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The effects of environmental support and secondary tasks on visuospatial working memory

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Abstract In the present experiments, we examined the effects of environmental support on participants' ability to rehearse locations and the role of such support in the effects of secondary tasks on memory span. In Experiment 1, the duration of interitem intervals and the presence of environmental support for visuospatial rehearsal (i.e., the array of possible memory locations) during the interitem intervals were both manipulated across four tasks. When support was provided, memory spans increased as the interitem interval durations increased, consistent with the hypothesis that environmental support facilitates rehearsal. In contrast, when environmental support was not provided, spans decreased as the duration of the interitem intervals increased, consistent with the hypothesis that visuospatial memory representations decay when rehearsal is impeded. In Experiment 2, the ratio of interitem interval duration to intertrial interval duration was kept the same on all four tasks, in order to hold temporal distinctiveness constant, yet forgetting was still observed in the absence of environmental support, consistent with the decay hypothesis. In Experiment 3, the effects of impeding rehearsal were compared to the effects of verbal and visuospatial secondary processing tasks. Forgetting of locations was greater when presentation of to-be-remembered locations alternated with the performance of a secondary task than when rehearsal was impeded by the absence of environmental support. The greatest forgetting occurred when a secondary task required the processing visuospatial information, suggesting that in addition to decay, both domain-specific and domain-general effects contribute to forgetting on visuospatial working memory tasks.

Keywords Visuospatial working memory · Environmental support · Secondary tasks · Interference · Decay

Although researchers have been studying the forgetting that occurs on short-term memory and working memory tasks for many decades, no consensus has been reached regarding whether such forgetting is due to decay, interference, or both. Classic findings that were initially interpreted as evidence for decay were quickly reinterpreted as being consistent with an interference hypothesis (Keppel & Underwood, 1962; Peterson & Peterson, 1959), and something of a similar debate continues in the working memory literature today (Barrouillet, Portrat, Vergauwe, Diependaele, & Camos, 2011; Lewandowsky & Oberauer, 2009). Although many studies have shown that when participants must perform secondary processing in addition to a memory task, their memory performance suffers (e.g., Hale, Myerson, Rhee, Weiss, & Abrams, 1996; Logie, Zucco, & Baddeley, 1990), the question of whether this impairment is due to interference or decay has proven difficult to resolve.

When participants are given a set of verbal items to remember, they are likely to rehearse those items, and as a result, little or no forgetting may occur (Baddeley, 1986). In order to observe forgetting in tasks that use verbal memory items, therefore, rehearsal must be prevented, and this is often accomplished by requiring participants to perform a secondary task (e.g., counting backward by threes or repeating an irrelevant word, such as "the"; Murray, 1967; Peterson & Peterson, 1959). Indeed, experiments that include a secondary task in addition to a primary memory task have provided much of the evidence for two modern theories of time-based forgetting: the task-switching model (Towse & Hitch, 1995; Towse,

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Hitch, & Hutton, 2000) and the time-based resource-sharing model (Barrouillet, Bernardin, & Camos, 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007). In addition to blocking rehearsal, however, secondary tasks may also overwrite the contents of working memory and create representation-based interference. Thus, when memory spans are smaller in experimental paradigms that involve secondary tasks (i.e., *complex span tasks*, to use the terminology introduced by Engle, Tuholski, Laughlin, & Conway, 1999) than in those that do not (i.e., *simple span tasks*), one often cannot be sure whether this effect is due to decay or interference, leaving the results open to conflicting interpretations.

As is the case with much of the research on working memory, most investigations of time-based forgetting have been conducted in the verbal domain, and the question of whether or not visuospatial memory items are lost over time in the absence of interference has received much less attention. Nevertheless, research has demonstrated that when they are asked to remember locations, participants are likely to rehearse through eye movements and/or shifts of spatial attention to those locations (e.g., Awh, Jonides, & Reuter-Lorenz, 1998), and as in verbal memory, rehearsal appears to decrease the amount of forgetting that occurs (e.g., Godijn & Theeuwes, 2012; Tremblay, Saint-Aubin, & Jalbert, 2006).

For example, Tremblay et al. (2006) presented participants with a sequence of seven circles in random locations, followed by a retention interval during which all seven circles were visible, after which participants were asked to indicate the presentation order of the circles. Participants were allowed to move their eyes freely during the retention interval, and the order in which locations were fixated was recorded. Tremblay et al. found that participants spontaneously rehearsed the order of the circles during the retention interval. Moreover, when the sequence of seven circles was divided into six successive pairs (e.g., 1–2, 2–3, 3–4, … 6–7) and then further divided into pairs that were and were not rehearsed, locations that were part of a rehearsed pair were more likely to be recalled in the correct order than were locations from pairs that were not rehearsed.

Further evidence that rehearsal using eye movements and spatial attention shifts can be effective in maintaining visuospatial information has come from studies in which participants were required to perform a secondary processing task between presentations of to-be-remembered locations. When the secondary task required participants to shift their eyes and/or spatial attention away from the to-be-remembered locations, memory for those locations was significantly decreased (e.g., Lawrence, Myerson, & Abrams, 2004; Lawrence, Myerson, Oonk, & Abrams, 2001; Pearson & Sahraie, 2003; Postle, Idzikowski, Della Sala, Logie, & Baddeley, 2006). For example, Pearson and Sahraie found that secondary tasks that required smooth-pursuit eye movements, saccadic eye movements, or discrete shifts of spatial attention all decreased visuospatial memory spans, and Lawrence et al. (2001) found that secondary tasks requiring reflexive saccades, prosaccades, and antisaccades all decreased memory spans to the same extent. Clearly, when participants are required to move their eyes and/or shift spatial attention in ways that prevent the rehearsal of to-be-remembered locations, visuospatial memory suffers. However, as is true of verbal memory experiments that use a secondary processing task to impede rehearsal, one cannot be sure whether such tasks decrease memory spans solely because they prevent rehearsal, or because they also lead to the overwriting of memory representations.

There is, however, a potentially important difference between visuospatial memory and verbal memory: Because visuospatial rehearsal is thought to involve directing one's eyes and/or attention to specific locations in the environment, it is possible that the degree of environmental support for rehearsal (i.e., the structural information, or lack thereof, provided by that environment) may directly influence the effectiveness of visuospatial rehearsal. Although the concept of *environmental support* has been invoked in the literature on age-related differences in memory, the term has never been rigorously defined. Rather, it has been used to describe a variety of manipulations presumed to affect the amount of self-initiated processing that is required by a task, and self-initiated processing is something that older adults have been hypothesized to have difficulty with, as compared to young adults (e.g., Craik, Byrd, & Swanson, 1987; Hasher & Zacks, 1979). Moreover, previous studies of environmental support have used verbal memory items (e.g., words, nameable objects) and focused on the effects of support at encoding and/or retrieval on differences in the performance of younger and older adults (e.g., Craik et al., 1987; Smith, Park, Cherry, & Berkovsky, 1990), and the possible effects of the presence and absence of environmental support on rehearsal of memory items have been largely ignored.

The present experiments, in contrast, directly addressed the role of environmental support in the rehearsal of visuospatial information, as well as its role in the effects of secondary processing tasks on memory span. If the rehearsal of to-be-remembered locations is impeded when environmental support is not provided, then one would expect to observe decreases in memory span with increases in retention time, even in the absence of any secondary task. Furthermore, if the main reason why secondary tasks decrease visuospatial memory span is because the presentation of secondary task stimuli is accompanied by the removal of environmental support for rehearsal, then the lack of environmental support should result in the same level of memory performance, regardless of whether or not participants must also perform a secondary task. The goal of the present experiments was to test these hypotheses.

Experiment 1

In order to investigate the effects of environmental support on visuospatial rehearsal and forgetting, Experiment 1 included four visuospatial simple span tasks. Across the four tasks, both the amount of time between the presentation of memory items (i.e., the interitem interval) and the presence of environmental support during that time were manipulated. If visuospatial rehearsal is impeded when environmental support is not provided, an interaction should be observed: Longer interitem intervals would be associated with smaller memory spans, but only when support was not provided.

Method

Participants A group of 24 students (16 female, eight male) at Washington University in St. Louis participated in this experiment in partial fulfillment of a course requirement.

Materials and procedure All participants performed four visuospatial simple span tasks, adapted from the dot span task used by Hale et al. (2011). In all four tasks, participants saw an array of 30 empty circles, each 1 cm in diameter, on a computer screen. The locations of these circles were chosen randomly, such that the average distance between the centers of the circles was approximately 1.75 cm and the array appeared to be unstructured (see Fig. 1). A different set of locations for the 30 circles was chosen for each trial.

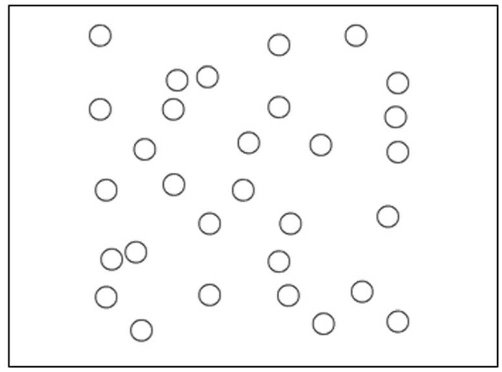

Fig. 1 Example of an array used in the visuospatial span tasks

On each trial, a subset of the circles in the array turned red one at a time, and participants were instructed to remember the locations of the red circles. Each red circle was presented for 1,000 ms, followed by an interitem interval that was either 1,000 or 4,000 ms, depending on the task. At recall, participants saw the same array of 30 empty circles that had been presented at the beginning of the trial and were asked to use the computer mouse to click on those circles that had turned red during that trial. Participants were allowed to recall the locations in any order and indicated when they were finished by clicking on an icon labeled "Done." Each task began with five practice trials, followed by 20 test trials. List lengths ranged from two to 11, and participants completed two test trials of each length. These test trials were ordered according to list length, from shortest to longest, and span was measured as one less than the shortest list length at which both test trials were incorrect.

The two manipulations of interest concerned the interitem intervals, or the time between the offset of one red circle and the onset of either the next red circle or the test array. Specifically, across the four tasks, the duration of the interitem intervals was either short or long (i.e., either 1,000 or 4,000 ms) and environmental support was either present or absent. Environmental support for rehearsal was provided by having the array of empty circles remain on the screen during the interitem intervals, whereas in the absence of environmental support, the screen became blank during the interitem intervals (see Fig. 2). Thus, one task had short interitem intervals with environmental support, one task had short interitem intervals without environmental support, one task had long interitem intervals with environmental support, and one task had long interitem intervals without environmental support.

Participants were administered these four tasks in one of four order conditions (six participants per condition). Half of the participants completed the two tasks with environmental support followed by the two tasks without environmental support, and the other half of the participants completed these tasks in the reverse order. Within each of those two groups of participants, half completed a task with short interitem intervals first, and half completed a task with long interitem intervals first; the interval durations were presented alternately (i.e., either short–long–short–long or long–short–long–short).

Results and discussion

A 2 (interitem interval: short vs. long) × 2 (environmental support: present vs. absent) repeated measures analysis of variance (ANOVA) was conducted on the memory span data. A main effect of environmental support was observed, $F(1, 23) = 50.50$, $p < .001$, $\eta_p^2 = .69$, and although the main effect of interval duration was not significant, $F < 1.0$, we observed a

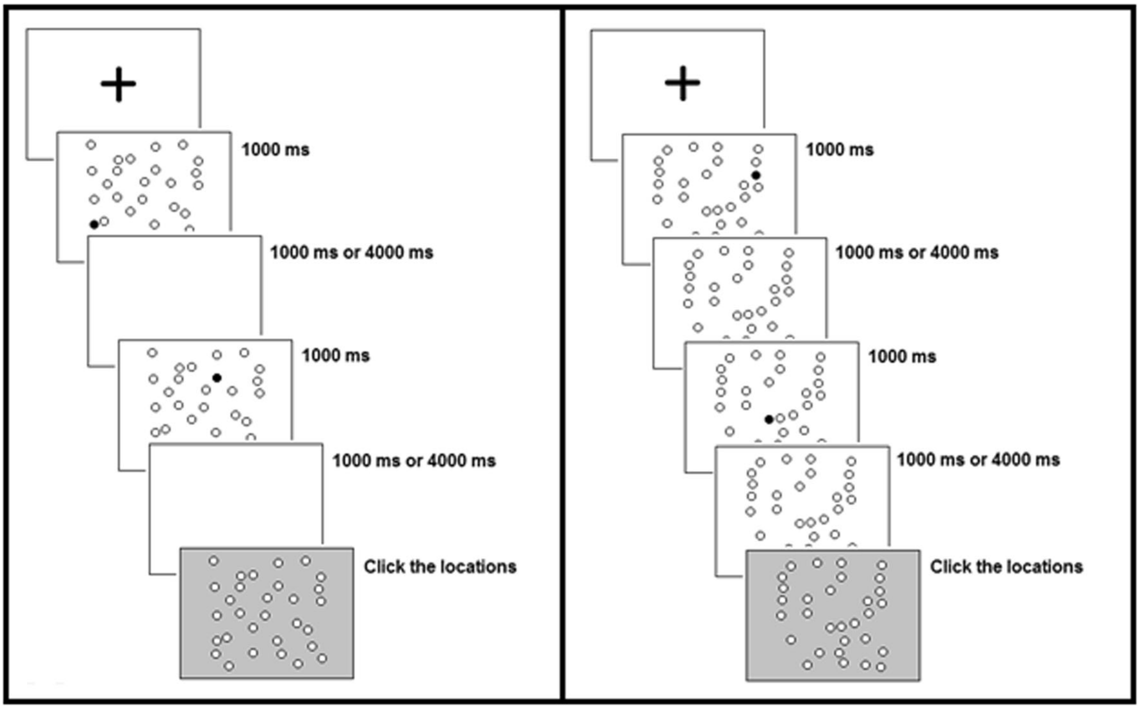

Fig. 2 Examples of the simple span tasks with and without environmental support in Experiment 1. The left panel shows a trial (list length 2) without environmental support, and the right panel shows a trial with environmental support

significant interaction between interitem interval duration and environmental support, $F(1, 23)= 35.32$, $p< .001$, $\eta_p^2= .61$. Planned comparisons revealed that this interaction reflected the fact that when environmental support was present, spans were significantly larger in the task with long interitem intervals than in the task with short interitem intervals, $t(23)= 3.26$, $p= .003$, whereas when environmental support was absent the opposite pattern was observed, and spans were significantly smaller in the task with long interitem intervals than in the task with short interitem intervals, $t(23)= 5.72$, $p< .001$ (see Fig. 3).

The observed interaction suggests that when environmental support was provided, rehearsal of the to-be-remembered locations was facilitated. More specifically, when participants were given long interitem intervals in which to rehearse as well as the environmental support needed to do so effectively, memory performance was better than when support was provided but the short interitem interval duration limited the time available for rehearsal. This finding further suggests that, given the right environmental support and sufficient time, rehearsal can improve visuospatial memory performance, perhaps because it provides more opportunity to engage in elaborative processing and/or more practice retrieving to-be-remembered locations using the array as a cue.

Previous findings related to the efficacy of maintenance rehearsal have been mixed: Some studies have shown that decreasing the presentation rate, and thereby giving participants additional time to rehearse between the presentations of items, improves memory performance (e.g., Mackworth, 1962; Tan & Ward, 2008), consistent with the present results, whereas other studies have shown that memory performance actually decreases with reductions in presentation rate (e.g., Conrad & Hille, 1958; Posner, 1964). Mixed results have also

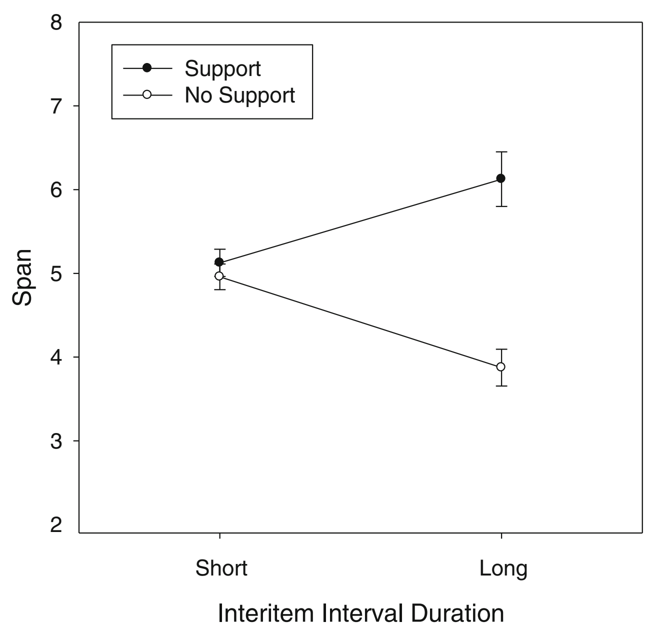

Fig. 3 Effects of interitem interval duration and environmental support on visuospatial memory spans in Experiment 1. The short and long interitem intervals were 1,000 and 4,000 ms in duration, respectively

been observed when the duration of a final retention interval is manipulated (e.g., cf. Craik & Watkins, 1973, and Peterson & Peterson, 1959). Of course, the vast majority of studies investigating this issue have been conducted using verbal memory items, and whatever the reasons for the mixed results, it is quite possible that they may not generalize to the visuospatial domain. Precisely because it is unclear whether the same principles apply in both the verbal and visuospatial domains, more research is needed that will investigate the possible benefits of increasing the opportunity for rehearsal in visuospatial memory.

The results of Experiment 1 are also consistent with the eyetracking results of Tremblay et al. (2006), who reported that memory for the order in which locations were presented improved as the number of rehearsed sequential locations increased, and who also found that the order of rehearsed locations was remembered better than the order of unrehearsed locations. The present experiment went beyond that of Tremblay et al., to suggest that visuospatial rehearsal can improve location memory itself, rather than just memory for the temporal order in which locations were presented.

The observed interaction also suggests that when environmental support was not provided, rehearsal of the to-be-remembered locations was apparently impeded, as evidenced by the finding that spans decreased by more than one location on the task with long interitem intervals, relative to the task with short interitem intervals (i.e., average spans went from 5.0 to 3.9). Importantly, all four tasks used in this experiment were true simple span tasks, meaning that participants were never required to perform any secondary processing task during the interitem intervals, and so were free to rehearse the locations, either overtly or covertly, as best they could. It is therefore unlikely that the reduced memory spans observed when environmental support was not provided were caused by interference, and instead the observed forgetting may have been due to the decay of memory traces over time.

Experiment 2

In Experiment 1, the amount of time between trials (i.e., the intertrial interval) was controlled by the participants, who were instructed to press the spacebar when they were ready to start the next trial. It is therefore possible for one to argue that the forgetting observed in the long-interitem-interval task without environmental support could have been due to the decreased temporal distinctiveness of the memory representations, rather than to decay. This is because the temporal distinctiveness of a memory item decreases as the amount of time since its presentation increases, and this can lead to poorer recall (e.g., Brown, Neath, & Chater, 2007; Crowder, 1976).

The durations of intertrial intervals were not recorded in Experiment 1, but if participants' intertrial interval durations were similar in the long-interitem-interval and the short-interitem-interval tasks, then the ratio of interitem interval duration to intertrial interval duration would have been smaller when the interitem intervals were long than when the interitem intervals were short, potentially causing the representations of current and previous memory items to be more compressed in time (e.g., Shipstead & Engle, 2013; Unsworth, Heitz, & Parks, 2008). Because such compression could increase proactive interference, it is possible that the decreased temporal distinctiveness when interitem intervals were long played a role in the forgetting observed when environmental support was not provided. In Experiment 2, therefore, participants completed the same four visuospatial simple span tasks as in Experiment 1, but the ratio between the interitem interval durations and the intertrial interval durations was kept constant across tasks.

Method

Participants A group of 24 students (nine female, 15 male) at Washington University in St. Louis participated in this experiment in partial fulfillment of a course requirement. None of the students in this experiment had participated in Experiment 1.

Materials and procedure All participants performed four visuospatial simple span tasks that were identical to the tasks used in Experiment 1, except that in this experiment the intertrial interval durations were experimentally controlled. In the two tasks with short (i.e., 1,000-ms) interitem intervals, each intertrial interval was 1,000 ms, and in the two tasks with long (i.e., 4,000-ms) interitem intervals, each intertrial interval was 4,000 ms. Thus, the ratio of intertrial interval to interitem interval was fixed at 1.0, thereby keeping the relative temporal distinctiveness of items constant across tasks. All other aspects of the procedure were the same as in Experiment 1.

Results and discussion

As in Experiment 1, a 2 (interitem interval: short vs. long) × 2 (environmental support: present vs. absent) repeated measures ANOVA was conducted on the memory span data. A main effect of environmental support was observed, $F(1, 23) = 29.07$, $p < .001$, $\eta_p^2 = .56$, and although the main effect of interval duration was not significant, $F(1, 23) = 2.12$, n.s., we again found a significant interaction between interitem interval duration and environmental support, $F(1, 23) = 7.93$, $p = .010$, $\eta_p^2 = .26$. Importantly, a planned comparison revealed that in the absence of environmental support, spans were significantly smaller in the task with long interitem intervals than in the task with short interitem intervals, $t(23)= 4.26$, $p< .001$ (see Fig. 4).

In Experiment 2, the ratio between the durations of the interitem intervals and the intertrial intervals was kept constant, and because memory spans in the long-interitem-interval task without environmental support remained significantly smaller than in the short-interitem-interval task without environmental support, this suggests that the forgetting observed in the long-interitem-interval task without environmental support in Experiments 1 and 2 was not due solely to reduced temporal distinctiveness. Since participants were again not required to perform any secondary processing task during the interitem intervals, and since differences in temporal distinctiveness were largely controlled in this experiment, it appears that the observed forgetting may have been due to the decay of memory traces over time.

Experiment 3

The effect that an interpolated secondary processing task can have on memory performance is well known, if not well understood: Typically, recall on complex span tasks, in which a secondary processing task alternates with the presentation of items for the primary memory task, is poorer than recall on simple span tasks, in which the memory task is performed alone. However, the reason why performance is poorer is not entirely clear. On the one hand, secondary tasks may create representation-based interference, effectively overwriting the contents of working memory. On the other hand, secondary tasks also likely block rehearsal, as when articulatory suppression is used to prevent covert repetition of to-be-remembered words. In the visuospatial domain, this could occur because environmental support is often removed when secondary-task stimuli are presented, making it difficult to rehearse using eye movements and/or shifts of spatial attention toward to-be-remembered locations. Such manipulations intended to impede rehearsal may lead to some form of time-based forgetting. Accordingly, Experiment 3 was designed to examine the extent to which the removal of environmental support for rehearsal might explain the forgetting caused by secondary tasks, as well as to explore the possibility that the reason why secondary tasks from the same domain as the primary memory task lead to forgetting may be different from the reason why secondary tasks from a different domain as the primary memory task lead to forgetting.

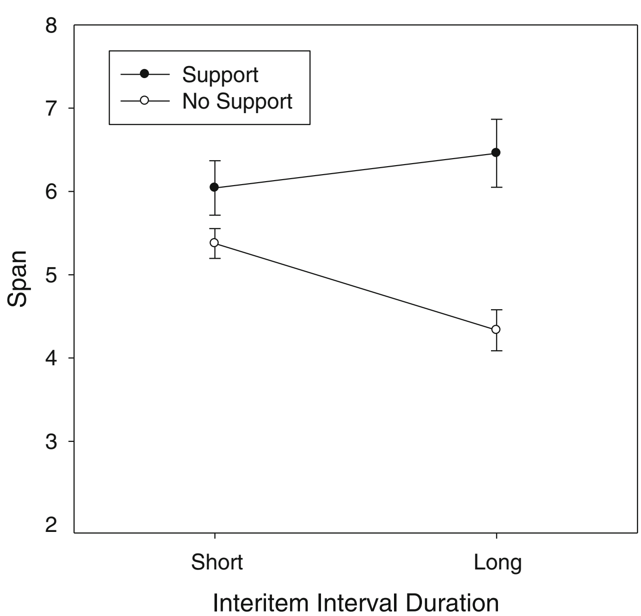

Fig. 4 Effects of interitem interval duration and environmental support on visuospatial memory spans in Experiment 2

The participants in Experiment 3 performed four memory tasks: two visuospatial simple span tasks that were essentially the same as the two tasks with long interitem intervals used in Experiment 1, and two visuospatial complex span tasks in which participants had to perform either a verbal or a visuospatial secondary processing task during the interitem intervals. If the memory spans on the two complex span tasks were both similar to the memory spans on the simple span task without environmental support, this would suggest that both secondary tasks simply impede rehearsal, consistent with a time-based forgetting framework. If, however, requiring participants to perform either secondary task lowers memory span more than does not providing environmental support, this would suggest that the secondary task did more than just impede rehearsal.

Some researchers have observed selective, domain-specific effects in both verbal and visuospatial working memory: Spans are typically lower when the items involved in the secondary processing task and the primary memory task are from the same domain, relative to when they are from different domains (e.g., Hale et al., 1996; Logie et al., 1990). However, other researchers have reported that, at least in the case of visuospatial memory, secondary tasks have only domain-general effects (e.g., Vergauwe, Barrouillet, & Camos, 2010). Experiment 3 included one complex span task in which both the memory task and the secondary task were visuospatial, as well as one complex span task in which the memory task was visuospatial and the secondary task was verbal. If domain-general effects were to be observed (i.e., if verbal and visuospatial secondary tasks led to similar memory spans), this finding would be consistent with the hypothesis that secondary processing tasks lower visuospatial spans because they require that domain-general attentional resources, and not just domain-specific spatial resources, be diverted from maintaining the representations of the memory items. If memory spans were significantly smaller when both memory and secondary tasks were visuospatial than when the former was visuospatial and the latter was verbal, however, this finding would be consistent with the hypothesis that visuospatial secondary tasks do more than just divert general attentional resources.

Method

Participants Another 24 students (15 female, nine male) at Washington University in St. Louis participated in this experiment in partial fulfillment of a course requirement or for monetary compensation. None of the students in this experiment had participated in Experiment 1 or 2.

Materials and procedure All participants performed four visuospatial memory span tasks; as in the previous experiments, on each trial of each task an array of 30 empty circles was presented, and a subset of the circles turned red one at a time. Each red circle was presented for 1,500 ms, followed by an interitem interval of at least 4,000 ms. Participants were instructed to remember the locations of the red circles. List lengths again ranged from two to 11 (two test trials at each length), and trials were ordered according to list length, from shortest to longest. At recall, participants saw the same array of 30 empty circles that had been presented at the beginning of the trial and were asked to use the computer mouse to click on those that had turned red during that trial. Participants were allowed to recall the locations in any order, and they indicated when they were finished by clicking on an icon labeled "Done." As in Experiment 1, the intertrial interval durations were controlled by the participants, since participants were instructed to press the spacebar when they were ready to begin the next trial. Span was again measured as one less than the shortest list length at which both test trials were incorrect.

The four memory span tasks differed with respect to what occurred during the interitem intervals (i.e., the time between the offset of one red circle and the onset of the next red circle, and also the time between the offset of the final red circle and the onset of the test array). In the simple span task with environmental support, the 30-circle array was presented during the interitem intervals, as in the long-interitem-interval task with environmental support in Experiments 1 and 2. In the simple span task without environmental support, a blank screen was presented during the interitem intervals, as in the long-interitem-interval task without environmental support in Experiments 1 and 2.

The two complex span tasks are depicted in Fig. 5. In the complex span task with the verbal secondary task, participants were asked to determine whether or not the solutions given for simple addition problems were correct (e.g., 7+ 3= 11?) during the interitem intervals (Turner & Engle, 1989). In the complex span task with the visuospatial secondary task, participants were asked to determine whether or not a horizontal line was able to fit in the gap between two boxes during each interitem interval (Vergauwe et al., 2010). The distance between the boxes varied from presentation to presentation, and the lines (presented either directly above or directly below the boxes) also varied in length. On both complex span tasks, participants indicated their decisions during the secondary task by pressing one of two labeled keys on the computer keyboard. Both complex span tasks began with two rounds of practice trials: Participants first responded to ten secondary-task items in the absence of a memory task, followed by four practice trials that were identical to the test trials.

Each interitem interval was designed to last at least 4,000 ms, consistent with the tasks with long interitem intervals used in Experiments 1 and 2. Thus, in the complex span tasks participants completed as many secondary-task problems (i.e., math problems or line judgments) as they could until 4,000 ms had elapsed (with one problem replacing another as soon as a participant responded), at which point participants were allowed to respond to the current problem before the next red circle was presented. Participants completed an average of 4.4 (*SD*= 1.1) math problems and 5.5 (*SD*= 0.9) line judgments per interitem interval, and the overall average accuracies were 98.6% for the math problems and 93.8% for the line judgments. Because participants were never stopped in the middle of a problem, the total length of each interval typically was longer than 4,000 ms: The average lengths of time of the interitem intervals were 4,538 ms (*SD*= 233.7) in the complex span task with the verbal secondary task (an average of 1,024 ms per problem) and 4,770 ms (*SD*= 366.4) in the complex span task with the visuospatial secondary task (an average of 864 ms per problem).

In the two simple span tasks, participants were free to rehearse the locations the best that they could during the interitem intervals, although they received no instructions to do so. Because the goal of Experiment 3 was to compare the effects of impeding rehearsal with those of diverting attention, domain-general as well as domain-specific, through secondary tasks, it was critical that the interitem intervals in the simple span tasks be equivalent in duration for each participant to the interitem intervals in the complex span tasks. To ensure that this would be the case for each individual, all participants completed the two complex span tasks first, although the order of the complex span tasks was counterbalanced across participants. A participant's interitem interval durations in these tasks were then used to determine the interitem interval durations for that participant in the simple span tasks that followed (the order of which was also counterbalanced); the interval durations for each of the simple span tasks

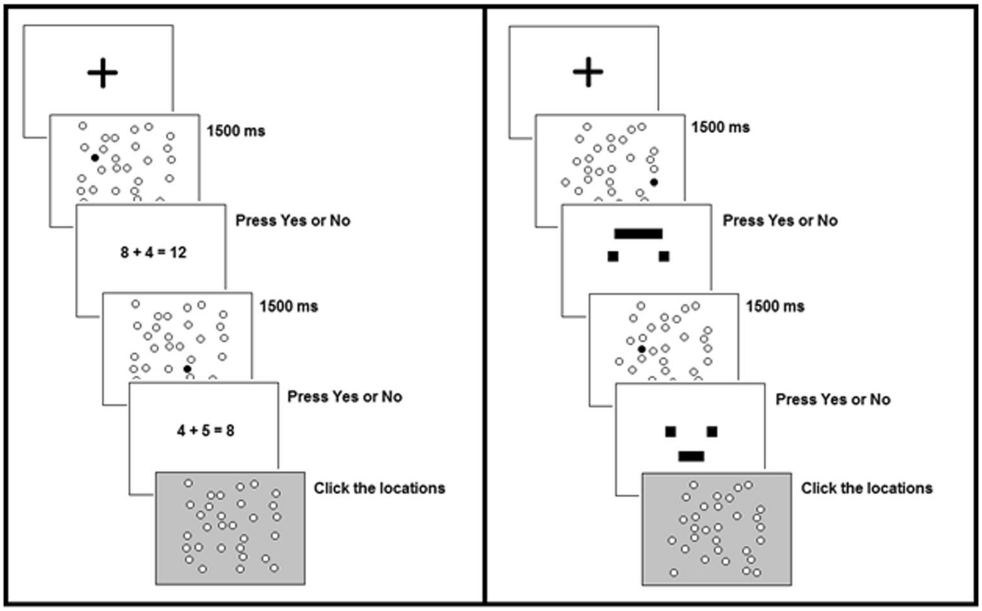

Fig. 5 Examples of the complex span tasks in Experiment 3. The left panel shows a trial from the complex span task with the verbal secondary task, and the right panel shows a trial from the complex span task with the visuospatial secondary task.

were drawn half from the complex span task with the verbal secondary task and half from the complex span task with the visuospatial secondary task.

Results and discussion

Figure 6 depicts the visuospatial memory spans obtained on the four tasks of Experiment 3. A planned contrast comparing the two simple span tasks revealed that spans were significantly larger when environmental support for rehearsal was provided than when support was not provided, $t(23)= 3.97$, $p= .001$, consistent with the results for the tasks with long interitem intervals in Experiments 1 and 2.

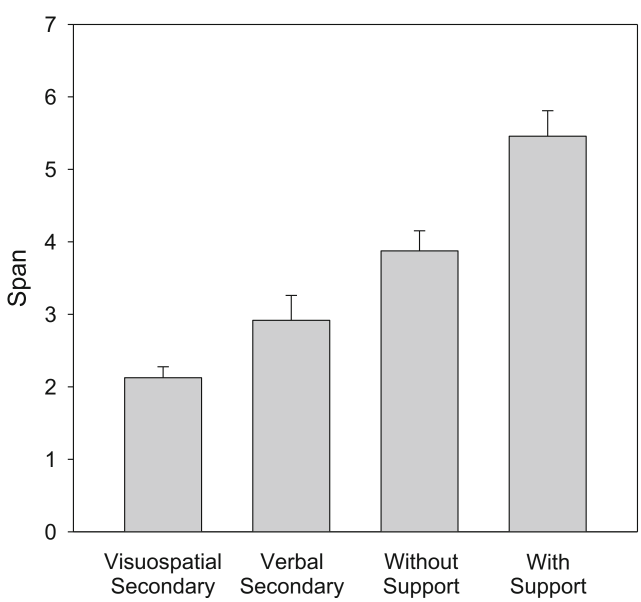

Fig. 6 Effects of environmental support and secondary task on visuospatial memory spans in Experiment 3

The primary goal of the present experiment, however, was to compare the forgetting of visuospatial information caused by secondary processing tasks with the forgetting caused by the absence of environmental support for rehearsal. Both the absence of environmental support and having to perform a secondary task presumably impeded the active maintenance of memory representations, although they may have done so in different ways: The absence of environmental support impeded rehearsal without necessarily diverting domain-general attention, whereas secondary tasks may have impeded not only rehearsal but also other forms of active maintenance (e.g., attentional refreshing) by diverting general attention from the representations of memory items.

To compare the effects of secondary processing tasks on visuospatial working memory with the effects of not having environmental support, a one-way ANOVA was conducted on the spans from the simple span task without environmental support, the complex span task with the verbal secondary task, and the complex span task with the visuospatial secondary task. A significant main effect of task emerged, $F(2, 46)= 17.02$, $p< .001$, $\eta_p^2= .43$, and a significant linear trend reflected the fact that spans decreased systematically from the simple span task without environmental support to the complex span task with the verbal secondary task, and then again to the complex span task with the visuospatial secondary task, $F(1, 23)= 63.79$, $p< .001$, $\eta_p^2= .73$. Importantly, spans were significantly smaller when the secondary task was visuospatial than when it was verbal, $t(23) = 2.49$, $p = .021$.

If the only reason why secondary tasks and the lack of environmental support both cause forgetting is that both impede visuospatial rehearsal, one would have expected spans in the two complex span tasks to be equivalent to those in the simple span task without environmental support, but this was not the case: Spans in the simple span task without environmental support were larger than those in the two complex span tasks. Moreover, if this had occurred simply because the lack of environmental support for rehearsal does not impede the active maintenance of memory representations as effectively as does diverting domain-general attention away from those representations in order to perform a secondary processing task, one would have expected spans on the two complex span tasks to be equivalent, but again, this was not the case: Spans in the complex span task with the verbal secondary task were larger than those in the complex span task with the visuospatial secondary task. Taken together, these findings suggest, first, that both verbal and visuospatial secondary tasks can divert general attention from to-be-remembered locations, and second, that visuospatial secondary processing tasks can additionally create interference with visuospatial memory representations and/or divert the domain-specific (spatial) attention necessary for maintaining these representations.

Domain-specific effects between secondary tasks and primary memory tasks traditionally have been considered to be evidence of a functional fractionation in the working memory system (e.g., Hale et al., 1996; Logie et al., 1990), and the results of Experiment 3 are consistent with this idea. According to Baddeley (1986) and others, domain-specific effects occur when memory items and secondary task items are from the same domain, because these items must compete for the same limited, domain-specific resources or because representations of the secondary task items may overwrite the representations of the to-be-remembered items.

When comparing the effects of secondary tasks, it is important to consider the cognitive loads of the tasks being compared (defined by Barrouillet and colleagues as the proportion of total time allowed for the processing task that was actually used for processing; e.g., Barrouillet et al., 2004), because some research has shown that what appear to be domain-specific effects can disappear when cognitive load is controlled (e.g., Vergauwe, Barrouillet, & Camos, 2009; Vergauwe et al., 2010). In the present experiment, both complex span tasks were designed to have very high cognitive loads, since participants were presented with the next secondary-task item (i.e., the next math problem or line judgment) immediately after responding to the current item. When the cognitive load of each complex span task was calculated using the response time data obtained in Experiment 3, the complex span task with the verbal secondary task had a cognitive load of .901, and the complex span task with the visuospatial secondary task had a cognitive load of .905. Thus, differences in cognitive load cannot easily explain the observed domain-specific effect.

Interestingly, if attention is considered to be a domain-general construct, such domain-specific effects are inconsistent with theoretical models in which time-based decay is the sole cause of forgetting. Such models posit that items are forgotten because memory representations fade over time when domain-general attention is not available to refresh them, as when attention is diverted by a secondary processing task (e.g., Barrouillet et al., 2004; Towse & Hitch, 1995). Spans were smaller on both complex span tasks than on the simple span task without environmental support, suggesting that domain-general attention can play a role, but the fact that performing a visuospatial secondary task resulted in smaller memory spans than did performing a verbal secondary task is difficult to reconcile with such decay models, since domain-general attention should have been diverted similarly by the two tasks. Clearly, both secondary tasks diverted attention from the memory items, allowing forgetting to occur, but the fact that different secondary tasks had different effects on memory suggests that a lack of attention, in the domain-general sense of the term, was not the only factor involved. That is, the fact that performing any secondary task decreased memory spans suggests that domain-general attention does play a role in complex span tasks, but these results also suggest that a visuospatial secondary task may selectively disrupt visuospatial maintenance and/or cause representation-based interference with visuospatial memory items. The results of Experiment 3 show that, consistent with past research by Baddeley and colleagues (e.g., Jarrold, Tam, Baddeley, & Harvey, 2011; Logie et al., 1990), both domain-specific and domain-general effects can contribute to the forgetting caused by secondary processing tasks.

General discussion

The present investigation of visuospatial working memory had three primary goals: first, to evaluate the effects of environmental support on visuospatial rehearsal; second, to examine the role of temporal distinctiveness in these effects; third, to compare the effects of the lack of environmental support for rehearsal with the effects of secondary processing tasks. The first goal was addressed in Experiment 1, in which participants performed simple visuospatial span tasks. Two critical factors were manipulated: whether or not environmental support was provided during the interitem intervals (i.e., whether or not the array of possible locations was present), and whether the duration of those interitem intervals was short (1,000 ms) or long (4,000 ms). Importantly, participants did not have to perform a secondary task during the interitem intervals, and thus were free to try to rehearse the to-be-remembered locations. When environmental support was not provided, spans were larger in the task with short interitem intervals than in the task with long interitem intervals, but the opposite pattern was observed when environmental support was provided. These findings are consistent with the hypothesis that environmental support is needed for the effective rehearsal of to-be-remembered locations, and that without such rehearsal, the representations of those locations will decay.

The second goal was addressed in Experiment 2. Because intertrial interval durations were not experimentally controlled in Experiment 1, it remained possible that decreases in the temporal distinctiveness of memory items played a role in the forgetting observed in the long-interitem-interval task without environmental support. Therefore, Experiment 2 included the same four visuospatial simple span tasks used in Experiment 1, except that the intertrial interval durations were controlled so as to keep the ratio of the interitem interval durations to the intertrial interval durations, and thus the temporal distinctiveness of memory items, constant across tasks. Importantly, when environmental support was not provided, memory spans were again significantly smaller in the long-interitem-interval task than in the short-interitem-interval task, suggesting that reduced temporal distinctiveness played at most a small role in the forgetting observed without environmental support in Experiment 1.

The third goal was addressed in Experiment 3, in which memory spans for a simple span task without environmental support were compared with memory spans for two complex span tasks, in which the interitem intervals were filled with a secondary processing task. Spans were smaller when participants had to perform a secondary task than when rehearsal was impeded simply by the absence of environmental support. It made a difference, however, whether the secondary processing task was verbal or visuospatial, since spans were even smaller in the complex span task with the visuospatial secondary task than in the one with the verbal processing task, consistent with the hypothesis that in addition to eliminating environmental support for rehearsal and diverting domain-general attention, visuospatial secondary tasks also interfere directly with the representations of to-be-remembered locations and/or disrupt domain-specific maintenance processes. Importantly, such domain-specific effects are consistent with the hypothesis that working memory utilizes at least two domain-specific stores, one of which temporarily maintains verbal information, and one of which maintains visuospatial information (e.g., Baddeley, 1986; Baddeley & Hitch, 1974; Logie, 1995).

Considered together, the present experiments provide evidence consistent with the occurrence of both decay and interference in visuospatial working memory. In Experiments 1 and 2, memory spans decreased with increases in interitem interval duration when environmental support for rehearsal was not provided, and this forgetting was most likely due to decay. One might argue against this interpretation on the grounds that the repeated appearance and disappearance of the array of possible locations in the tasks without environmental support could have distracted participants, thereby disrupting encoding processes. Notably, however, spans did not differ on the basis of the presence or absence of environmental support in the simple span tasks with short interitem intervals, suggesting that participants' abilities to encode were likely similar across conditions of environmental support.

In the verbal domain, it has been difficult to draw clear conclusions regarding the possible effects of decay in working memory, because studies typically have blocked rehearsal by having participants perform a secondary processing task in addition to the primary memory task. The present experiments have introduced a new, potentially important experimental paradigm for the investigation of decay in the visuospatial domain that does not require the use of a secondary task. The results of Experiments 1 and 2 suggest that, at least when the array of possible memory locations is relatively unstructured and unfamiliar, removing that array during the interitem intervals impedes rehearsal and produces forgetting that, by default, is presumed to reflect the decay of memory representations. This experimental paradigm also allowed for a comparison of the forgetting caused by impeding rehearsal with the forgetting caused by secondary processing tasks, and the results of Experiment 3 revealed that having to perform a secondary task was more detrimental to participants' retention of visuospatial items in working memory than was simply impeding rehearsal by removing environmental support, suggesting that both interference and decay can play roles in forgetting.

It is interesting to note that not all theories of working memory that posit that forgetting occurs through decay would have predicted the present results. For example, the time-based resource-sharing model proposed by Barrouillet and colleagues (e.g., Barrouillet et al., 2004; Barrouillet & Camos, 2012) hypothesizes that domain-general attention is required to refresh memory traces, so that when attention is directed to a secondary processing task, for example, memory traces cannot be refreshed, and therefore will decay over time. In the first two experiments of the present study, however, general attention was never diverted by a secondary processing task, yet forgetting occurred when environmental support was not provided, a result that is difficult to explain in terms of the time-based resource-sharing model.

The domain-specific effect observed in Experiment 3 is also largely inconsistent with the hypothesis that forgetting is caused exclusively by decay. Contemporary theories of decay typically focus on the role of attention, which is a domain-general construct (e.g., Barrouillet et al., 2004; Towse & Hitch, 1995), and domain-general attention should have been diverted similarly by both the verbal and visuospatial secondary tasks in Experiment 3. Therefore, both tasks should have had similar effects on memory span. Instead, however, visuospatial memory spans were smaller when the secondary task was visuospatial than when it was verbal. Both secondary tasks led to forgetting, suggesting they both successfully diverted general attention from the memory representations, but the fact that the two secondary tasks had different effects on visuospatial working memory, with the visuospatial secondary task leading to smaller spans than the verbal secondary task, suggests that both decay and interference likely played roles.

Conclusions

The present experiments have been the first to demonstrate that the presence of environmental support, or the lack thereof, can systematically affect the efficacy of visuospatial rehearsal, and thus, visuospatial working memory. In addition, the present experiments clarify the consequences of processing nonmemory stimuli while simultaneously trying to maintain temporary memory of a set of locations. Taken together, the findings from the present experiments resist oversimplification, yet tell a story that is quite orderly and comprehensible, with rehearsal, decay, and interference—both domain-general and domain-specific—all having important roles to play in determining visuospatial memory span. For someone trying to remember locations, the story has clear implications. If environmental support for rehearsal is available, then rehearsing by moving one's eyes and/or shifting spatial attention to the to-be-remembered locations will help prevent forgetting. If environmental support is not available, it is then best to avoid shifting one's attention to nonmemory stimuli. Finally, if attention must be diverted to process nonmemory stimuli, then it is better to process verbal than visuospatial stimuli. Although the mechanism(s) underlying these prescriptions remain a matter of current debate, the present results suggest that forgetting in visuospatial memory span tasks involves more than one mechanism, ultimately raising the question of the extent to which the same or different mechanisms are involved in forgetting in verbal memory span tasks.

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References

Awh, E., Jonides, J., & Reuter-Lorenz, P. A. (1998). Rehearsal in spatial working memory. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 780–790. doi:10.1037/0096-1523.24.3.780

Baddeley, A. (1986). *Working memory.* Oxford: Oxford University Press, Clarendon, Press.

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. A. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 8, pp. 47–89). New York: Academic Press.

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General, 133,* 83–100. doi:10.1037/0096-3445.133.1.83

Barrouillet, P., Bernardin, S., Portrat, S., Vergauwe, E., & Camos, V. (2007). Time and cognitive load in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33,* 570–585. doi:10.1037/0278-7393.33.3.570

Barrouillet, P., & Camos, V. (2012). As time goes by: Temporal constraints in working memory. *Current Directions in Psychological Science, 21,* 413–419. doi:10.1177/0963721412459513

Barrouillet, P., Portrat, S., Vergauwe, E., Diependaele, K., & Camos, V. (2011). Further evidence for temporal decay in working memory: Reply to Lewandowsky and Oberauer (2009). *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37,* 1302–1317. doi:10.1037/a0022933

Brown, G. D. A., Neath, I., & Chater, N. (2007). A temporal ratio model of memory. *Psychological Review, 114,* 539–576. doi:10.1037/0033-295X.114.3.539

Conrad, R., & Hille, B. A. (1958). The decay theory of immediate memory and paced recall. *Canadian Journal of Psychology, 12,* 1–6. doi:10.1037/h0083723

Craik, F. I. M., Byrd, M., & Swanson, J. M. (1987). Patterns of memory loss in three elderly samples. *Psychology and Aging, 2,* 79–86. doi:10.1037/0882-7974.2.1.79

Craik, F. I. M., & Watkins, M. J. (1973). The role of rehearsal in short-term memory. *Journal of Verbal Learning and Verbal Behavior, 12,* 599–607. doi:10.1016/S0022-5371(73)80039-8

Crowder, R. G. (1976). *Principles of learning and memory.* Hillsdale: Erlbaum.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General, 128,* 309–331. doi:10.1037/0096-3445.128.3.309

Godijn, R., & Theeuwes, J. (2012). Overt is no better than covert when rehearsing visuo-spatial information in working memory. *Memory & Cognition, 40,* 52–61. doi:10.3758/s13421-011-0132-x

Hale, S., Myerson, J., Rhee, S. H., Weiss, C. S., & Abrams, R. A. (1996). Selective interference with the maintenance of location information in working memory. *Neuropsychology, 10,* 228–240.

Hale, S., Rose, N. S., Myerson, J., Strube, M. J., Sommers, M., Tye-Murray, N., & Spehar, B. (2011). The structure of working memory abilities across the adult life span. *Psychology and Aging, 26,* 92–110. doi:10.1037/a0021483

Hasher, L., & Zacks, R. T. (1979). Automatic and effortful processes in memory. *Journal of Experimental Psychology: General, 108,* 356–388. doi:10.1037/0096-3445.108.3.356

Jarrold, C., Tam, H., Baddeley, A. D., & Harvey, C. E. (2011). How does processing affect storage in working memory tasks? Evidence for both domain-general and domain-specific effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37,* 688–705. doi:10.1037/a0022527

Keppel, G., & Underwood, B. J. (1962). Proactive inhibition in short-term retention of single items. *Journal of Verbal Learning and Verbal Behavior, 1,* 153–161. doi:10.1016/S0022-5371(62)80023-1

Lawrence, B. M., Myerson, J., & Abrams, R. A. (2004). Interference with spatial working memory: An eye movement is more than a shift of attention. *Psychonomic Bulletin & Review, 11,* 488–494. doi:10.3758/BF03196600

Lawrence, B. M., Myerson, J., Oonk, H. M., & Abrams, R. A. (2001). The effects of eye and limb movements on working memory. *Memory, 9,* 433–444.

Lewandowsky, S., & Oberauer, K. (2009). No evidence for temporal decay in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35,* 1545–1551. doi:10.1037/a0017010

Logie, R. H. (1995). *Visuo-spatial working memory*. Hove: Erlbaum.

Logie, R. H., Zucco, G. M., & Baddeley, A. D. (1990). Interference with visual short-term memory. *Acta Psychologica, 75,* 55–74.

Mackworth, J. F. (1962). Presentation rate and immediate memory. *Canadian Journal of Psychology, 16,* 42–47. doi:10.1037/h0083229

Murray, D. J. (1967). The role of speech responses in short-term memory. *Canadian Journal of Psychology, 21,* 263–276. doi:10.1037/h0082978

Pearson, D., & Sahraie, A. (2003). Oculomotor control and the maintenance of spatially and temporally distributed events in visuo-spatial working memory. *Quarterly Journal of Experimental Psychology, 56A,* 1089–1111. doi:10.1080/02724980343000044

Peterson, L., & Peterson, M. J. (1959). Short-term retention of individual verbal items. *Journal of Experimental Psychology, 58,* 193–198. doi:10.1037/h0049234

Posner, M. I. (1964). Rate of presentation and order of recall in immediate memory. *British Journal of Psychology, 55,* 303–306.

Postle, B. R., Idzikowski, C., Della Sala, S., Logie, R. H., & Baddeley, A. D. (2006). The selective disruption of spatial working memory by eye movements. *Quarterly Journal of Experimental Psychology, 59,* 100–120. doi:10.1080/17470210500151410

Shipstead, Z., & Engle, R. W. (2013). Interference within the focus of attention: Working memory tasks reflect more than temporary maintenance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39,* 277–289. doi:10.1037/a0028467

Smith, A. D., Park, D. C., Cherry, K., & Berkovsky, K. (1990). Age differences in memory for concrete and abstract pictures. *Journal of Gerontology, 45,* 205–P209.

Tan, L., & Ward, G. (2008). Rehearsal in immediate serial recall. *Psychonomic Bulletin & Review, 15,* 535–542. doi:10.3758/PBR.15.3.535

Towse, J. N., & Hitch, G. J. (1995). Is there a relationship between task demand and storage space in tests of working memory capacity? *Quarterly Journal of Experimental Psychology, 48A,* 108–124. doi:10.1080/14640749508401379

Towse, J. N., Hitch, G. J., & Hutton, U. (2000). On the interpretation of working memory span in adults. *Memory & Cognition, 28,* 341–348. doi:10.3758/BF03198549

Tremblay, S., Saint-Aubin, J., & Jalbert, A. (2006). Rehearsal in serial memory for visual–spatial information: Evidence from eye movements. *Psychonomic Bulletin & Review, 13,* 452–457. doi:10.3758/BF03193869

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language, 28,* 127–154.

Unsworth, N., Heitz, R. P., & Parks, N. A. (2008). The importance of temporal distinctiveness for forgetting over the short term. *Psychological Science, 19,* 1078–1081. doi:10.1111/j.1467-9280.2008.02203.x

Vergauwe, E., Barrouillet, P., & Camos, V. (2009). Visual and spatial working memory are not that dissociated after all: A time-based resource-sharing account. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35,* 1012–1028. doi:10.1037/a0015859

Vergauwe, E., Barrouillet, P., & Camos, V. (2010). Do mental processes share a domain-general resource? *Psychological Science, 21,* 384–390. doi:10.1177/0956797610361340