( M = 0.6 \) items lost).

Discussion

The results of Experiment 2 indicated that all three types of eye movements (reflexive saccades, pro-saccades, and anti-saccades) significantly interfered with the maintenance of information in spatial working memory and that the magnitude of the interference effect was independent of the type of eye movement executed. In contrast, peripheral flashes did not interfere with memory for spatial locations. A similar pattern was observed with respect to verbal working memory, but the amount of interference produced by eye movements was much smaller. These findings (i.e., the differential sensitivity of spatial working memory and the similar effects of different types of eye movements) suggest that the observed interference primarily reflects a general characteristic of the way in which the eye movement system interacts with the system responsible for spatial working memory. The results of the analysis of eye movement latencies are consistent with this suggestion. This analysis revealed no significant differences between latencies in the spatial and verbal domains, implying that the greater effect of eye movements on memory for locations was due to the greater sensitivity of spatial working memory rather than to any difference between the eye movements executed in the verbal and spatial working memory conditions.

In Experiment 2, eye movements had a significantly greater effect on spatial working memory than on verbal working memory, whereas in Experiment 1, eye movements affected spatial working memory but did not significantly affect verbal working memory. It is possible that this difference between the results of the present two experiments reflects sample differences or that the addition of more secondary task conditions, with a resultant increase in the number of times the primary task had to be performed, increased subjects’ sensitivity to interference. The important point, however, is that the results of both of the present experiments are in agreement with respect to the fact that eye movements produce much more interference with spatial than with verbal working memory. Even in Experiment 2, where some effect on verbal working memory was observed, the effect on spatial working memory was approximately three times as large. These results suggest that eye movement interference with spatial working memory is primarily at the level of the visuospatial sketchpad.

![Figure 4](image.png)

**Figure 4.** The mean verbal and spatial memory spans for secondary conditions without an eye movement requirement (fixate and fixate plus) and those secondary conditions with an eye movement requirement (reflexive, pro- and anti-saccade) from Experiment 2, with standard error bars.

**EXPERIMENT 3**

Although the previous two experiments demonstrate that eye movements interfere with spatial working memory, it is possible that eye movements interfere because of their visual consequences (i.e., because they produce visual transients, saccadic suppression, and changes in retinal coordinates) or because they are spatially planned and executed movements. That is, it is possible that any spatially directed movement
would interfere with the maintenance of information in spatial working memory. Hale et al. (1996, Experiment 3) demonstrated that the concurrent execution of eye and limb movements interferes with spatial working memory to a significantly greater extent than the execution of eye movements alone. Although these results suggest that limb movements interfere with spatial working memory, it is possible that the interference in the Hale et al. experiment did not result from the execution of the limb movements per se, but from an interaction between the eye and limb movement systems (e.g., Bekkering et al., 1994; Bekkering et al., 1995). Therefore, the purpose of the present experiment was to determine if limb movements executed in the absence of eye movements interfere with spatial working memory.

Method

Subjects. A total of 18 undergraduate students from Washington University completed the experiment in a 1-hour session for course credit.

Apparatus and procedure. The apparatus for Experiment 3 was the same as that used in the previous experiments except for the addition of a button panel (47 cm in length) containing three equally spaced (12.5 cm between each button) buttons (6 cm in diameter), which rested on the subject’s lap. The button panel was not visible to the subject while they were performing the experiment. Eye movement monitoring was also the same as in the previous experiments except for slight changes in the time requirements that were modified to be the same as those for limb movement monitoring (described later).

The presentation of stimuli for the primary spatial working memory task interleaved with either a secondary task requiring fixation (fixate), a secondary task requiring a limb movement (limb), or a secondary task requiring a reflexive eye movement (reflexive). For both working memory and secondary task stimuli, the background colour was dark grey.

The stimuli for the working memory task consisted of a series of blue circles (1.25° in diameter), each presented for 2000 ms in one of 20 cells of a white cross-shaped grid (4.7° × 4.7°) located in the centre of the screen. The locations of the circles were selected randomly without replacement for each series such that no location could be cued more than once in a series. The centrally located cell was filled white and could not contain a memory item (i.e., a circle). This was because a discrimination stimulus would appear in that same location during the secondary task. Subjects were instructed to remember the locations of the circles as accurately as possible. At the end of each series, the appearance of an empty grid signalled subjects to recall the memory items by moving a mouse cursor to each of the previously cued locations, clicking the left mouse button once in each location. Subjects signalled the completion of the recall period by clicking once in the space outside the grid. A 200 Hz tone was sounded if the subjects did not correctly recall the memory items.

The number of memory items (i.e., the series length) was determined by a modified version of the WAIS–III memory span procedure (Wechsler, 1997) rather than by the staircase procedure used previously. Like the WAIS–III procedure, subjects were given two trials at each series length until they missed two trials at any one series length. Unlike the WAIS–III procedure, when subjects missed two trials at any one series length, they were given one last trial at a series length of one item less. If the subject was correct on this trial, their span was determined to be the length of the series in this trial. If, however, the subject was incorrect on this trial, their span was determined to be this series length minus half an item. Each condition began with a series of two memory items.

The secondary tasks were interleaved between the presentation of each of the working memory items (i.e., circles), as opposed to simultaneously with the primary memory items, so that completion of the secondary task would not interfere with encoding of the primary task items. In all conditions, the secondary task discrimination stimulus consisted of either a white “x” (0.6°) or a white “+” (0.6°) which appeared for 2500 ms in all conditions. Each discrimination stimulus had a 50% probability of appearing.

In the fixate condition, subjects were required to maintain fixation on the center of the screen where the stimulus appeared. In addition, subjects were required to maintain hand position on the center button of the button pad. In both the reflexive and limb conditions, the stimulus appeared in the periphery (i.e., 6.5° to the left or the right of fixation) signalling the direction of the to-be-executed movement. In the reflexive condition, subjects were required to execute an eye movement in the direction of the peripheral stimulus and then execute an eye movement back
to the centre of the screen. In this condition, subjects were required to maintain hand position on the centre button. In the limb condition, subjects were to execute a limb movement to the button in the corresponding direction of the peripheral item (i.e., left or right) and then execute a limb movement back to the centre button.

**Limb movement monitoring.** In all conditions, an error message was presented if the subject’s hand was not on the centre button prior to the presentation of each working memory item. After the onset of the secondary task stimulus, an error message was presented in the fixate and reflexive conditions if the subject’s hand was not on the centre button throughout the presentation of the secondary task stimuli. In the limb condition, error messages were also presented under the following circumstances: if the subject’s hand was not on the centre button by 100 ms after the onset of the secondary task stimulus; if the subject’s hand was not removed from the centre button until 700 ms after the onset of the secondary task stimulus; if the subject’s hand was not removed from the centre button and 2333 ms had passed, or if 2333 ms had passed and the subject’s hand was not back to the centre button. If one of the preceding errors occurred, the memory trial was aborted and immediately rerun at the same series length.

**Design.** Subjects participated in all three separately blocked conditions (fixate, reflexive, limb). The order of conditions was completely counterbalanced across subjects. Subjects received six practice trials prior to each condition. Practice consisted of two trials each at series lengths one, two, and three.

**Results**

The mean saccade latency in the reflexive condition was 278.2 ms (SD = 60.0). The mean limb movement latency in the limb condition was 419.7 ms (SD = 43.8). The mean memory spans and standard errors for each task condition are presented in Figure 5. A one-way repeated measures ANOVA conducted on memory spans indicated a significant main effect of condition, $F(2,34) = 8.02, p < .005$, reflecting the fact that memory spans in the reflexive and limb conditions were smaller than the memory spans in the fixate condition. Planned comparisons revealed a significant difference in memory spans between the fixate and the limb conditions, $t(17) = 3.06, p < .01$. There was also a significant difference in memory spans between the fixate and reflexive conditions $t(17) = 3.42, p < .005$, but no significant difference between the limb and reflexive conditions $t(17) < 1.0$.

**Discussion**

The results of Experiment 3 indicate that both eye movements (executed in the absence of limb movements) and limb movements (executed in the absence of eye movements and without visual guidance) interfere with spatial working memory. These results suggest that a common aspect of spatially directed movements (e.g., movement planning or shifts of spatial attention), rather than some property specific to a particular type of movement (e.g., the visual consequences of eye movements or the visual and kinesthetic consequences of limb movements), underlies the interference with spatial working memory observed in all three of the present experiments.

**GENERAL DISCUSSION**

The results of Experiment 1 revealed that reflexive eye movements selectively interfered with the maintenance of location information in working memory. This finding was replicated in Experi-
movement 2, which yielded the additional finding that other types of eye movements, specifically anti-saccades and pro-saccades, also significantly interfere with spatial working memory. Moreover, the magnitude of the interference effects in the spatial working memory domain was independent of the type of eye movement executed, and was much greater than the interference effects in the verbal domain. The results of Experiment 3 indicated that limb movements also interfere with spatial working memory. Taken together, the present findings suggest that interference results from a common property of spatially directed movements, and that the effects of this common property are primarily localised within the visuospatial sketchpad.

In addition, the results of the first two experiments suggest that the inhibition of a saccade does not interfere with the maintenance of information in spatial or verbal working memory. In both experiments, the fixate plus condition, in which subjects were required to inhibit a saccade to a peripheral flash, failed to produce interference with spatial working memory. Moreover, there were no significant differences among the different types of eye movements in the amount of interference they produced, even though one of them (anti-saccades) required inhibition of reflexive saccades. Both the lack of effect of inhibition on memory for locations and the relative insensitivity of verbal working memory to eye movements suggest that such movements exert their effects more on the visuospatial sketchpad and less on the central executive component of working memory which is often assumed to be responsible for inhibitory control (e.g., Engle, Tuholski, Laughlin, & Conway, 1999).

The finding that eye movements of various kinds interfere with the maintenance of information in spatial working memory would be consistent with Baddley’s (1986) suggestion that eye-movement-based rehearsal subserves the maintenance of spatial information. That is, it could be that secondary tasks requiring eye movements interrupt rehearsal, resulting in the loss of spatial information. However, the present finding that a secondary task requiring limb movements also interferes with working memory for locations (Experiment 3) is not readily explainable in terms of an eye-movement-based rehearsal process. Moreover, the eye movement rehearsal interpretation assumes that rehearsal is necessary to maintain information in working memory, whereas the results of recent studies both by psychologists, (e.g., Washburn & Astur, 1998) and cognitive neuroscientists (e.g., Fuster, 1995) raise the possibility that visuospatial information does not have to be rehearsed in order to be maintained.

What mechanism or mechanisms might be responsible for interference by eye and limb movements? If one assumes that a single common mechanism is involved, then the mechanism would appear to involve some property common to spatially directed movements in general, rather than a mechanism that relies on properties specific to one particular type of movement (e.g., the visual consequences of saccades). For example, both eye and limb movements, rather than interrupting a rehearsal sequence, may interrupt activity in the positive feedback loop between prefrontal and posterior cortices that, it has been hypothesised, serves to maintain visuospatial information (Chafee & Goldman-Rakic, 2000; Fuster, 1995; Hale et al., 1996).

Other possible mechanisms for interference with memory for locations involve the effects of shifting spatial attention and planning spatially directed movements. More specifically, shifts in spatial attention may interfere because they interrupt an attention-based rehearsal process or simply because attention is required to maintain spatial information (Awh, Jonides, & Reuter-Lorenz, 1998; Smyth & Scholey, 1994). Alternatively, movement planning might interfere either directly by interrupting rehearsal, or indirectly because such planning itself involves shifts of spatial attention (Rizzolatti, Riggio, & Shelig, 1994). Finally, it is possible that different mechanisms are involved in the interference produced by different types of movement. Obviously, further research will be needed to discriminate between these possibilities, but the present results suggest that, whatever the mechanism or mechanisms involved, spatially directed movements interfere with working memory primarily by disrupting processes localised in the visuospatial sketchpad.

REFERENCES


