Spring 5-15-2015

The Effects of Environmental Support and Age on Visuospatial Rehearsal

Lindsey Lilienthal
Washington University in St. Louis

WASHINGTON UNIVERSITY IN ST. LOUIS

Department of Psychology

Dissertation Examination Committee:
Sandra Hale, Chair
Richard Abrams
David Balota
Joel Myerson
Nancy Tye-Murray

The Effects of Environmental Support and Age on Visuospatial Rehearsal

by

Lindsey Clara Lilienthal

A dissertation presented to the
Graduate School of Arts and Sciences
of Washington University in
partial fulfillment of the
requirements for the degree
of Doctor of Philosophy

May 2015
St. Louis, Missouri

Table of Contents

List of Figures ... iii
List of Tables ... iv
Acknowledgments ... v
Abstract ... vi
Chapter 1: Introduction ... 1
1.1 Distinction between Verbal and Visuospatial Working Memory ... 3
1.2 Visuospatial Working Memory and Aging ... 6
1.3 Rehearsal ... 8
1.4 Environmental Support ... 11
1.5 Present Experiments ... 20
Chapter 2: Experiment 1 ... 21
2.1 Method ... 22
2.1.1 Participants ... 22
2.1.2 Materials and Procedure ... 23
2.2 Results and Discussion ... 27
Chapter 3: Experiment 2 ... 35
3.1 Method ... 37
3.1.1 Participants ... 37
3.1.2 Materials and Procedure ... 38
3.2 Results and Discussion ... 43
3.2.1 Visual Search ... 43
3.2.2 Memory Performance ... 43
3.2.3 Eye-Movement Behavior ... 46
Chapter 4: Experiment 3 ... 57
4.1 Method ... 61
4.1.1 Participants ... 61
4.1.2 Materials and Procedure ... 61
4.2 Results and Discussion ... 66
Chapter 5: General Discussion ... 70
5.1 Environmental Support During Retention ... 71
5.2 Overt Visuospatial Rehearsal ... 73
5.3 Covert Visuospatial Rehearsal ... 76
5.4 Conclusions ... 79
References ... 81

List of Figures

Figure 1.1: Effects of inter-item duration and environmental support on visuospatial memory spans in Lilienthal et al. (2014b)..14

Figure 1.2: Effects of inter-item duration and environmental support on visuospatial memory spans in Lilienthal et al. (2014a)..18

Figure 1.3: Effects of environmental support on visuospatial memory spans in conditions with long inter-item intervals in Lilienthal et al. (2014a)..19

Figure 2.1: Example trials from each task condition in Experiment 1..24

Figure 2.2: Effects of retention interval duration and environmental support on visuospatial memory spans in Experiment 1...28

Figure 2.3: Effects of environmental support on visuospatial memory spans in conditions with long retention intervals in Experiment 1..29

Figure 2.4: Visuospatial memory spans in the condition with no retention interval, the condition with a short retention interval without environmental support, and the condition with a long retention interval without environmental support in Experiment 1.................32

Figure 3.1: Example arrays from the visual search task in Experiment 2....................................39

Figure 3.2: Average response times on the visual search task in Experiment 2...........................44

Figure 3.3: Average proportion of locations recalled correctly in Experiment 2.........................45

Figure 3.4: Eye-movement rate in Experiment 2...47

Figure 3.5 Proportion of eye movements made to the left half of the screen during retention intervals as a function of the proportion of to-be-remembered locations presented on the left half of the screen in Experiment 2..50

Figure 3.6: Average rehearsal-allocation correlations in Experiment 2.......................................51

Figure 3.7: Average median distance of eye movements made during retention intervals in Experiment 2...53

Figure 3.8: Average median fixation duration during retention intervals in Experiment 2...........55

Figure 4.1: Example trials from each task condition in Experiment 3..62

Figure 4.2: Effects of retention interval duration and environmental support on visuospatial memory spans in Experiment 3...67

List of Tables

Table 2.1: Retention interval durations in short and long conditions for each list length in Experiment 1..25

Table 4.1 Mean number of trials thrown out due to breaks in fixation in Experiment 3...............66

Acknowledgments

I would like to thank my dissertation committee for their invaluable time and feedback throughout this process. I especially would like to thank the members of my core committee – my advisors, Sandy and Joel, for their unwavering support and their incredible investment in my growth and success over the past six years, and Richard, for allowing me access to his lab and his expertise, and for his seemingly endless patience while doing so.

I would also like to express my gratitude to the Washington University Psychology Department as a whole, including the faculty, staff, undergraduates, and my wonderful classmates – this truly is a special place, and I feel so lucky to have been a part of it. In addition, I am very grateful for the financial support I received, both from the Graduate School and from NIA Training Grant AG00030, which provided funding for my dissertation research as well as other projects.

Finally, I'd like to thank my parents for, well, everything – for their love, encouragement, sacrifice, and inspiration – and my husband, Hank, for being my partner on this journey, and for being so willing to let me, more often than not, choose our destinations.

Lindsey Lilienthal

Washington University in St. Louis

May 2015

ABSTRACT OF THE DISSERTATION

The Effects of Environmental Support and Age on Visuospatial Rehearsal

by

Lindsey Clara Lilienthal

Doctor of Philosophy in Psychology

Washington University in St. Louis, 2015

Dr. Sandra Hale, Chair

Although there is substantial evidence supporting the functional distinction between verbal working memory and visuospatial working memory, most research focuses on the verbal domain, and much is still unknown about how people maintain and manipulate visuospatial information. Previous experiments have demonstrated that the amount of environmental support for rehearsal provided to participants can have an important impact on their memory for locations (Lilienthal, Hale, & Myerson, 2014b), and that young adults may benefit more from the presence of support than older adults (Lilienthal, Hale, & Myerson, 2014a). The goal of the three experiments presented in this dissertation was to further explore a number of questions related to the effects of environmental support and age on visuospatial rehearsal, which is thought to occur through eye movements and/or shifts of spatial attention to the to-be-remembered locations (e.g., Baddeley, 1986; Awh, Jonides, & Reuter-Lorenz, 1998). In Experiment 1, across five task conditions, environmental support was either present or absent during a final retention interval, which was either short or long; the same pattern of results observed in Lilienthal et al. (2014a) was replicated using this new procedure, providing additional support for a role of decay in visuospatial working memory. In Experiment 2, young and older adults' eye movements were recorded as they rehearsed, and although young adults rehearsed less, and did so less precisely,

when environmental support was absent than when support was present, no such differences were observed in older adults. In Experiment 3, participants were limited to covert rehearsal strategies (i.e., rehearsal performed through shifts of attention in the absence of eye movements), and rehearsal appeared to be impeded, and equally so, in both age groups. Overall, although the present study found further evidence for decay in visuospatial working memory, few age-related differences in the rehearsal of locations were observed, suggesting that such differences cannot account for the differential decline of visuospatial working memory observed with age.

Chapter 1: Introduction

Working memory refers to a complex function that allows for the temporary storage and manipulation of a limited amount of information. Working memory has become an increasingly important construct in psychology over the past few decades, in part because individual differences in the capacity of working memory have been found to be important predictors of many higher-order cognitive abilities, such as comprehension (e.g., Daneman & Carpenter, 1980; Just & Carpenter, 1992), learning (e.g., Kyllonen & Stephens, 1990; Lilienthal, Tamez, Myerson, & Hale, 2013), and reasoning (e.g., Engle, Tuholski, Laughlin, & Conway, 1999; Unsworth & Engle, 2007b).

Although multiple frameworks of the structure of working memory exist today, perhaps one of the most influential is the multicomponent model, proposed by Baddeley and Hitch (1974). This model originally posited a distinction between three components: the central executive, the phonological loop, and the visuospatial sketchpad. The central executive was proposed as an attentional system, responsible for a number of control processes (e.g., task switching, inhibition, and updating; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000) and for coordinating the two limited-capacity "slave" systems, the phonological loop and the visuospatial sketchpad. The phonological loop and the visuospatial sketchpad were proposed as largely passive information stores, with the loop responsible for storing and maintaining verbal information (e.g., words, digits, sentences) and the sketchpad responsible for storing and maintaining visuospatial information (e.g., shapes, textures, locations; Baddeley, 1986).

One important early question related to the multicomponent model was whether the phonological loop and the visuospatial sketchpad are actually functionally distinct, as suggested by the model, or whether working memory involves only a single, domain-general store. Even though a substantial amount of evidence has since been obtained for the distinction between the two domain-specific stores (discussed in the following section), it is interesting to note that the majority of research conducted regarding working memory has focused solely on memory for verbal information. This is important; as mentioned, a number of additional theories and models of working memory have since been proposed (e.g., Cowan, 1999; Unsworth & Engle, 2007a; Barrouillet, Bernardin, & Camos, 2004), and much of the research that has contributed to the development and support of these theories has primarily investigated verbal working memory, but there is an often an assumption, even if only implicit, that the proposed structures, principles, and processes should apply in both domains. However, as will be discussed, it seems that this assumption does not always hold true (e.g., Lilienthal, Hale, & Myerson, 2014b).

The literature's focus on verbal working memory also has important implications for what is known regarding age-related changes in working memory. As will be discussed, a number of studies have shown that visuospatial working memory tends to decline at a faster rate with age than verbal working memory, but the reasons behind this differential rate of decline are still unclear. Numerous possible causes have been proposed, such as declines in processing speed and reductions in available attentional resources, but relatively little empirical evidence speaking directly to these possibilities has been reported. Therefore, the primary purpose of the three experiments in the present study was to explore potential age-related differences in visuospatial rehearsal as a possible contributing factor to the differential age-related decline observed in visuospatial working memory.

1.1 Distinction between Verbal and Visuospatial Working Memory

As mentioned, following Baddeley and Hitch's (1974) proposal of the multicomponent model, one question that received a lot of attention was whether working memory involves two functionally distinct, domain-specific information stores (i.e., the phonological loop and visuospatial sketchpad), as suggested by the multicomponent model, or just a single, domain-general information store. Much of the early evidence supporting a distinction between the stores came from dual-task experiments that demonstrated selective, or domain-specific, interference. Typically, participants in dual-task studies are asked to remember one or more items, either verbal or visuospatial, while also performing a verbal or visuospatial secondary task. Selective interference would be said to have occurred if, when compared to a baseline condition in which participants perform the memory task alone, verbal memory performance were disrupted by the verbal secondary task but not the visuospatial secondary task, or vice versa for visuospatial memory. According to Baddeley (1986), selective interference occurs because when the secondary task and the memory task are from the same domain, they both require the same limited-capacity, domain-specific resources, thus creating competition for those resources and resulting in poorer memory performance; when the secondary task and memory task are from different domains, they do not compete for resources and thus very little, if any, interference is observed.

In an early study on selective interference, Brooks (1968) asked participants to make decisions about a learned piece of information that was either verbal or visuospatial. In the verbal memory condition, participants listened to a sentence and then were asked to categorize each word in the sentence in order, from memory, according to whether or not it was a noun. In the visuospatial memory condition, participants were shown a line drawing of a block letter and then were asked to categorize each corner in order, from memory, according to whether or not it was an extreme top or bottom point. Brooks considered the secondary task to be the reporting of these decisions, and participants were asked to provided responses for each word/corner either by saying “yes” or “no” (the verbal secondary task) or by pointing to a “y” or “n” in an array (the visuospatial secondary task). Brooks’ results revealed a cross-over interaction known as a double dissociation, considered to be one of the more conclusive forms of evidence of functional fractionation: When participants were reporting on sentences, their verbal responses were significantly slower than pointing responses, but when participants were reporting on the letters, their pointing responses were significantly slower.

Hale, Myerson, Rhee, Weiss, and Abrams (1996) observed a similar pattern of results using more typical working memory tasks. Participants performed two memory tasks, one in which they were asked to remember a series of digits and one in which they were asked to remember a series of locations in a grid. In both cases, the memory items were presented in different colors, and the secondary task was to report the color of the item, either by saying the color name out loud (the verbal secondary task) or by pointing to the matching color in a color palette (the visuospatial secondary task). Again, the results revealed a double dissociation: The digit memory task was disrupted only by the verbal secondary task, whereas the location memory task was disrupted only by the visuospatial secondary task. When participants were asked to remember digits and point to colors or remember locations and say color names out loud, they could remember as many of the to-be-remembered items as in conditions in which they performed the memory task alone, suggesting that when the two tasks were from different domains, the resources the tasks required did not overlap.

The proposed distinction between verbal and visuospatial memory has also been supported by evidence from a variety of other sources, including brain lesion patients, neuroscience, sex differences, latent-variable analyses, development and aging. For example, de Renzi and Nichelli (1975) reported that patients with brain damage to the left hemisphere had a deficit in verbal memory but relatively intact visuospatial memory, whereas patients with damage to the right hemisphere had a selective visuospatial memory deficit. Positron emission tomography (PET) studies with healthy participants also have supported the distinction by demonstrating that brain activation during verbal memory tasks is somewhat localized to the left hemisphere, whereas activation during visuospatial memory tasks is largely localized to the right hemisphere (e.g., Smith & Jonides, 1997; Smith, Jonides, & Koeppe, 1996; Buckner & Tulving, 1995), suggesting that different neural components are responsible for maintaining verbal and visuospatial information in memory.

Studies looking at individual and group differences in working memory have also supported the verbal/visuospatial distinction. For example, Lejbak, Crossley, and Vrbancic (2011) found that men performed significantly better than women on an n-back working memory task when to-be-remembered information was visuospatial, but not when it was verbal, also pointing to a separation between the domains (see also, Vecchi & Girelli, 1998). Latent-variable analyses have shown that verbal and visuospatial working memory are distinct at the construct level (e.g., Hale et al., 2011; Gilhooly, Wynn, Phillips, Logie, & Della Sala, 2002; Park, Lautenschlager, Hedden, Davidson, Smith, & Smith, 2002). Additional evidence comes from the developmental literature: Alloway, Gathercole, and Pickering (2006) investigated verbal and visuospatial working memory in children and reported separable verbal and visuospatial storage components in children as young as 4 years old, indicating that this fractionated working memory structure is present even at an early age. In the aging literature, a number of studies investigating working memory have reported greater differences between young and older adults in visuospatial working memory than in verbal working memory (e.g., Hale et al., 2011; Myerson, Emery, White, & Hale, 2003; Jenkins, Myerson, Joerding, & Hale, 2000), suggesting that visuospatial memory declines at a faster rate with age; these age-related differences will be discussed in more detail in the following section.

A great deal of evidence supporting a functional distinction between memory for verbal information and memory for visuospatial information has been reported from a wide variety of paradigms and sources. However, as mentioned previously, few of the more recent models of working memory have included such a distinction, instead treating working memory as essentially domain-general. This may be a useful simplification, and to the extent that the processes and mechanisms at work in the verbal domain are the same as those in the visuospatial domain, it is not necessarily a problem. However, because of the past focus on verbal memory, it is unclear which working memory processes and mechanisms are similar across the two domains and which may be different.

1.2 Visuospatial Working Memory and Aging

The differential age-related decline observed in visuospatial working memory compared to verbal working memory has provided additional support for a functional distinction between the two domains, but it is also particularly interesting because the reasons why visuospatial memory is more sensitive to age are still largely unknown. Although numerous possibilities have been proposed, they have been introduced primarily as part of discussion sections, and relatively little empirical evidence has been reported to explain the different rates of age-related decline across domain.

For example, Jenkins et al. (2000) suggested that the age-related difference could be caused by differences in the novelty of the verbal and visuospatial information commonly used as to-be-remembered items in memory tasks. Whereas most older adults have had extensive practice with verbal information over the course of their lifetimes, visuospatial memory items, things such as locations and abstract shapes, may be less familiar. This idea is consistent with the finding that verbal ability, typically measured by vocabulary tests, is often the cognitive function most resistant to age, as in some cases it even continues to improve into old age (e.g., Salthouse, Atkinson, & Berish, 2003; Salthouse, 2010). Therefore, it is possible that older adults' relatively intact verbal ability is bolstering their verbal working memory performance, reducing the severity of age-related declines compared to those they experience in visuospatial working memory.

An alternative, although not mutually exclusive, explanation of the different rates of age-related decline in memory across domain is the differential decline of processes involved in visuospatial working memory. Although verbal and visuospatial memory stores have the same general purpose, to accurately maintain information, the two stores may accomplish this goal at least in part using different, domain-specific processes. As suggested by both Jenkins et al. (2000) and Hale et al. (2001), visuospatial processes may be more sensitive to age, and this could also lead to different rates of age-related memory decline. Which specific processes may be changing at different rates is not entirely clear, but one reasonable possibility is processing speed, as it has been well documented that processing speed slows with age and that this slowing has important effects on many cognitive functions, including memory (e.g., Salthouse, 1994; Salthouse, 1996a).

Consistent with this idea, a number of studies have demonstrated that visuospatial processing speed seems to decline at a faster rate with age than verbal processing speed (e.g., Jenkins et al., 2000; Lawrence, Myerson, & Hale, 1998). Salthouse and colleagues (e.g., Salthouse, 1996b) have proposed that age-related reductions in processing speed likely have a direct impact on cognitive functions such as memory by preventing older adults from reaching later stages of processing and causing them to lose the products of early processing stages, but such slowing may also have an indirect effect on memory, perhaps through rehearsal (e.g., Jenkins, et al., 2000; Salthouse, 1996b).

1.3 Rehearsal

Rehearsal refers to the process or strategy of repeating information over and over in order to keep it active in working memory, and importantly, rehearsal in the two domains does seem to occur through different mechanisms. The rehearsal of verbal information is performed through articulation, either overt or covert, whereas the rehearsal of visuospatial information (i.e., specifically, locations) is believed to be performed through eye movements and/or shifts of spatial attention to the to-be-remembered locations (e.g., Baddeley, 1986; Awh, Jonides, & Reuter-Lorenz, 1998; Tremblay, Saint-Aubin, & Jalbert, 2006; Geng, Ruff, & Driver, 2008). As is common, more research has focused on verbal rehearsal than visuospatial rehearsal, and interestingly, much of the work that has investigated the rehearsal of locations has focused primarily on the consequences of preventing rehearsal (e.g., Pearson & Sahraie, 2003; Lawrence, Myerson, Oonk, & Abrams, 2001).

For example, in their third experiment, Hale et al. (1996) asked participants to remember the locations of a series of symbols presented in a grid. In one task condition, participants also performed an interpolated secondary task that required them to move their eyes away from the grid to the edge of the computer screen. In another task condition, participants performed an interpolated secondary task that required them to make the same eye movement but then also to determine whether a symbol presented at the edge of the screen matched the symbol they had just seen in the grid. Hale et al. found that simply having to make an eye movement following the presentation of each to-be-remembered location significantly disrupted participants' memory performance compared to a task condition with no secondary task, in which participants were allowed to continue looking at the grid following the presentation of each location. Importantly, the secondary task requiring only an eye movement produced as much interference as did the secondary task requiring an eye movement and a discrimination judgment. This suggests that moving one's eyes away from the to-be-remembered locations, regardless of whether one then has to engage in any processing or decision making, is enough to disrupt memory for those locations. Lawrence et al. (2001) expanded on these results, showing that eye movements indeed cause selective interference and disrupt memory for locations but not memory for letters (see also, Postle & Hamidi, 2007).

In addition, a few studies have attempted to investigate the benefits of visuospatial rehearsal, in that researchers allowed participants to rehearse locations and measured the effects. Tremblay et al. (2006) presented participants with a series of seven circles in random positions, and following a retention interval, participants were asked to recreate the order of the series. During the retention interval, the seven circles remained visible on the screen and the amount of rehearsal engaged in by each participant was measured by calculating the number of circle pairs at which participants looked in the correct temporal order. Tremblay et al found that as the number of rehearsed pairs increased, memory performance also increased, and, importantly, there was a significant performance advantage for circles that were rehearsed compared to those that were not (see also, Godijn & Theeuwes, 2012). This suggests that, as in the verbal domain (e.g., McCabe, 2008; Tan & Ward, 2000), visuospatial rehearsal can improve memory performance.

As mentioned, it is possible that age-related changes in rehearsal contribute to the declines observed in working memory, as Baddeley (1986) suggested that the capacity of working memory in part depends on the rate at which one can rehearse. If rehearsal rate and processing speed are correlated, the pervasive age-related slowing observed in a large number of studies may also have the effect of reducing older adults' working memory capacity by affecting rehearsal. Because visuospatial processing speed seems to be especially sensitive to age (Jenkins et al., 2000; Lawrence et al., 1998), one might then expect that visuospatial rehearsal, and thus visuospatial working memory, would be differentially affected with age.

For verbal information, there is evidence that rehearsal rate changes across the lifespan, speeding up through childhood (e.g., Hulme, Thomson, Muir, & Lawrence, 1984) and slowing down through later adulthood (e.g., Smith, Wasowicz, & Preston, 1987), and that verbal rehearsal rate is related to memory span (e.g., Gathercole, 1998; Multhaup, Balota, & Cowan, 1996; Kynette, Kemper, Norman, & Cheung, 1990); however, relatively little is known regarding age and visuospatial rehearsal. There is some evidence that certain aspects of eye movements, such as saccadic reaction time, peak velocity, and saccade duration, may change as people age (e.g., Munoz, Broughton, Goldring, & Armstrong, 1998; Spooner, Sakala, & Baloh, 1980; Warabi, Kase, & Kato, 1984; cf. Abel, Troost, Dell'Osso, 1983), and because the rehearsal of locations can occur through eye movements made to the to-be-remembered locations, it is possible that these types of physical changes may also influence the effectiveness of visuospatial rehearsal. In addition, it has also been suggested that older adults may be less likely to spontaneously engage in effective strategies, such as rehearsal, when performing a memory task (e.g., Dunlosky & Hertzog, 2001; Craik & Byrd, 1982; cf. Bailey, Dunlosky, & Hertzog, 2009), but the majority of this research has been conducted using verbal to-be-remembered items and it is unclear whether this age-related deficit is also present in the visuospatial domain.

These studies suggest that there are a number of ways in which aging may influence visuospatial rehearsal; for example, older adults may be rehearsing locations more slowly, or not as much, or differently in some other way, and such changes may have a significant effect on their memory, but no previous studies have investigated visuospatial rehearsal in older adults. Interestingly, because visuospatial rehearsal can involve moving one's eyes to the specific to-be-remembered locations in the environment, it is also possible that the amount of structural information provided by the environment may influence the effectiveness of visuospatial rehearsal, and it is unclear how such environmental support might affect age-related differences in visuospatial rehearsal and memory.

1.4 Environmental Support

The concept of environmental support, introduced in the literature as part of Craik's processing view of memory (e.g., Craik & Byrd, 1982; Craik, 1994), originally was used to describe manipulations affecting the similarity of the context at retrieval to the context at encoding, with the idea that increases in the similarity between the two contexts (i.e., increases in the amount of environmental support) reduces the need for self-initiated, effortful processing during encoding and/or retrieval and typically improves memory performance (e.g., Craik, 1986). For example, Craik has suggested that different types of memory tests (e.g., recognition, cued-recall, free-recall) differ in the amount of environmental support they provide. In a recognition test, participants are able to rely most heavily on cues present in the environment at retrieval, limiting the need for active reconstruction; similarly, cued-recall tests may provide more environmental support than free-recall tests (e.g., Craik 1983; Craik & McDowd, 1987; cf. Naveh-Benjamin, 2000).

In addition, the concept of environmental support has been extended to describe manipulations of visuospatial memory items. For example, Smith, Park, Cherry, & Berkovsky (1990) varied environmental support by manipulating the amount of visual detail (complex vs. simple) and propositional content (concrete vs. abstract) present in to-be-remembered pictures, and both Sharps and Gollin (1987) and Park, Cherry, Smith, and Lafronza (1990) varied environmental support by manipulating the complexity of the environment in which to-be-remembered location-object pairs were placed (e.g., on a two-dimensional map vs. on a three-dimensional colored model).

Recently, Lilienthal et al. (2014b) extended environmental support to describe a manipulation of support for the rehearsal of locations. When a memory task includes an interpolated processing task, as in complex span tasks, or lists of more than four to-be-remembered items (i.e., supraspan lists), it is assumed that items are displaced from primary memory, and at test, must be retrieved from secondary memory (Unsworth & Engle, 2007a). Importantly, the results of McCabe (2008) suggest that when participants are given the opportunity to rehearse to-be-remembered items during a memory task, the eventual retrieval of those items from secondary memory is improved, presumably because rehearsal serves as a form of retrieval practice. Based on this finding, if environmental support influences the effectiveness with which participants can rehearse locations, or the liklihood that they do so, that should have important effects on their visuospatial memory spans.

In order to investigate this possibility, participants in Lilienthal et al. (2014b) completed four conditions of a location memory task, and across conditions, both the amount of time between the presentation of each to-be-remembered location (i.e., the inter-item interval durations) and the presence of environmental support during the inter-item intervals were manipulated. In conditions in which environmental support was present, the array of possible locations remained on the computer screen during inter-item intervals, whereas in conditions in which environmental support was absent, a blank screen was presented during inter-item intervals. It was predicted that, if environmental support impacts participants' ability to rehearse to-be-remembered locations, an interaction would be observed: If the rehearsal of locations is impeded when environmental support is not provided, participants should forget locations with increases in retention time, and so longer inter-item intervals should be associated with poorer recall performance, but only when environmental support is absent.

The results of Lilienthal et al. (2014b), presented in Figure 1.1, were consistent with this prediction and a significant interaction between inter-item interval duration and environmental support was observed. When environmental support was absent, location memory spans were significantly smaller when inter-item intervals were each 4,000 ms compared to 1,000 ms, suggesting that rehearsal was somewhat impeded. When environmental support was present,

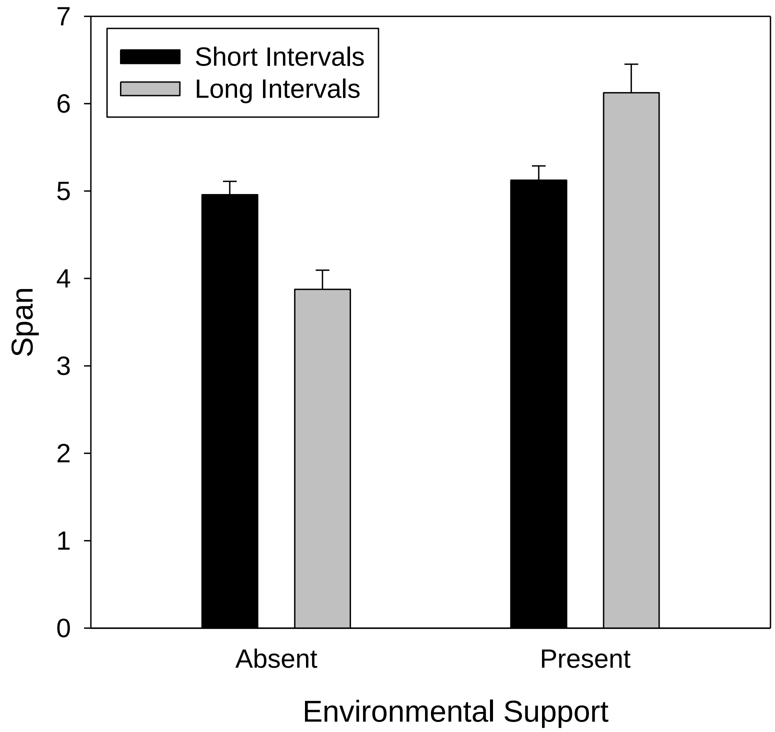

Figure 1.1: Effects of inter-item interval duration and environmental support on visuospatial memory spans in Lilienthal et al. (2014b). Inter-item intervals were each either 1,000 ms or 4,000 ms (short or long, respectively).

spans were significantly larger when inter-item intervals were each 4,000 ms compared to 1,000 ms, suggesting that rehearsal was actually somewhat facilitated.

Importantly, span differences only emerged when inter-item intervals were long (i.e., spans were not different between environmental support conditions when inter-item intervals were each 1,000 ms; see Figure 1.1), indicating that environmental support only influenced memory performance when participants were given sufficient time to engage in a strategy such as rehearsal; this finding also suggests that simply presenting a blank screen in between each to-be-remembered item did not disrupt encoding. Overall, the results of Lilienthal et al. (2014b) are consistent with what was suggested by McCabe (2008), in that participants' recall from secondary memory (i.e., most trials involved supraspan list lengths) was improved when they were given the opportunity to rehearse the to-be-remembered items; however, the present results suggest that for visuospatial memory items, environmental support for rehearsal is needed to obtain this effect.

The results of Lilienthal et al. (2014b) are also important because they suggest that there may be important differences between the two domains. For example, these results indicate that in visuospatial working memory, the structure and support provided by the task environment can influence participants' ability to rehearse to-be-remembered items in a way for which it is difficult to imagine an analogous situation in the verbal domain. In addition, the fact that participants forgot locations over time, even in the absence of any secondary task (and even when the temporal distinctiveness of locations was controlled across conditions, see Lilienthal et al., 2014b, Experiment 2), suggests that decay plays a role in forgetting from visuospatial working memory.

It is interesting to note, however, that because attention was never diverted from the to-be-remembered items, not all theories that posit time-based forgetting would have predicted forgetting in the present experiment. For example, the time-based resource-sharing model proposed by Barrouillet and colleagues (e.g., Barrouillet et al., 2004; Barrouillet, Portrat, Vergauwe, Diependaele, & Camos, 2011; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007) posits that attention is required to repeatedly refresh memory traces, and therefore, when attention is diverted, memory traces cannot be refreshed and will decay over time. In Lilienthal et al. (2014b), attention was never diverted, yet forgetting occurred in the absence of environmental support. This result is difficult to explain in terms of the time-based resource-sharing model; although Barrouillet and colleagues have acknowledged that it is possible for forgetting to occur even when attention is available, such conditions have yet to be accounted for by the theory. Importantly, this result suggests that even the maintenance and forgetting of information across domains may not always occur in the same way.

Environmental support is also an important concept in the aging literature. It has been proposed that older adults have a specific deficit in effortful, self-initiated processing compared to young adults (e.g., Craik, 1994; Hasher & Zacks, 1979), and because environmental support is thought to reduce the need for self-initiated processing, the presence of environmental support should differentially benefit older adults. The results of a number of studies have supported this idea (e.g., Craik, Byrd, & Swanson, 1987; Craik & Rabinowitz, 1985).

For example, Craik and McDowd (1987) asked young and older adults to learn pairs of phrases and target words (e.g., a body of water – pond), followed by both cued-recall and recognition tests. Although young adults remembered significantly more words than older adults on the cued-recall test, the age-related difference was not significant on the recognition test, which is thought to provide additional environmental support. In addition, Smith et al. (1990) asked young and older adults to remember pictures that varied in their level of both perceptual detail and propositional content, and found that although young adults outperformed older adults when environmental support was low (i.e., when the pictures were abstract and/or lacking detail), the age-related difference disappeared when environmental support was high (i.e., when the pictures were concrete and detailed). Based on these results, then, it seemed possible that providing environmental support for rehearsal during a visuospatial memory task would encourage participants to rehearse and reduce the need to remember the array of possible locations while doing so, and that this would differentially benefit older adults.

In order to investigate this possibility, Lilienthal, Hale, and Myerson (2014a) asked young and older adults to complete the same four task conditions used in Lilienthal et al. (2014b), across which environmental support and inter-item interval duration again were manipulated. It was predicted that the same pattern of results observed previously in young adults would be replicated in both age groups, in that both young and older adults would have larger memory spans with more time to rehearse when environmental support was present, but smaller memory spans with more time when environmental support was absent. Importantly, based on Craik's processing view, it was also predicted that the presence of environmental support would benefit the older adults more than the young adults, resulting in a reduced age-related difference when environmental support was provided.

Young and older adults' memory spans in all conditions in Lilienthal et al. (2014a) are presented in Figure 1.2. The interaction between inter-item interval duration and environmental support was significant in both age groups when they were considered separately (young adults: $F[1, 23] = 22.1$, $p < .001$; older adults: $F[1, 23] = 4.6$, $p = .04$). The three-way interaction between interval duration, environmental support, and age group was also significant ($F[1, 46] = 4.5$, $p = .039$), reflecting the fact that when environmental support was absent, both young and older adults had significantly smaller spans when inter-item intervals were long than when intervals were short (young adults: $t[23] = 5.0$, $p < .001$; older adults: $t[23] = 2.1$, $p = .047$); however, when environmental support was present, although young adults had significantly larger spans when inter-item intervals were long ($t[23] = 2.1$, $p = .045$), older adults' spans were not different

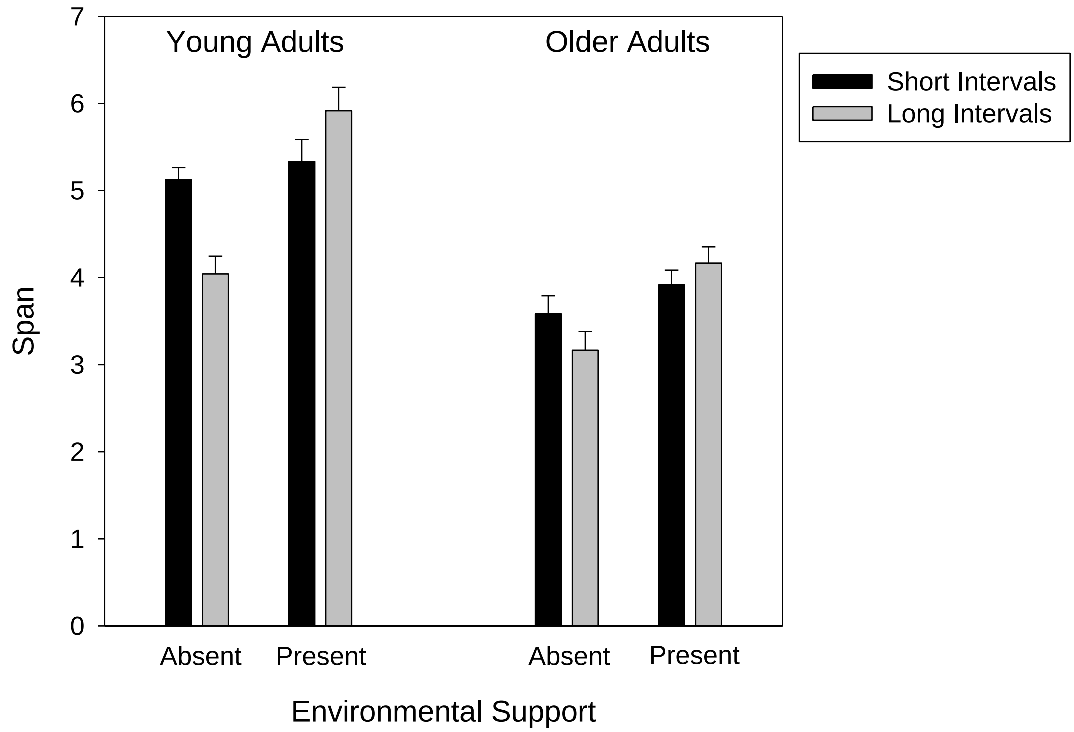

Figure 1.2: Effects of inter-item interval duration and environmental support on visuospatial memory spans for both young and older adults in Lilienthal et al. (2014a). Inter-item intervals were each either 1,000 ms or 4,000 ms (short or long, respectively).

between inter-item interval conditions ($t[23] = 1.2$, *ns*). In order to address the question of whether the age-related difference in memory was reduced by environmental support, the two long inter-item interval conditions were compared (see Figure 1.3), and, contrary to what was predicted based on the processing view, young adults benefited significantly more from the presence of environmental support than older adults ($F[1, 46] = 5.1$, $p = .028$).

These results indicate that when environmental support for rehearsal was present, although older adults were able to use the support to prevent forgetting, they did not receive the same kind of benefit from more time as did young adults. In both Lilienthal et al. (2014a) and (2014b), when

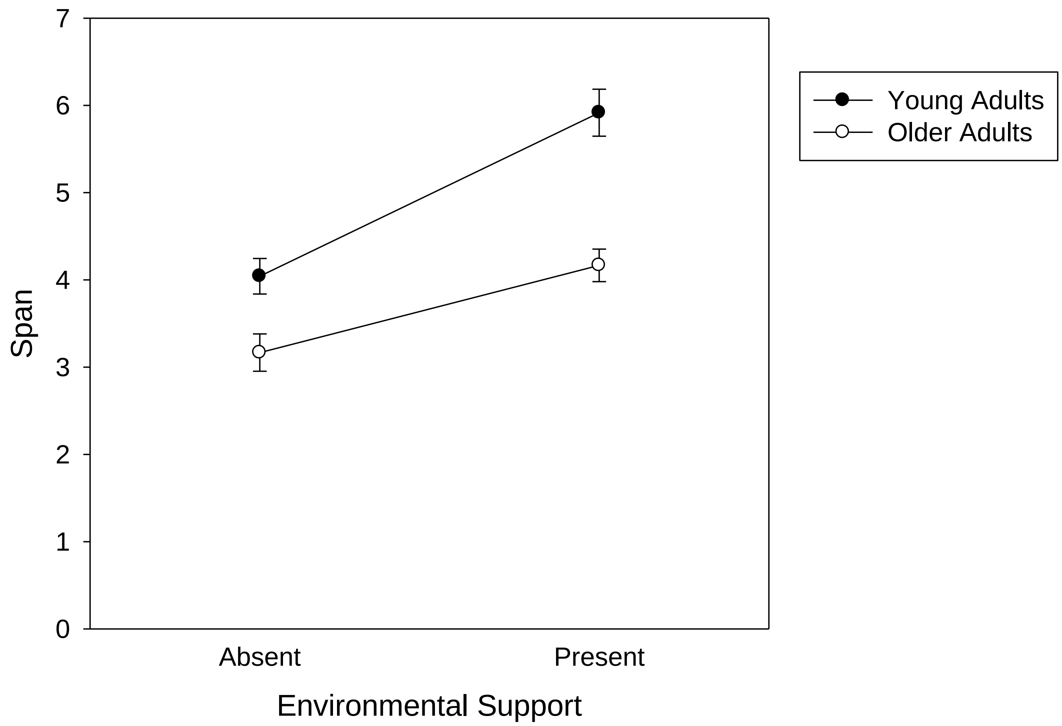

Figure 1.3: Effects of environmental support on visuospatial memory spans in conditions with long inter-item intervals (4,000 ms each), for both young and older adults, in Lilienthal et al. (2014a).

environmental support was present, young adults may have been able to use the additional time provided in conditions with long inter-item intervals to engage in some additional strategy or process that allowed them to remember more locations, whereas the best older adults in Lilienthal et al. (2014a) could do was maintain the same number of locations over time. This finding, that environmental support had different effects on young and older adults, suggests that there may be important age-related differences in visuospatial rehearsal. However, the exact nature of such potential differences is not yet clear.

1.5 Present Experiments

Therefore, the purpose of the present experiments was to further investigate visuospatial rehearsal in young and older adults by continuing to utilize manipulations of environmental support. Experiment 1 examined the effects of manipulating environmental support and the amount of time given for rehearsal during final retention intervals rather than during inter-item intervals, as was done in Lilienthal et al. (2014a) and (2014b), in both young and older adults. Experiment 2 attempted to examine the effects of environmental support and age on visuospatial rehearsal more directly, in that the eye movements of young and older adults were recorded as they performed tasks similar to those used in Lilienthal et al. (2014a) and (2014b). Experiment 3 examined the effects of environmental support on covert visuospatial rehearsal (i.e., rehearsal performed through shifts of spatial attention in the absence of overt eye movements) in both young and older adults.

Chapter 2: Experiment 1

In both Lilienthal et al. (2014a) and (2014b), participants were given an opportunity to rehearse either with or without environmental support during each inter-item interval (i.e., following the presentation of each to-be-remembered location). Although the purpose of the environmental support manipulation was to influence the effectiveness of rehearsal, it is possible that the absence of support (i.e., the presentation of a blank screen following each to-be-remembered location) also influenced participants' ability to encode the items. The fact that the environmental support manipulation did not affect participants' spans when inter-item intervals were short, when the effects of the alternating arrays and blank screens arguably would be the greatest, does reduce the likelihood of this alternative explanation, but possible differences in encoding across the task conditions are still a concern. Therefore, the present experiment was designed to attempt to replicate the results of Lilienthal et al. (2014a) using a procedure that minimizes encoding differences and better isolates the effects of the environmental support manipulation to maintenance and rehearsal.

In the present experiment, young and older adults were asked to complete five conditions of a location memory task. Importantly, in all five of the task conditions, inter-item intervals were always short (i.e., 1,000 ms each) and environmental support during the inter-item intervals was always present, thus equating the conditions during encoding. In four of the conditions, a retention interval followed the presentation of the final to-be-remembered location, and it was during this retention interval that the manipulations of time and environmental support occurred. If the pattern of results in Lilienthal et al. (2014a) and (2014b) were due to variations in the effectiveness of rehearsal rather than to differences in encoding, as is suspected, the pattern of results in the present experiment should be similar to the pattern observed in those previous studies. Participants in the present experiment also completed a fifth task condition in which no retention interval was included, meaning that participants recalled immediately following the presentation of the final to-be-remembered location, and the addition of this condition allows for the effects of retention time in the absence of environmental support to be more closely examined than in the past.

2.1 Method

2.1.1 Participants

Twenty-four young adults (11 female; age M = 19.1, SD = 1.1, range = 18-21) and 24 older adults (16 female; age M = 74.2, SD = 4.3, range = 65-82) participated in this experiment. The young adults were undergraduate students at Washington University in St. Louis who participated in exchange for the partial fulfillment of a course requirement. The older adults were community-dwelling residents of the St. Louis area who participated in exchange for monetary compensation. Older adults were screened using the Telephone Interview for Cognitive Status (Brandt, Spencer, & Folstein, 1988) and for significant health issues (e.g., stroke, Parkinson's disease), as well as for colorblindness. The average number of years of education was 13.2 (SD = 1.2) for young adults and 15.3 (SD = 2.3) for older adults. All participants reported English as their native language and had normal or corrected-to-normal visual acuity, as evidenced by their performance on the Wormington Pocket Acuity test (median acuity: young adults = 20/20, older adults = 20/25).

2.1.2 Materials and Procedure

All participants performed five conditions of a visuospatial simple span task in a single experimental session that lasted approximately 1.5 hours (see Figure 2.1). On each trial in all five task conditions, participants were shown an array of 30 circles on a computer screen. Each circle was 1 cm in diameter, and the average distance between the centers of the circles in the array was 1.75 cm. The circles were arranged so that the array appeared unstructured, and the configuration of the array was changed on every trial (i.e., a different set of 30 locations was chosen for each trial). A subset of the circles then turned red one at a time and participants were instructed to remember the locations of the red circles (i.e., the to-be-remembered locations). Each red circle was presented for 1,000 ms, followed by a 1,000 ms inter-item interval during which the array of empty circles remained on the screen.

As in Lilienthal et al. (2014b) and Lilienthal et al. (2014a), both the amount of time participants were given to rehearse the locations and whether or not environmental support for rehearsal was present during that time were manipulated across the five task conditions. Critically, in the present experiment, these manipulations occurred during a final retention interval (i.e., the period of time between the presentation of the final red circle and recall). In four of the conditions, the duration of the retention intervals was either short (500 ms multiplied by the number of to-be-remembered locations [i.e., the list length]) or long (2,000 ms multiplied by the list length; see Table 2.1), and environmental support during the retention intervals was either present or absent. In the final condition, no retention interval was included and participants were asked to recall the to-be-remembered locations immediately following the presentation of the final red circle. When environmental support was present, the array of 30 circles remained visible on the computer screen during the retention intervals, whereas when environmental support was absent,

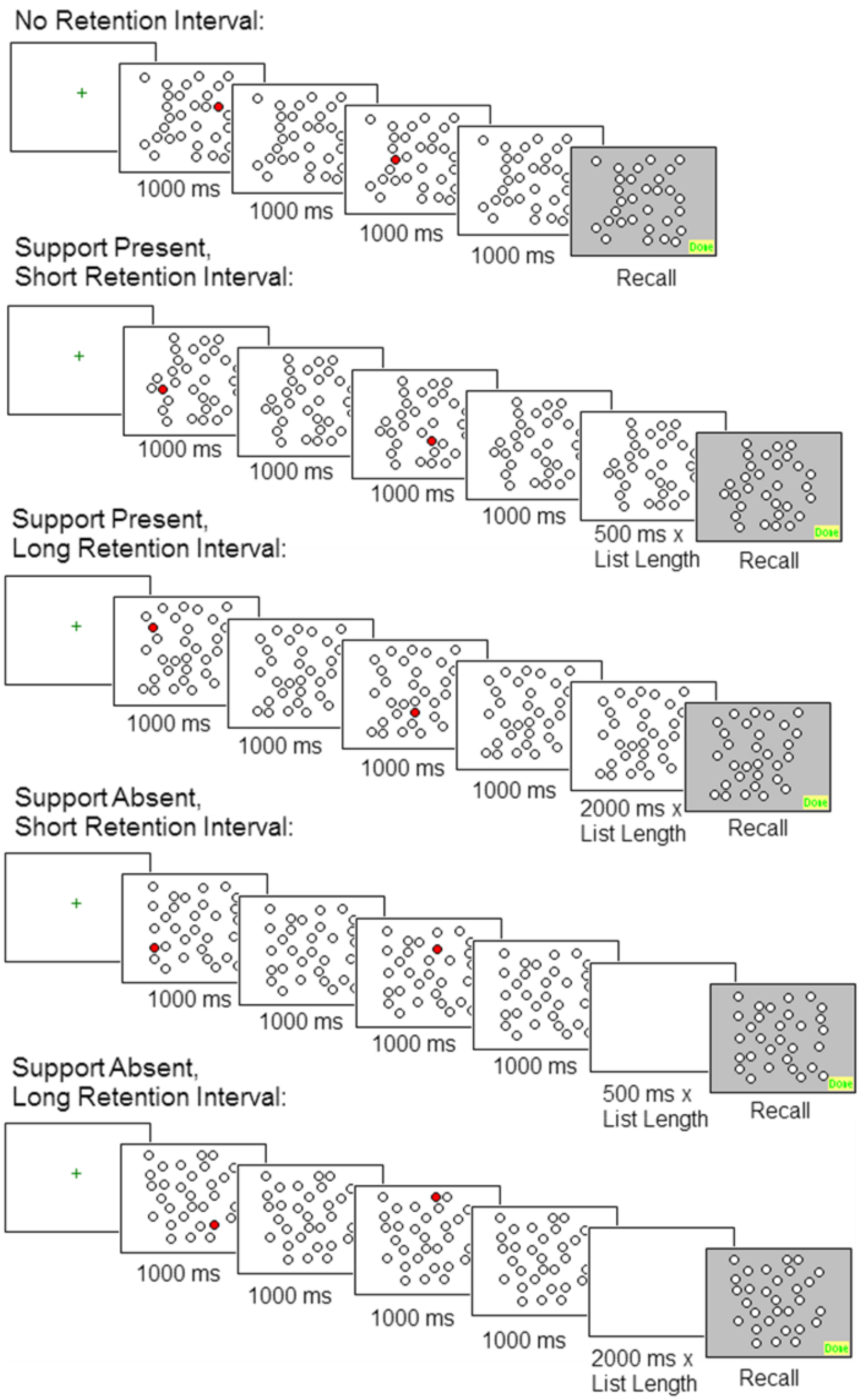

Figure 2.1: Example trials from each task condition in Experiment 1. Retention intervals (the time preceding recall, during which environmental support was manipulated) were either short or long, except in one additional condition in which no retention interval was included.

Table 2.1: Retention interval durations for short and long conditions for each list length (i.e., number of to-be-remembered circles presented on the trial) in Experiment 1. Short retention intervals were equal to 500 ms multiplied by the list length, and long retention intervals were equal to 2,000 ms multiplied by the list length.

List Length	Short Retention-Interval Conditions	Long Retention-Interval Conditions
2	1000 ms	4000 ms
3	1500 ms	6000 ms
4	2000 ms	8000 ms
5	2500 ms	10000 ms
6	3000 ms	12000 ms
7	3500 ms	14000 ms
8	4000 ms	16000 ms
9	4500 ms	18000 ms
10	5000 ms	20000 ms
11	5500 ms	22000 ms

participants instead viewed a blank screen during the retention intervals (Figure 2.1). Thus, one condition had no retention interval, one condition had short retention intervals with environmental support present, one condition had long retention intervals with environmental support present, one condition had short retention intervals with environmental support absent, and one condition had long retention intervals with environmental support absent.

Following the retention interval (or, in the condition with no retention interval, following the presentation of the final red circle), participants were asked to recall the to-be-remembered locations. In order to do this, participants were presented again with the array of 30 circles, now appearing against a gray background (see Figure 2.1), and they were asked to click on the circles that had turned red during that trial using the computer mouse. Upon being clicked, the circles turned green, and this was done to indicate to participants which locations they already had chosen. Participants were allowed to recall the locations in any order and were given as much time as they needed to do so. They were instructed to click on an icon labeled “Done,” located in the bottom right corner of the computer screen, when they were finished recalling.

Each of the five task conditions began with four practice trials, followed by 20 test trials. List lengths (i.e., the number of to-be-remembered locations presented on a trial) ranged from two to 11, and participants completed two trials at each length in each condition. List lengths were presented in ascending order, so that participants first performed the two list-length-one trials, followed by the two list-length-two trials, and so on. Memory performance in each condition was assessed using a span measure, scored as one less than the shortest list length at which both test trials were incorrect.

The order of the five task conditions was counterbalanced across participants so that each participant performed the conditions in one of four orders (six participants in each age group per order condition). Half of the participants completed the two conditions with environmental support first, followed by the condition with no retention interval, followed by the two conditions without environmental support. The other half of the participants completed the two conditions without environmental support first, followed by the condition with no retention interval, followed by the conditions with environmental support. Within each of these two groups of participants, half completed a condition with short retention intervals first, and the other half completed a condition with long retention intervals first; however, the interval durations were always presented alternately (i.e., either short-long-none-short-long, or long-short-none-long-short).

2.2 Results and Discussion

Young and older adults' memory spans in the four task conditions that included a retention interval are presented in Figure 2.2. A 2 (environmental support: present vs. absent) x 2 (retention interval duration: short vs. long) x 2 (age group: young vs. old) ANOVA performed on these spans revealed a significant main effect of age group, $F(1, 46) = 29.92$, $p < .001$, reflecting the fact that young adults' spans were larger overall compared to older adults' spans. The main effect of environmental support was also significant, $F(1, 46) = 27.07$, $p < .001$, but the effect of interval duration was not, $F(1, 46) = 0.57$, *ns*. However, these results must be interpreted in light of two significant two-way interactions, between environmental support and interval duration, $F(1, 46) = 14.53$, $p < .001$, and between environmental support and age group, $F(1, 46) = 4.17$, $p = .047$. The interaction between environmental support and interval duration reflects the fact that when environmental support was present, spans were larger when the retention intervals were long, whereas when environmental support was absent, spans were larger when the retention intervals were short. The interaction between environmental support and age group reflects the fact that for young adults, memory spans were 1.0 item larger on average when support was present than when it was absent, but for older adults, this difference was only 0.5 items.

The three-way interaction between environmental support, retention interval duration, and age group was only marginally significant, $F(1, 46) = 2.80$, $p = .101$, but planned comparisons were conducted due to predictions based on the results of Lilienthal et al. (2014a) and (2014b). These planned comparisons revealed that, consistent with previous results, when environmental support was absent, both young and older adults had significantly smaller spans when retention intervals were long compared to when intervals were short (young adults: $t[23] = 2.58$, $p = .017$; older adults: $t[23] = 2.30$, $p = .031$); however, when environmental support was present, only young

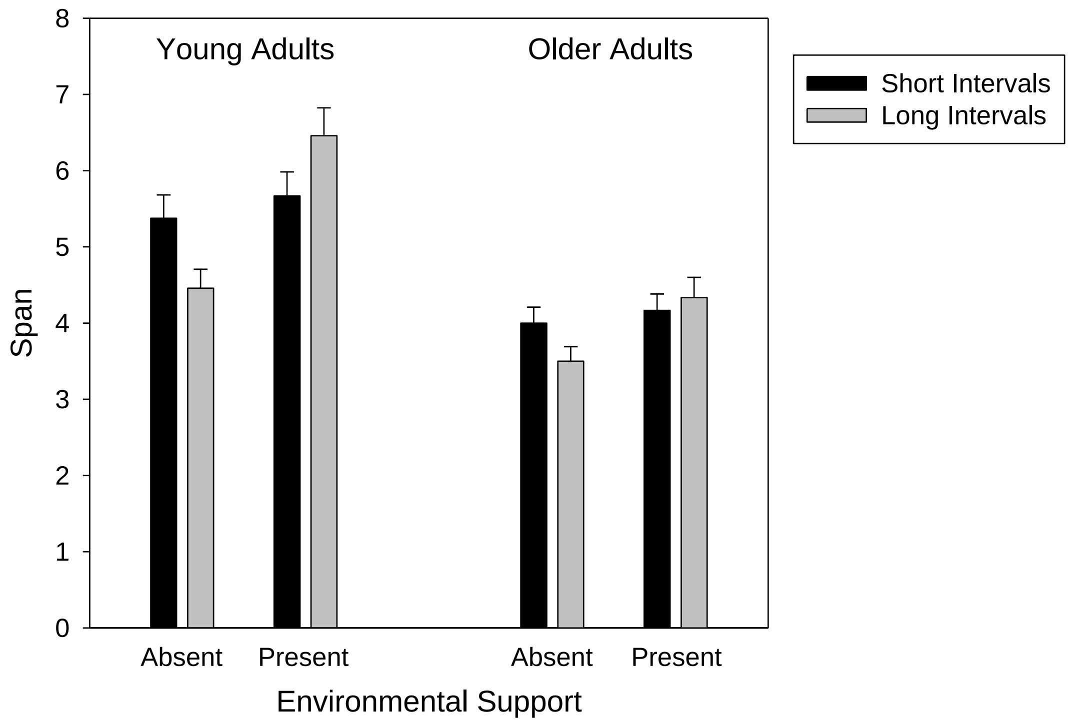

Figure 2.2: Effects of retention interval duration and environmental support on visuospatial memory spans for both young and older adults in Experiment 1.

adults' spans were significantly larger when retention intervals were long (young adults: t[23] = 2.33, p = .029; older adults: t[23] = 0.56, ns; see Figure 2.2).

In addition, in order to address whether the presence of environmental support reduced age-related differences in memory span, a 2 (environmental support) x 2 (age group) ANOVA was performed on spans from just the two conditions with long retention intervals. This analysis revealed significant main effects of both environmental support, $F(1, 46) = 35.36$, $p < .001$, and age group, $F(1, 46) = 25.09$, $p < .001$, as well as a significant interaction, $F(1,46) = 6.00$, $p = .018$. As can be seen in Figure 2.3, when retention intervals were long, both age groups did significantly better when environmental support was present than when support was absent

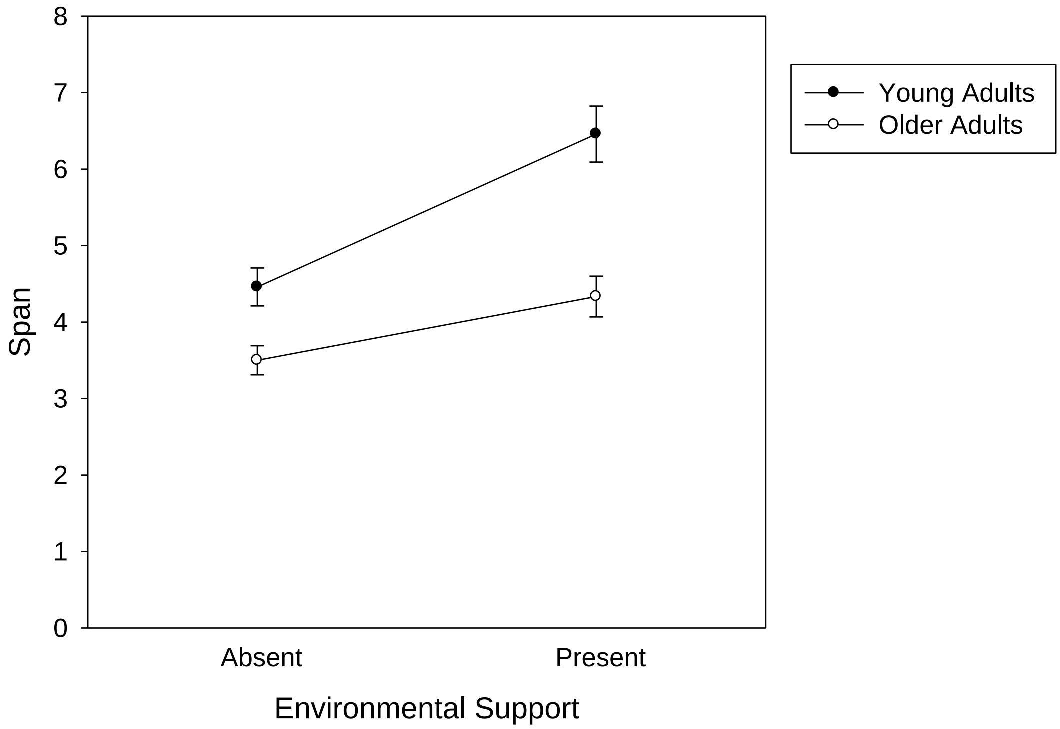

Figure 2.3: Effects of environmental support on visuospatial memory spans in conditions with long retention intervals, for both young and older adults, in Experiment 1.

(young adults: $t[23] = 4.85$, $p < .001$; older adults: $t[23] = 3.50$, $p = .002$). However, the difference in memory spans between young and older adults actually increased with the presence of environmental support, from a difference of 0.96 items without support to a difference of 2.12 items with support.

The results of the present experiment are remarkably similar to those obtained by Lilienthal et al. (2014a). When environmental support was not provided, both young and older adults remembered significantly fewer locations when retention intervals were long than when intervals were short, indicating that the absence of environmental support may impede participants' ability to rehearse locations. When environmental support was provided, the opposite pattern of results emerged for young adults, who remembered significantly more locations when retention intervals were long compared to short, indicating that the presence of environmental support may facilitate young adults' ability to rehearse locations. However, as in Lilienthal et al., older adults did not differ in their memory spans across interval durations when environmental support was present, indicating that although older adults were able to use support to prevent the forgetting over time that was observed in its absence, they were not able to use age-related difference in span was actually significantly larger when environmental support was present; this result is inconsistent with the predictions made by Craik's processing view of memory (e.g., Craik, 1986) and provides additional evidence for potential age-related differences in rehearsal.

In the present experiment, the presence of environmental support and the amount of time for rehearsal both were manipulated during a retention interval that followed the presentation of the final to-be-remembered location, ensuring that the five task conditions did not differ from one another until after participants had finished encoding the locations. Even so, the same pattern of results observed in Lilienthal et al. (2014a) was found in the present experiment, suggesting that the differences in memory span in the presence and absence of environmental support were not due to effects on participants' ability to encode to-be-remembered locations, and instead, were due to effects on participants' ability to maintain those locations in working memory. This is further evidenced in the present experiment by the fact that memory spans did not differ across support conditions when retention intervals were short, $t(23) = 0.89$, *ns*, suggesting that support only had an effect when participants were given considerable time to rehearse. Because the retention-interval procedure likely helps isolate the effects of the manipulations to maintenance and rehearsal, it represents an improvement over the inter-item-interval procedure used in previous experiments (i.e., Lilienthal et al. 2014a; 2014b) and accordingly, this procedure also will be used in Experiments 2 and 3 of the present study.

In the absence of environmental support, participants in the present experiment had significantly smaller memory spans when retention intervals were long than when intervals were short, consistent with what was observed in Lilienthal et al. (2014a) and (2014b). The inclusion of the task condition without a retention interval in the present experiment allows for this forgetting to be examined in more detail, and a 3 (retention interval duration: none vs. short vs. long) x 2 (age group: young vs. old) ANOVA was performed on memory spans from conditions without environmental support. Significant main effects of both interval duration ($F[2, 92] = 17.81$, $p < .001$) and age group ($F[1, 46] = 26.30$, $p < .001$) were revealed, although the interaction between the two did not reach significance ($F[2, 92] = 2.39$, $p = .097$). Of special interest were the linear contrasts, significant for both interval duration ($F[1, 46] = 39.85$, $p < .001$) and for the interaction between duration and age group ($F[1, 46] = 5.41$, $p = .024$).

The significant linear contrast for interval duration indicates that for both young and older adults, spans decreased as retention time increased; this can be seen in Figure 2.4, which shows forgetting curves for the three conditions (i.e., no retention interval, short retention interval without environmental support, and long retention interval without environmental support) plotted as a function of the average retention-interval duration across all list lengths. The significant linear contrast for the interaction between interval duration and age group indicates that the decrease in span associated with increases in retention time was larger in the young adult group. This would seem to suggest that older adults did not forget information over time as

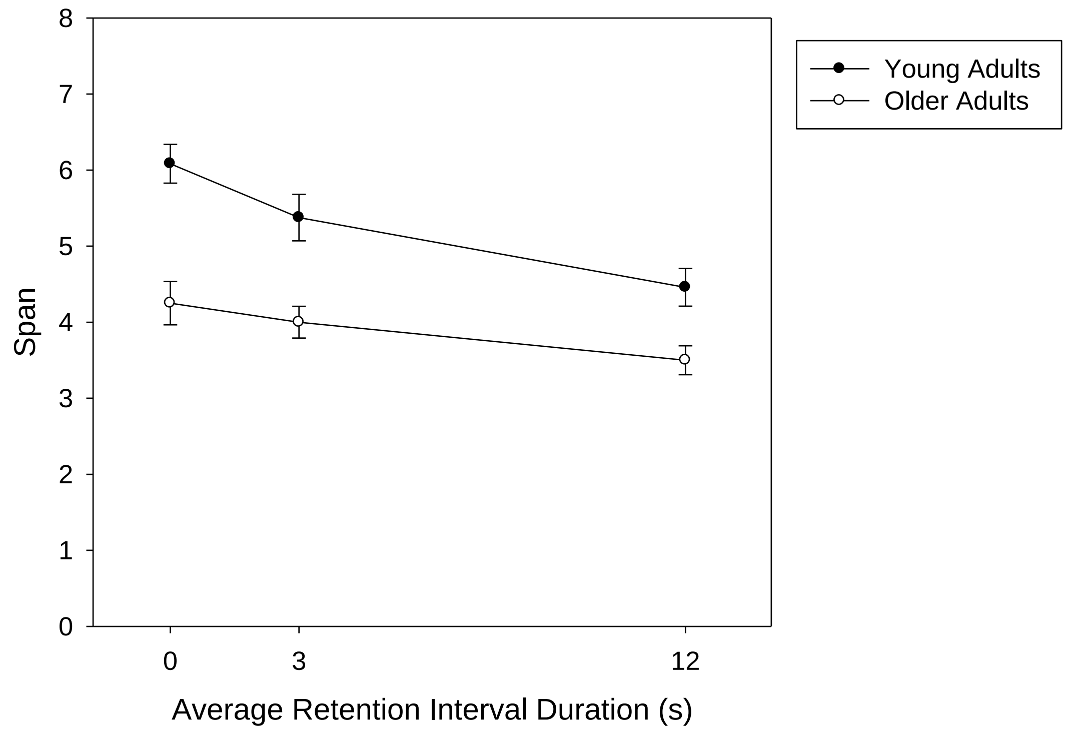

Figure 2.4: Visuospatial memory spans in the condition with no retention interval (average retention interval duration of 0 s), the condition with a short retention interval without environmental support (average retention interval duration of 3 s), and the condition with a long retention interval without environmental support (average retention interval duration of 12 s) for both young and older adults in Experiment 1. Average retention interval duration is the mean duration of retention intervals across list lengths in each task condition.

rapidly as did young adults, but when the slopes of the forgetting curves obtained from low-span young adults and high-span older adults (i.e., young adults in the bottom tertile and older adults in the top tertile, respectively, based on their performance in the condition with no retention interval) were compared, the slopes were not significantly different, $t[14] = 1.06$, $p = .306$. This indicates that young and older adults who had similar spans did not differ in their rate of forgetting, suggesting that the significant interaction contrast was a result of differences in overall span rather than true differences in rate of forgetting.

Thus, the present experiment provides further evidence of decay in visuospatial working memory: In the absence of environmental support, both young and older adults' memory spans decreased as the time in which they were asked to maintain to-be-remembered locations increased. As mentioned previously, this forgetting is not predicted by models of working memory that posit a role for decay. For example, the time-based resource-sharing model suggests that forgetting occurs when attention is diverted from refreshing memory traces (e.g., Barrouillet et al., 2004), typically by requiring participants to perform a secondary processing task in addition to the memory task. Participants in the present experiment were always free to rehearse (and/or refresh) the to-be-remembered locations, but forgetting was still observed. Importantly, the time-based resource-sharing model does not necessarily suggest that forgetting cannot occur even when attention is present, but how and when this would be expected is still unclear, and more research on this issue is needed.

It should be noted, however, that the results of the present experiment cannot rule out the possibility that the forgetting observed over time was the result of reduced temporal distinctiveness, rather than of decay. This is because as the duration of a retention interval increases, and thus as the time since the presentation of the to-be-remembered items increases, it is thought that the temporal distinctiveness of the memory traces decreases, making it more difficult to discriminate one item from another (e.g., Brown, Neath, & Chater, 2007; Crowder, 1976). The loss of temporal distinctiveness is considered to be a type of proactive interference, and, because it is assumed to lead to poorer recall, it can mimic the effects of decay. In the present experiment, it is not possible to separate the possible effects of decay from those of reduced temporal distinctiveness; however, when Lilienthal et al. (2014b) limited the role of temporal distinctiveness by keeping the ratio between the inter-item intervals and the inter-trial intervals constant across the task conditions, the pattern of results did not change, suggesting that the forgetting observed in this type of visuospatial working memory task may be largely due to the decay of memory traces over time.

Chapter 3: Experiment 2

The results of Experiment 1 replicated what was observed in Lilienthal et al. (2014a), in that environmental support had an important effect on participants' memory for locations, older adults had poorer memory performance overall compared to young adults, and young adults benefited more from the presence of support than did older adults. The effects of environmental support emerged primarily when retention intervals were long (i.e., spans were not different across support conditions when intervals were short), and so it was assumed that these effects occurred, at least in part, because of changes in participants' ability to rehearse the to-be-remembered locations. Notably, it is believed that visuospatial rehearsal can occur through eye movements made to the to-be-remembered locations (e.g., Baddeley, 1986; Awh et al., 1998), and therefore the goal of the present experiment was to investigate young and older adults' eye-movement behavior during a location memory task, both with and without environmental support, in the hope of identifying specific rehearsal differences.

In the present experiment, young and older adults were asked to complete two conditions of a location memory task that was very similar to the task used in Experiment 1. Retention intervals in both conditions were long, and the presence of environmental support during the retention intervals was manipulated across conditions. Importantly, participants' eye movements during retention intervals were recorded, and data from four primary measures of eye-movement behavior were compared across support conditions and across age group.

Participants typically remember fewer locations when environmental support is absent compared to when support is present, thus it is possible that participants rehearse less (i.e., make fewer eye movements) during retention intervals that do not include support, and therefore participants' rate of eye movements was examined. However, participants also may rehearse to-be-remembered locations differently in some way when environmental support is absent. For example, participants may be less precise in their eye movements without support, and so, as a coarse-level measure of precision, the correlation between the proportion of eye movements participants made ending on the left half of the computer screen (regardless of the starting position) and the proportion of to-be-remembered locations presented on the left half of the computer screen (which was manipulated systematically across trials) was examined. In addition, participants' eye-movement behavior may differ in other ways across support conditions, and so two additional measures of eye-movement behavior were also examined: the average median distance (i.e., size) of participants' eye movements, and the average median duration of the fixations that followed eye movements. Although these measures are common in eye tracking studies of visual search and change detection (e.g., Scialfa & Joffe, 1997; Veiel, Storandt, & Abrams, 2006), this is the first time they will be applied to visuospatial rehearsal and memory, and predictions regarding how such measures might differ across environmental support are not entirely clear.

Typically, older adults typically remember fewer locations compared to young adults, and thus these same measures of eye-movement behavior are also of interest across age. It is possible that older adults rehearse to-be-remembered locations less than young adults, and therefore may have a reduced eye-movement rate. Young and older adults also may rehearse locations differently in some way; older adults may be less precise in their rehearsal, or may differ in the size of their eye movements or the duration of their fixations. As mentioned, these measures have been used to investigate eye-movement behavior in other paradigms, such as visual search and change detection, and some of these studies also investigated the effects of age. However, the present experiment is the first time older adults' eye movements have been examined during visuospatial rehearsal, and it is unclear how similar age-related differences in eye-movement behavior will be across paradigms.

For example, a number of studies have found that when searching for a target, older adults tend to make more eye movements than do young adults (e.g., Veiel et al., 2006; Scialfa, Thomas, & Joffe, 1994; Scialfa & Joffe, 1997; Ho, Scialfa, Caird, & Graw, 2001). However, the goal in these experiments was to find the target as soon as possible, meaning that additional eye movements (i.e., additional search time) actually indicated poorer performance; in the present experiment, it is assumed that additional eye movements (i.e., additional rehearsal) instead may be helpful to participants' memory spans. In studies of visual search, older adults also have been found to make shorter eye movements (e.g., Scialfa & Joffe, 1997; Veiel et al., 2006; Maltz & Shinar, 1999) and to have longer fixation durations than young adults (e.g., Scialfa & Joffe, 1997; Ho et al., 2001; cf. Veiel et al., 2006; Maltz & Shinar, 1999), and it is possible that similar age-related differences will be observed in participants' rehearsal in the present experiment, although, as was mentioned, this has not been previously investigated.

3.1 Method

3.1.1 Participants

Twenty-four young adults (17 female; age M = 19.9, SD = 1.2, range = 18-22) and 24 older adults (15 female; age M = 72.2, SD = 4.8, range = 65-88) participated in this experiment. The young adults were undergraduate students at Washington University in St. Louis who participated in exchange for the partial fulfillment of a course requirement. The older adults were community-dwelling residents of the St. Louis area who participated in exchange for monetary compensation. Older adults were screened using the Telephone Interview for Cognitive Status (Brandt et al., 1988) and for significant health issues (e.g., stroke, Parkinson's disease), as well as for colorblindness. The average number of years of education was 13.9 (*SD* = 1.1) for young adults and 15.7 (*SD* = 2.8) for older adults. All participants reported English as their native language and had normal or corrected-to-normal visual acuity, as evidenced by their performance on the Wormington Pocket Acuity test (median acuity: young adults = 20/15, older adults = 20/25).

3.1.2 Materials and Procedure

All participants performed a visual search task as well as two conditions of a visuospatial simple span task in a single experimental session that lasted approximately 1.5 hours.

Visual search task. On each trial on the visual search task, participants were asked to search an array of shapes (i.e., green squares and red circles) and indicate whether or not a target shape (i.e., a red square) was present in the array (see Figure 3.1). Participants were asked to make this decision as quickly and accurately as possible, and to indicate their decision by pressing one of two keys on the computer keyboard. The locations of these keys were counterbalanced across participants: Half of the participants pressed a right key (i.e., the '/'key) to indicate that the target shape was present and pressed a left key (i.e., the 'Z' key) to indicate that the target shape was absent, and the other half of the participants pressed a left key (i.e., the 'Z' key) to indicate that the target shape was present and pressed a right key (i.e., the '/' key) to indicate that the target shape was absent. On each trial, participants' accuracy and response time (RT) were recorded; this visual search task was included in order to verify that the older adults who volunteered for the present experiment demonstrated the typical steeper rate required to visually search an array.

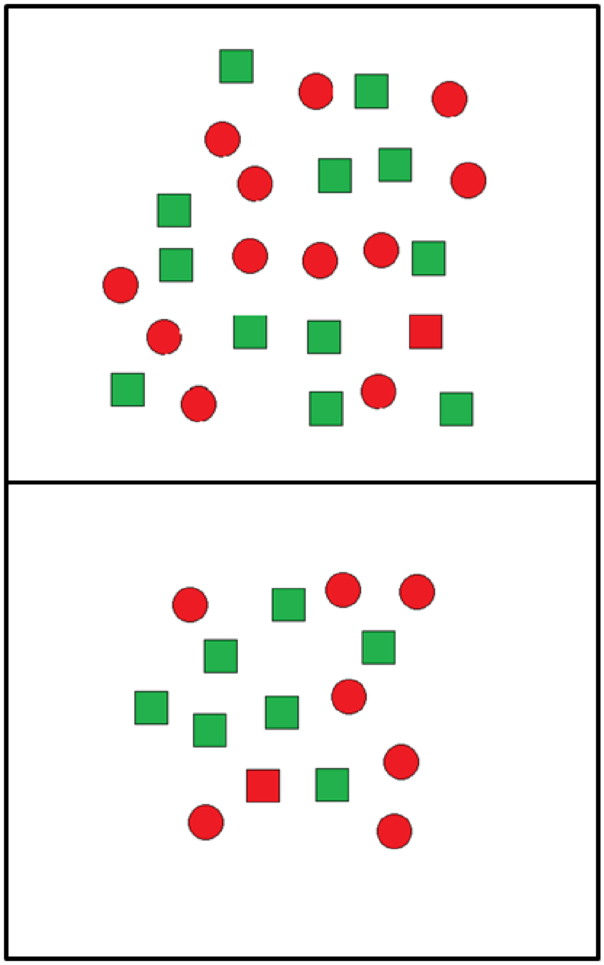

Figure 3.1: Example arrays from the visual search task in Experiment 2. The top panel shows an example of a large array (i.e., 25 shapes) trial without a target shape (i.e., a red square) present; the bottom panel shows an example of a small array (i.e., 15 shapes) trial with a target shape present.

Two sizes of arrays were used, one small (i.e., containing 15 shapes) and one large (i.e., containing 25 shapes). Participants completed a total of 64 test trials, 32 of which involved small arrays and 32 of which involved large arrays. For each array size, there were 16 trials on which the target shape was present and 16 trials on which the target shape was absent. Trials were presented in a way that seemed random to participants but that was pre-determined and the same for each participant. Prior to the start of the test trials, participants completed six practice trials that were identical to the test trials.

Visuospatial simple span task. On each trial of both task conditions of the visuospatial simple span task, participants were shown an array of 30 circles on a computer screen, the configuration of which was changed on every trial (i.e., a different set of 30 locations was chosen for each trial). A subset of the circles then turned red one at a time and participants were instructed to remember the locations of the red circles (i.e., the to-be-remembered locations). Each red circle was presented for 1,000 ms, followed by a 1,000 ms inter-item interval during which the array of empty circles remained on the screen.

Then, as in Experiment 1, a retention interval followed the presentation of the final red circle, and whether or not environmental support was present during that time was manipulated across the two conditions: When environmental support was present, the array of 30 circles remained visible on the computer screen during the retention intervals, whereas when environmental support was absent, participants instead viewed a blank screen during the retention intervals. The duration of the retention intervals was not manipulated in the present experiment, and intervals in both conditions were long (i.e., 2,000 ms multiplied by the list length).

Following the retention interval, participants were asked to recall the to-be-remembered locations. In order to do this, participants were presented again with the array of 30 circles, now appearing against a gray background, and were asked to click on the circles that had turned red during that trial using the computer mouse. Upon being clicked, the circles turned green, and this was done in order to indicate to participants which locations they already had chosen. Participants were allowed to recall the locations in any order and were given as much time as they needed to do so. They were instructed to click on an icon labeled “Done,” located in the bottom right corner of the computer screen, when they were finished recalling.

Each of the two conditions began with a practice block of six trials, followed by 40 test trials. The test trials were split into two blocks, each consisting of 20 test trials, and participants were allowed to take a break following each block. Importantly, only two list lengths, four and six, were used in the present experiment; thus, either four or six to-be-remembered locations were presented on every trial. Each block of test trials involved 10 trials of each list length, and trials were presented in a way that seemed random to participants but that was pre-determined and the same for each participant. Memory performance in each condition was measured as the proportion of locations recalled correctly.

The order of the two task conditions was counterbalanced across participants so that each participant performed the conditions in one of two orders (12 participants in each age group per order condition). Half of the participants completed the condition with environmental support first, followed by the condition without environmental support, and the other half of the participants completed the conditions in the opposite order. In addition, two sets of materials were created (i.e., set A and set B), including the non-repeated arrays of 30 circles and lists of to-be-remembered locations; these material sets were counterbalanced so that half of the participants saw set A in the condition with environmental support and set B in the condition without environmental support, and the other half of the participants saw the two sets in opposite conditions.

Importantly, the lists of to-be-remembered locations in the present experiment were constructed so that the number of red circles that were presented on the left half of the computer screen was manipulated across trials. Five trial types were created for each list length: For list-length-four trials, zero, one, two, three, or four to-be-remembered locations were presented on the left half of the screen, and for list-length-six trials, one, two, three, four, or five to-be-remembered locations were presented on the left half of the screen. In each task condition, participants saw four trials of each type; participants were not told about the different trial types and the types were presented in a way that seemed random but was the same for each participant.

Finally, participants' eye movements were monitored during retention intervals using an eye position tracking system (ISCAN RK 426-PC, Iscan, Inc., Cambridge, MA). Participants' head position was fixed by a chinrest during both task conditions so that they viewed the computer screen from a distance of 94 cm. The eye tracking system recorded the position of a corneal reflection and the position of the pupil at a rate of 60 Hz, and participants' gaze direction was calculated based on the difference between these two positions. At the beginning of the experimental session, calibration was performed with each participant; this was done by having the participant consecutively fixate on nine crosses that appeared one at a time in an imaginary 3x3 grid on the computer screen.

During retention intervals, eye-movement start and end times were identified based on the velocity of the eye. The starting point of an eye movement was defined as when the velocity of the eye first exceeded 40°/s, provided that the velocity then remained above that value for at least three consecutive samples; the ending point of the eye movement then was defined as when the velocity of the eye fell below 40°/s. Eye movements deemed to end outside the boundary of the computer screen were not included in analyses. Four primary measures of eye-movement behavior were obtained for each participant, in each condition and for each list length: the eye movement rate (i.e., the average number of eye movements made per second), the proportion of the total number of eye movements that ended on the left half of the screen, the median distance of the eye movements, and the median duration of periods of fixation (i.e., the durations of the time from the start of the retention interval to the first eye movement, the time between eye movements, and the time from the final eye movement to the end of the retention interval).

3.2 Results and Discussion

3.2.1 Visual Search

The average RTs on correct trials for young and older adults are presented in Figure 3.2, plotted as a function of the number of items searched; the average number of items searched on target-absent trials was assumed to be the same as the array size, and the average number of items searched on target-present trials was assumed to be half of the array size, plus 0.5 (Hale, Myerson, Faust, & Fristoe, 1995). Based on these four data points, search slope was calculated for each participant to serve as a measure of processing speed. This slope was significantly correlated with age (r = .64, p < .001) as well as memory performance in all four task conditions (all rs < -.51, all ps < .001), indicating that a slower search rate was associated with increased age as well as with poorer memory, as was expected based on previous research.

3.2.2 Memory Performance

The average proportion of locations recalled correctly by young and older adults is presented in Figure 3.3. A 2 (environmental support: present vs. absent) x 2 (list length: four vs. six) x 2 (age group: young vs. old) ANOVA performed on this measure of memory performance revealed a significant main effect of environmental support, $F(1, 46) = 168.96$, p < .001, indicating that participants recalled more correct locations when environmental support was present than when

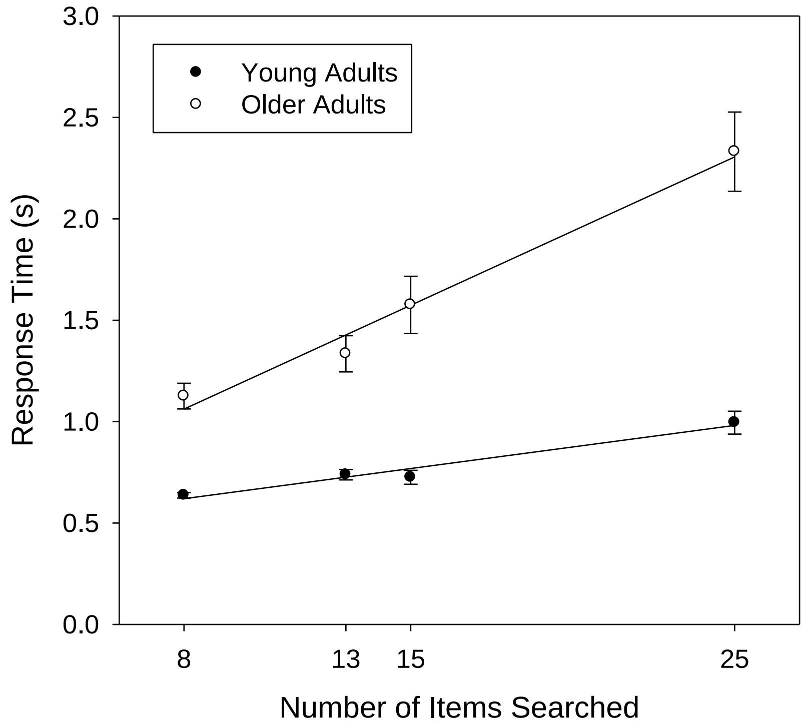

Figure 3.2: Average response time (in seconds) for young and older adults on the visual search task in Experiment 2, with linear regression lines representing search slope. The average number of items searched on target-present trials was assumed to be half of the array size plus 0.5, and the average number of items searched on target-absent trials was assumed to be the array size.

it was absent. The ANOVA also revealed significant main effects of list length, $F(1, 46) = 788.18$, $p < .001$, and age group, $F(1, 46) = 34.51$, $p < .001$; however, these main effects must be interpreted in light of the significant two-way interaction between list length and age group, $F(1, 46) = 6.59$, $p = .014$. This interaction reflects the fact that although both age groups remembered a significantly larger proportion of the locations on list-length-four trials than on list-length-six trials (young adults: $t[23] = 18.02$, $p < .001$; older adults: $t[23] = 21.69$, $p < .001$), the difference in memory performance across list length was larger in older adults than in young adults. No other interactions were significant (all Fs < 0.8, all ps > .380). In addition, it is worth noting that

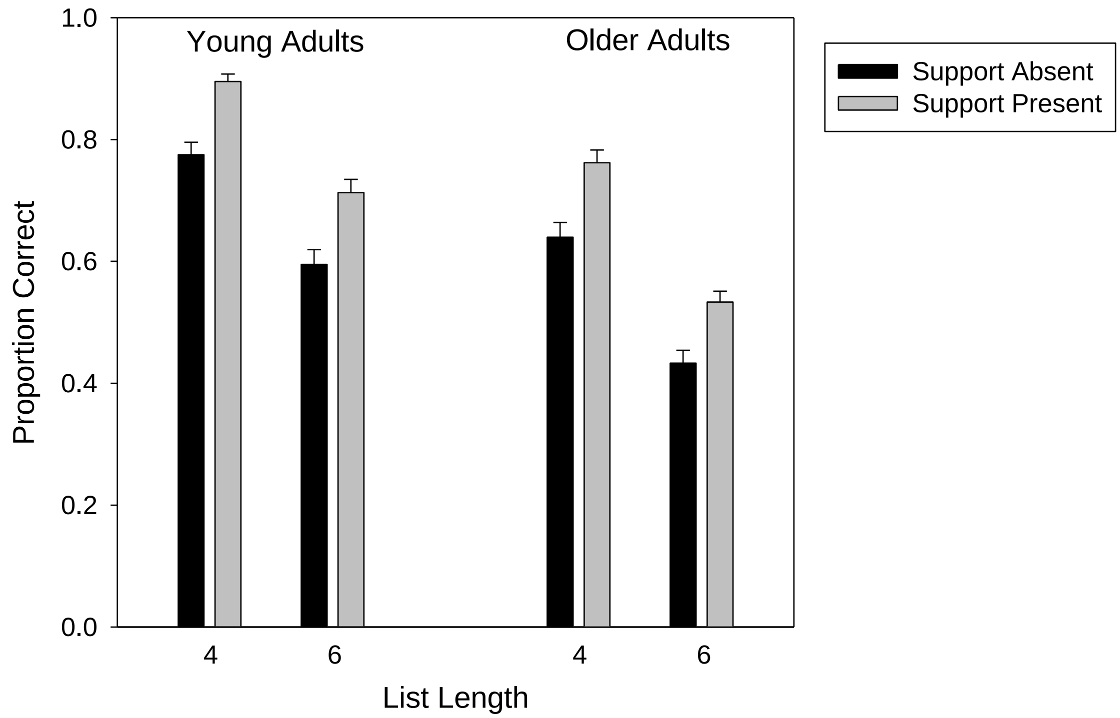

Figure 3.3: Average proportion of locations recalled correctly for young and older adults in each condition and for each list length (i.e., number of to-be-remembered locations), in Experiment 2.

it was very rare for participants to make extra responses (i.e., for participants to click more locations at recall than the number presented on that trial) in either condition, as this only occurred on 1.00% and 1.04% of trials for young and older adults, respectively. The fact that older adults did not make extra responses more often than did young adults suggests they did not have greater difficulty using the mouse at recall.

These results are relatively consistent with what has been observed previously: As expected, young adults remembered significantly more locations than did older adults, and members of both age groups remembered significantly more locations when environmental support was present during retention intervals than when support was absent. However, the interaction between environmental support and age was not significant, suggesting that young adults did not benefit more from the presence of support than did older adults. This was something of a surprise, as such a pattern was observed in both Lilienthal et al. (2014a) and Experiment 1, and it is unclear why the results of the present experiment differed in this way, although it is possible that procedural differences across the experiments played a role. For example, in the present experiment, participants only completed trials with list lengths of four and six, and memory performance was measured as proportion items correct rather than as span. As a result of the non-significant interaction between environmental support and age group, the following analyses of eye-movement behavior will focus on potential differences across environmental-support conditions and across age; it will not be possible to directly address possible explanations for the increased benefit associated with support observed in young adults in previous experiments.

3.2.3 Eye-Movement Behavior

Four primary measures of eye-movement behavior were examined in the present experiment: eye-movement rate, proportion of eye movements made to the left half of the computer screen, median eye-movement distance, and median fixation duration. All four measures are discussed separately in the following sections.

Eye-movement rate. The first measure of eye-movement behavior that was obtained was eye-movement rate, or the average number of eye movements made per second by young and older adults during retention intervals; these eye-movement rates are presented for each condition in Figure 3.4. A 2 (environmental support: present vs. absent) x 2 (list length: four vs. six) x 2 (age group: young vs. old) ANOVA performed on eye-movement rate revealed a significant main

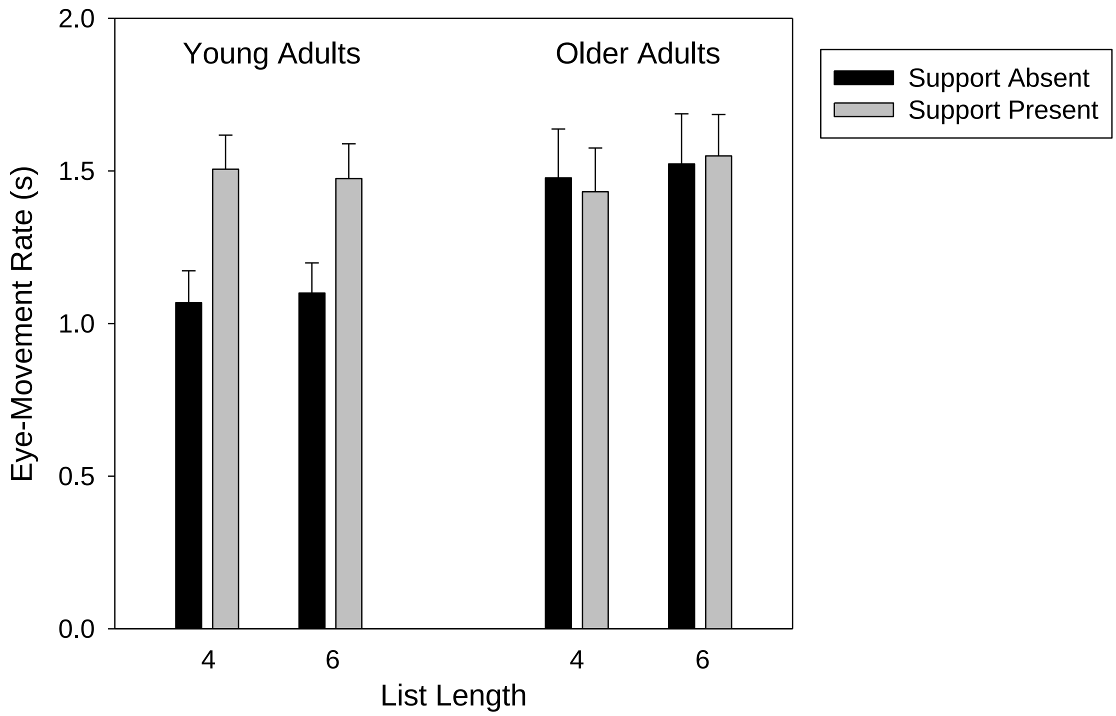

Figure 3.4: Eye-movement rate, or the average number of eye movements made per second, during retention intervals, for young and older adults in each condition, for each list length (i.e., number of to-be-remembered locations) in Experiment 2. Retention intervals were 8 s in duration for list-length-four trials, and 12 s in duration for list-length-six trials.

effect of environmental support, $F(1, 46) = 7.80$, $p = .008$. The main effects of list length and age group both failed to reach significance (list length: $F[1, 46] = 3.66$, $p = .062$; age group: $F[1, 46] = 1.53$, $p = .223$). However, these effects also must be interpreted in light of a significant two-way interaction between environmental support and age group, $F(1, 46) = 8.58$, $p = .005$. This interaction reflects the fact that although young adults' eye-movement rate was significantly greater when environmental support was present than when it was absent ($t[23] = 5.40$, $p < .001$), older adult's eye-movement rate did not differ across support conditions ($t[23] = 0.08$; see Figure 3.4). No other interactions were significant (all Fs < 3.6, all ps > .06).

Because of the differences in memory performance in the presence and absence of environmental support observed here and in previous experiments, it was hypothesized that participants may rehearse to-be-remembered locations less during retention intervals when environmental support is absent. The eye-movement rate results support this hypothesis for young adults, but not for older adults: Although young adults' eye-movement rates were significantly greater when environmental support was present than when support was absent, older adults' eye-movement rates did not differ across support conditions. Thus, it seems that although young adults rehearse less during retention intervals without environmental support, the amount of rehearsal engaged in by older adults does not depend on environmental support.

Because of the differences observed in memory performance across age, it was also hypothesized that older adults may rehearse to-be-remembered locations less during retention intervals than young adults. The eye-movement rate results do not support this hypothesis: young and older adults did not differ in their eye-movement rate when environmental support was present ($t[46] = 0.00$, $p = .999$), and older adults actually had a significantly greater eye-movement rate than young adults when environmental support was absent ($t[46] = 2.2$, $p = .033$). Thus, it seems that differences in the amount of rehearsal engaged in by young and older adults during retention intervals, as measured using eye-movement rate, cannot explain the observed age-related differences in memory performance.

Proportion of eye movements made to the left half of the screen. The second measure of eye-movement behavior that was obtained in the present experiment was the proportion of eye movements that ended on the left half of the screen, regardless of their starting position, for young and older adults during retention intervals, and this was examined as a function of the proportion of to-be-remembered locations presented on the left half of the screen; these proportions are presented for each condition in Figure 3.5. A correlation between these two proportions was calculated for each participant as a measure of appropriate allocation of rehearsal, and this was done for both list lengths in each of the two conditions. These rehearsal-allocation correlations were quite strong in both age groups, and the average correlations are presented in Figure 3.6.

A 2 (environmental support: present vs. absent) x 2 (list length: four vs. six) x 2 (age group: young vs. old) ANOVA performed on the rehearsal-allocation correlations revealed significant main effects of environmental support, $F(1, 46) = 37.50$, $p < .001$, and list length, $F(1, 46) = 49.17$, $p < .001$. The main effect of age group was not significant, $F(1, 46) = 0.28$, $p = .600$. The ANOVA also revealed two significant two-way interactions, between environmental support and age group, $F(1, 46) = 12.99$, $p < .001$, and between list length and age group, $F(1, 46) = 11.58$, $p < .001$, as well as a significant three-way interaction, $F(1, 46) = 4.91$, $p = .032$. In order to further explore this three-way interaction, 2 (environmental support) x 2 (list length) ANOVAs were conducted for each age group separately; the interaction between environmental support and list length was significant in young adults ($F[1, 23] = 5.20$, $p = .032$) but not in older adults ($F[1, 23] = 0.69$, $p = .415$), indicating that the rehearsal-allocation correlations were more similar across support conditions and across list lengths in older adults than in young adults (see Figure 3.6).

Because of the differences observed in memory performance across conditions of environmental support, it was hypothesized that participants may be less precise in their rehearsal when environmental support is not provided during retention intervals, resulting in a reduced rehearsal-allocation correlation (i.e., the average correlation between the proportion of eye movements

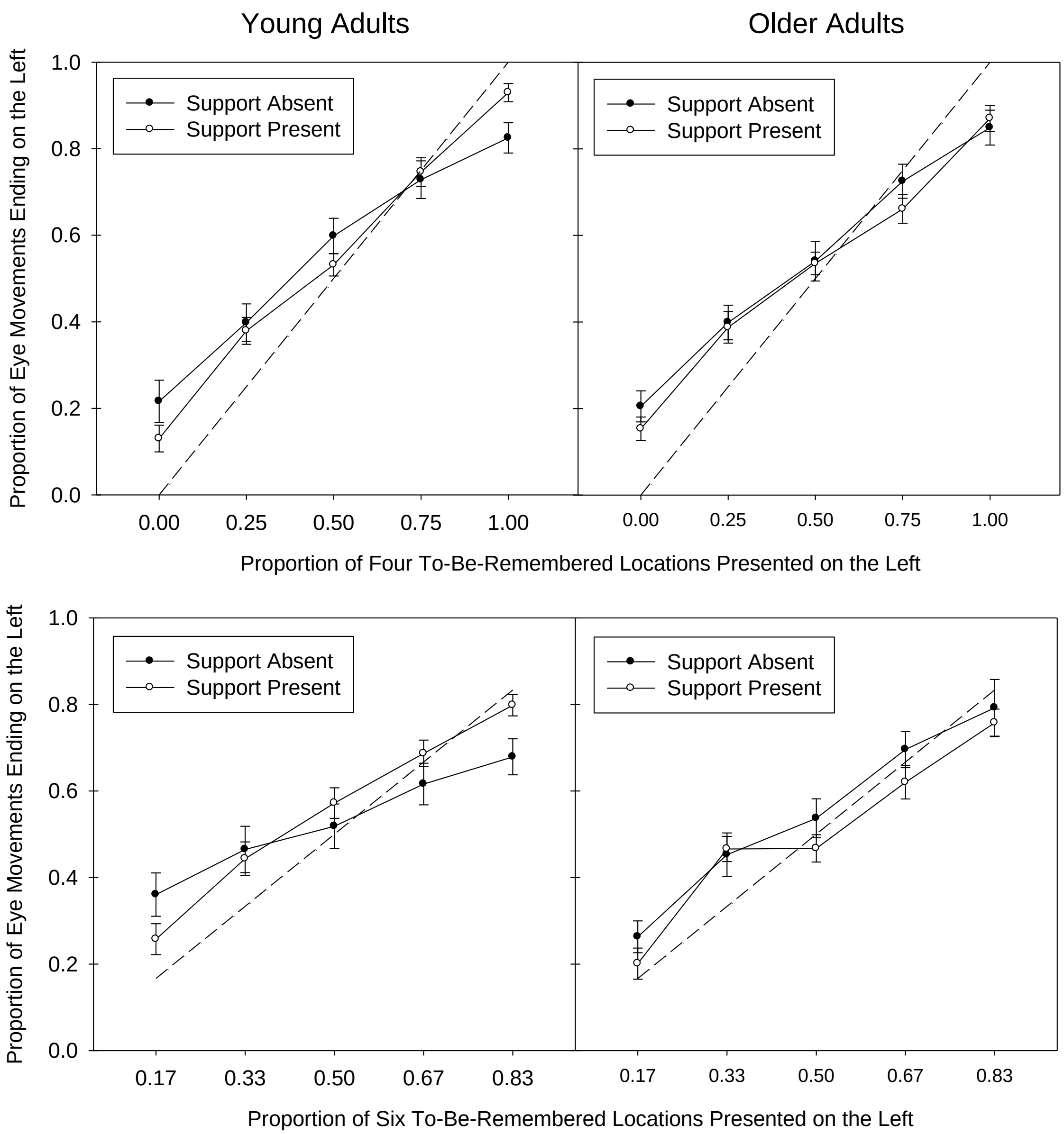

Figure 3.5: Proportion of eye movements ending on the left half of the screen during retention intervals as a function of the proportion of to-be-remembered locations presented on the left half of the screen in Experiment 2. These proportions for list-length-four trials are presented in the two top panels, and proportions for list-length-six trials are presented in the two bottom panels. Proportions for young adults are presented in the two left panels, and proportions for older adults are presented in the two right panels. In each panel, the dashed line represents the proportion of to-be-remembered locations presented on the left half of the screen (i.e., presumably, the ideal proportion of eye movements).

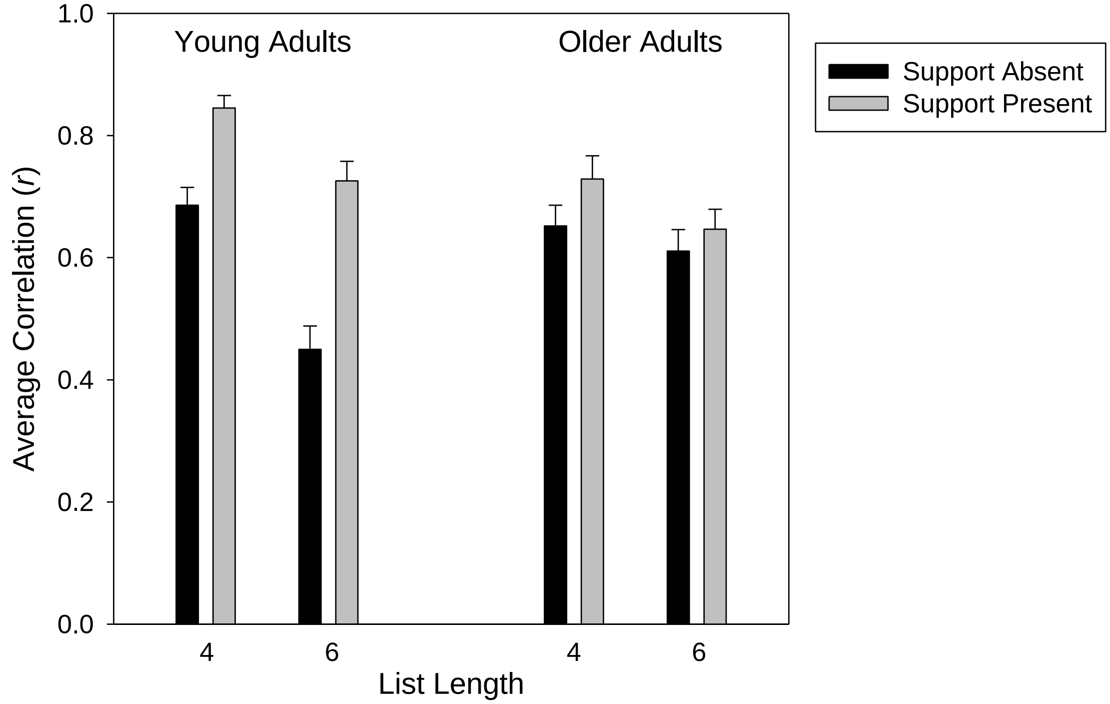

Figure 3.6: Average rehearsal-allocation correlations (i.e., the correlations between the proportion of eye movements ending on the left half of the screen and the proportion of to-be-remembered locations presented on the left half of the screen) for young and older adults in each condition, for each list length (i.e., number of to-be-remembered locations) in Experiment 2.

ending on the left half of the screen and the proportion of to-be-remembered locations presented on the left half of the screen, for each person). The rehearsal-allocation correlation results provide some support for this hypothesis: Average correlations were significantly higher when environmental support was present than when support was absent for young adults ($t[23] = 6.48$, $p < .001$), although the difference in average correlation did not reach significance for older adults ($t[23] = 1.91$, $p = .069$). Thus, it seems that the precision with which young adults rehearse depends on environmental support, but that environmental support plays a smaller role in older adults' rehearsal; interestingly, this is consistent with what was observed in young and older adults' eye-movement rates in the presence and absence of environmental support.

It was also hypothesized that because older adults' memory performance was poorer than that of young adults, older adults may be less precise in their rehearsal compared to young adults. The rehearsal-allocation correlation results are somewhat mixed in regards to this hypothesis. The interaction between environmental support and age was significant, reflecting the fact that young adults' average correlations were significantly greater than older adults' correlations when environmental support was present ($t[46] = 2.57$, $p = .01$), but correlations did not differ across age when environmental support was absent ($t[46] = 1.6$, $p = .127$). However, the three-way interaction including list length was also significant: Young adults' average correlations were significantly greater than older adults' when environmental support was present only when list length was four ($t[46] = 2.70$, $p = .010$; list-length six: $t[46] = 1.7$, $p = .090$), and older adults' average correlations were significantly greater than young adults' when environmental support was absent and list length was six ($t[46] = 3.11$, $p = .003$; list-length four: $t[46] = 0.76$, $p = .453$). Thus, although the pattern of results is somewhat noisy across the list lengths, it seems that differences in the precision of visuospatial rehearsal, at least when considered at this coarse level (i.e., left half of the screen vs. right half of the screen), cannot account for the observed age-related differences in memory performance.

Median eye-movement distance. The third measure of eye-movement behavior that was obtained in the present experiment was the median distance, or size, of the eye movements. These distances (in degrees) are presented for each condition in Figure 3.7. A 2 (environmental support: present vs. absent) x 2 (list length: four vs. six) x 2 (age group: young vs. old) ANOVA

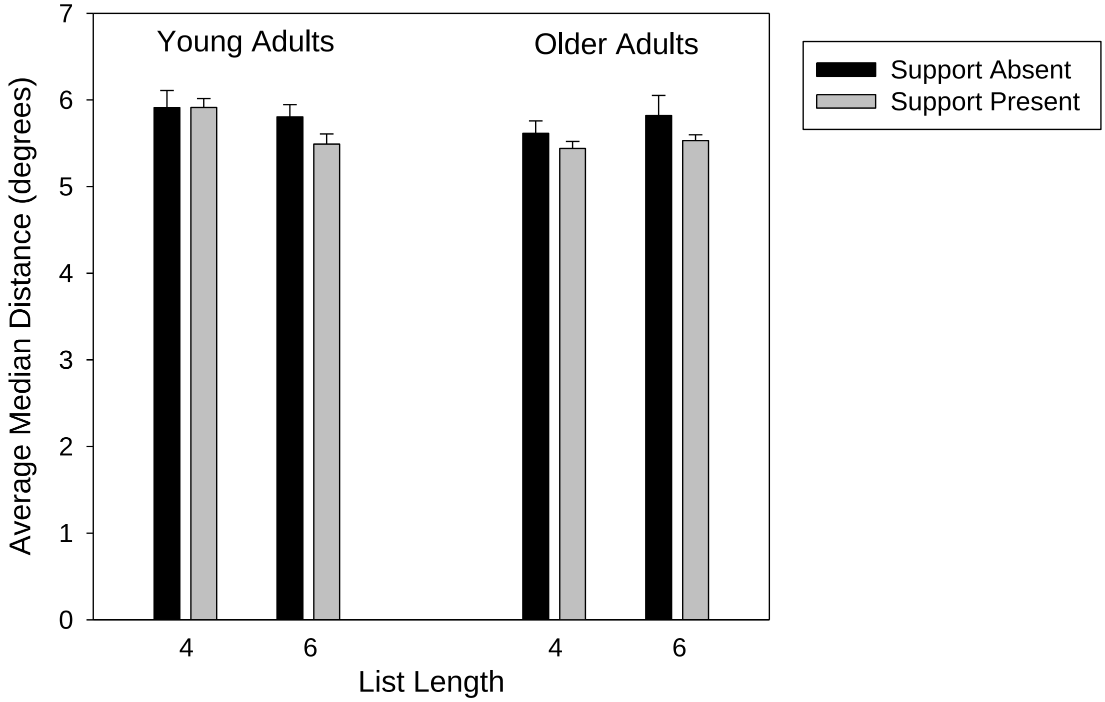

Figure 3.7: Average median distance of eye movements (in degrees) during retention intervals for young and older adults in each condition, for each list length (i.e., number of to-be-remembered locations) in Experiment 2. Retention intervals were 8 s in duration for list-length-four trials, and 12 s in duration for list-length-six trials.

performed on the distances revealed only a significant interaction between list length and age group, $F(1, 46) = 6.93$, $p = .012$, reflecting the fact that although younger adults made longer eye movements on list-length-four trials than on list-length-six trials ($t[23] = 3.79$, $p = .001$), this difference was not significant in older adults ($t[23] = 1.05$, $p = .304$). No main effects or other interactions reached significance (all Fs < 3.3, all ps > .075).

Eye-movement distance is a relatively common measure when investigating eye-movement behavior on visual search tasks, but it has never before been examined in the context of visuospatial rehearsal, and it seemed possible that the size of participants' eye movements might differ across environmental-support conditions. The results of the present experiment do not support this idea: The main effect of environmental support was marginally significant, $F(1, 46) = 3.26$, $p = .078$, suggesting that eye movements may have been slightly longer when environmental support was absent; however, this difference was very small (i.e., an average difference of 0.2°). In addition, eye-movement distance has been found to differ across age on visual search tasks, and it was hypothesized that a similar difference might be observed in visuospatial rehearsal, in that older adults might make shorter eye movements than young adults, perhaps due to a reduced useful field of view (e.g., Veiel et al., 2006). The results of the present experiment, however, were not consistent with this idea, as no difference in eye-movement size was observed across age group.

Median fixation duration. The final measure of eye-movement behavior that was obtained in the present experiment was the median duration of the periods of fixation (i.e., the time between the start of the retention interval and the first eye movement, the time between eye movements, and the time between the final eye movement and the end of the retention interval) for young and older adults during retention intervals; these fixation durations are presented for each condition in Figure 3.8. A 2 (environmental support: present vs. absent) x 2 (list length: four vs. six) x 2 (age group: young vs. old) ANOVA performed on the fixation durations revealed that only the three-way interaction was significant, $F(1, 46) = 9.30$, $p = .004$. Follow-up analyses suggest that this interaction reflects the fact that on list-length-four trials, the difference between median fixation duration across support conditions was not significant for young adults ($t[23] = 0.94$, $p = .358$), but it was marginally significant for older adults ($t[23] = 2.02$, $p = .055$), with somewhat longer median fixation durations when support was present; however, for list-length-six trials,

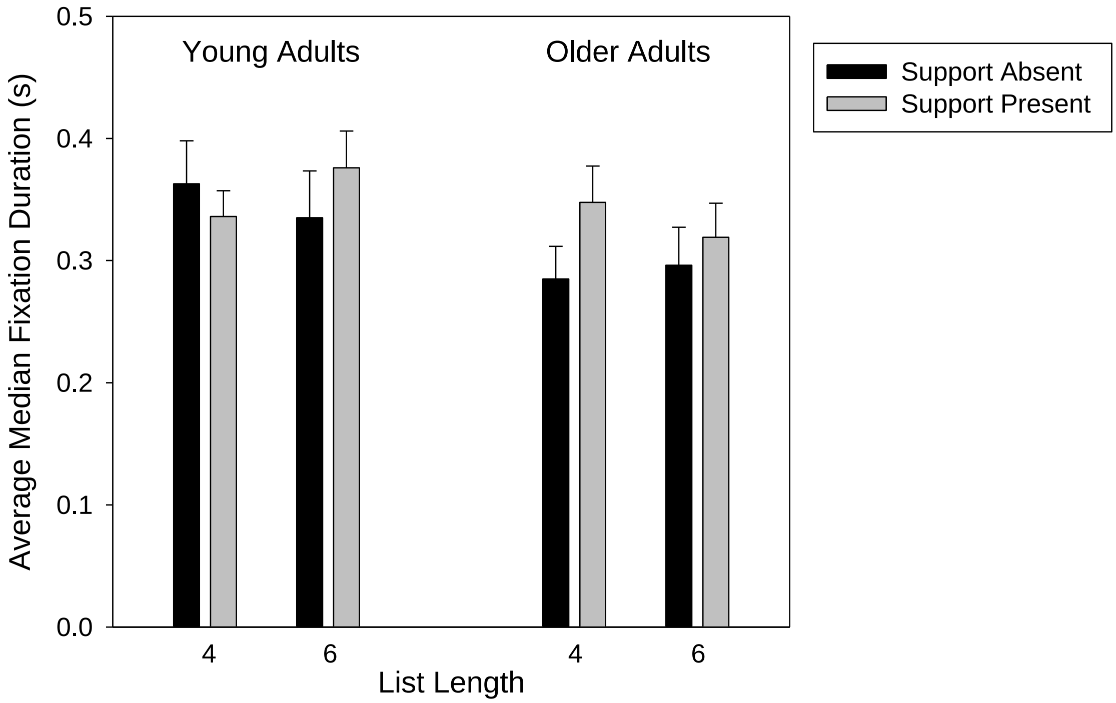

Figure 3.8: Average median fixation duration (in seconds; i.e., amount of time spent fixating) during retention intervals for young and older adults in each condition, for each list length (i.e., number of to-be-remembered locations) in Experiment 2. Retention intervals were 8 s in duration for list-length-four trials, and 12 s in duration for list-length-six trials.

the difference between median fixation duration across support conditions was marginally significant for young adults ($t[23] = 2.06$, $p = .051$), with somewhat longer median fixation durations when support was present, but not significant for older adults ($t[23] = 0.78$, $p = .442$).

Just as with eye-movement distance, fixation duration has never before been examined in the context of visuospatial rehearsal, and it seemed possible that it might differ in the presence and absence of environmental support. The results from the present experiment provide only weak evidence for this idea: When environmental support was present, young adults tended to fixate slightly longer on list-length-six trials and older adults tended to fixate slightly longer on list-length-four trials, but no difference was observed on the remaining trials (and no differences reached statistical significance). Thus, it is possible that participants spend more time fixating when environmental support is present, but more research on this issue is needed before a strong conclusion can be reached. The present experiment also investigated whether fixation duration differed across age; no such age-related difference was found in either condition, at either list length.

Chapter 4: Experiment 3

In Experiments 1 and 2 of the present study, participants were allowed to move their eyes freely during retention intervals, as was also the case during the inter-item intervals in Lilienthal et al. (2014a) and (2014b); thus, these previous experiments primarily investigated aspects of overt visuospatial rehearsal (i.e., rehearsal accomplished using eye movements). Importantly, when one directs their eyes to a spatial location, spatial attention presumably also is directed to the same location. Spatial attention, sometimes known as selective spatial attention, refers to one's ability to process information in a specific location in space, often at the expense of other, unattended locations. Orienting one's spatial attention to a certain location can be accomplished with either overt head and eye movements or with covert shifts of attention alone (e.g., Posner, 1980); therefore, it has been proposed that visuospatial rehearsal also can occur covertly, through shifts of spatial attention in the absence of overt eye movements (e.g., Smyth & Scholey, 1994; Awh et al., 1998).

The results of a number of selective interference experiments have supported the idea that spatial attention is important for visuospatial rehearsal and maintenance. For example, Lawrence, Myerson, and Abrams (2004) asked participants to remember either a series of letters or a series of locations, and also to perform an interpolated secondary task while they fixated on the center of the computer screen. During the secondary task, participants were presented consecutively with two symbols and were asked to respond as to whether or not the two symbols matched; participants completed two conditions of the secondary task across which the location of the symbols was varied. In one condition, the symbols were presented in the center of the screen, at participants' fixation, and in the other condition, the symbols were presented at the edge of the computer screen while participants continued to fixate at the center. Thus, the two conditions differed in whether or not participants were required to shift their spatial attention in order to perform the secondary task. Lawrence et al. found that although the two secondary-task conditions had similar effects on verbal memory, visuospatial memory was significantly worse in the secondary-task condition requiring attention shifts than in the no-shift condition. These results indicate that even in the absence of overt eye movements, requiring participants to shift their spatial attention away from to-be-remembered locations hurts memory, presumably because such shifts limit rehearsal.

Only one study has investigated the potential benefits of covert visuospatial rehearsal. Godijn and Theeuwes (2012) presented participants with a single display containing the digits 1-6, randomly arranged on the computer screen, followed by a 7.5 s retention interval. During the interval, participants either were instructed to fixate at a location of their choice or to move their eyes however they wished. At test, participants were asked to click on the locations of the digits, in ascending numerical order, and memory performance was assessed using the mean deviation in distance of the mouse clicks from the presented locations. Godijn and Theeuwes reported no difference in memory performance across the two conditions, concluding that rehearsal performed using attention shifts is equally effective in maintaining locations in working memory as rehearsal performed using eye movements.

While interesting, the results of Godijn and Theeuwes (2012) may be somewhat inconsistent with what has been reported in the selective interference literature. For example, in their second experiment, Lawrence et al. (2004) also directly compared the disruptive effects of eye movements to those of attention shifts alone. Participants were asked to remember a series of locations presented in a grid, in addition to performing three conditions of a secondary task: the two conditions described previously (i.e., an attention-shift secondary-task condition and a no-shift secondary-task condition) as well as a condition in which participants were asked to actually move their eyes to symbols presented at the edge of the screen. Lawrence et al. found that shifts of attention again caused significant interference compared to the no-shift condition, but interestingly, that memory performance was significantly lower still when participants moved their eyes. This finding was replicated by Pearson and Sahraie (2003) using different memory and secondary tasks: Pearson and Sahraie found that secondary tasks requiring continuous and discrete attention shifts (analogous to smooth pursuit and saccadic eye movements, respectively) each significantly disrupted performance on the Corsi Blocks location memory task, but that this interference was significantly less than the interference created by secondary tasks requiring eye movements. The results of both Lawrence et al. and Pearson and Sahraie indicate that eye movements may be more disruptive of memory than are attention shifts, and based on these results, one might have expected overt rehearsal to be more effective than covert; as this was not what was observed by Godijn and Theeuwes (2012), more research on this issue is needed.

The present experiment was designed to investigate the effects of environmental support on covert rehearsal, and also whether such effects differ across age. Young and older adults were asked to complete four conditions of a location memory task. These conditions were very similar to those described in Experiment 1: Across the four conditions, both the duration of a final retention interval as well as whether or not environmental support was present during the interval were manipulated. However, the critical difference between the present experiment and Experiment 1 was that here, participants were required to fixate on a central point during the retention intervals, thus limiting them to covert rehearsal strategies. If covert visuospatial rehearsal is as effective as overt visuospatial rehearsal, as suggested by Godijn and Theeuwes (2012), the same pattern of results as observed in Experiment 1 would be expected in the present experiment. However, if covert rehearsal is not as effective, or different from overt rehearsal in some other way, the memory benefits previously associated with the presence of environmental support likely would be reduced in the present experiment.

Importantly, no previous study has investigated older adults' ability to engage in covert visuospatial rehearsal, and whether older adults have more difficulty using a covert strategy than do young adults is unknown. A number of studies have addressed the effects of age on RTs in spatial cueing paradigms, and although the results have been somewhat mixed, it seems that there may be little or no age-related difference in the ability to shift attention to cued locations, suggesting that visuospatial attention may be relatively preserved with age (e.g., Folk & Hoyer, 1992; Hartley, 1993; Greenwood, Parasuraman, & Haxby, 1993). However, shifting one's attention in response to a cue may be different from shifting one's attention as a method of keeping representations of to-be-remembered locations active in working memory. That older adults did not make fewer eye movements than young adults in Experiment 2 suggests that they were not rehearsing less, but this does not rule out age-related differences in the likelihood or amount of covert rehearsal. In addition, age-related reductions in participants' useful field of view could affect older adults' ability to covertly rehearse locations and to benefit from environmental support. Such reductions often are less of a concern in spatial cueing paradigms, due to the typical proximity of the targets to the fixation point, but it is possible that in the present experiment, if the area from which information can be acquired without eye movements is smaller for older adults than young adults (e.g., Scialfa et al., 1994), this could make covert rehearsal especially difficult for older adults.

4.1 Method

4.1.1 Participants

Twenty-four young adults (21 female; age *M* = 19.5, *SD* = 1.3, range = 18-22) and 24 older adults (18 female; age *M* = 71.0, *SD* = 3.8, range = 65-80) participated in this experiment. The young adults were undergraduate students at Washington University in St. Louis who participated in exchange for the partial fulfillment of a course requirement. The older adults were community-dwelling residents of the St. Louis area who participated in exchange for monetary compensation. Older adults were screened using the Telephone Interview for Cognitive Status (Brandt et al., 1988) and for significant health issues (e.g., stroke, Parkinson’s disease), as well as for colorblindness. The average number of years of education was 13.4 (*SD* = 1.2) for young adults and 15.6 (*SD* = 3.0) for older adults. All participants reported English as their native language and had normal corrected-to-normal visual acuity, as evidenced by their performance on the Wormington Pocket Acuity test (median acuity: young adults = 20/20, older adults = 20/30).

4.1.2 Materials and Procedure

All participants performed four conditions of a visuospatial simple span in a single experimental session that lasted approximately 1.5 hours (see Figure 4.1). As in Experiment 1, on each trial participants were shown an array of 30 circles on a computer screen, the configuration of which was changed on every trial (i.e., a different set of 30 locations was chosen for each trial). A subset of the circles then turned red one at a time and participants were instructed to remember

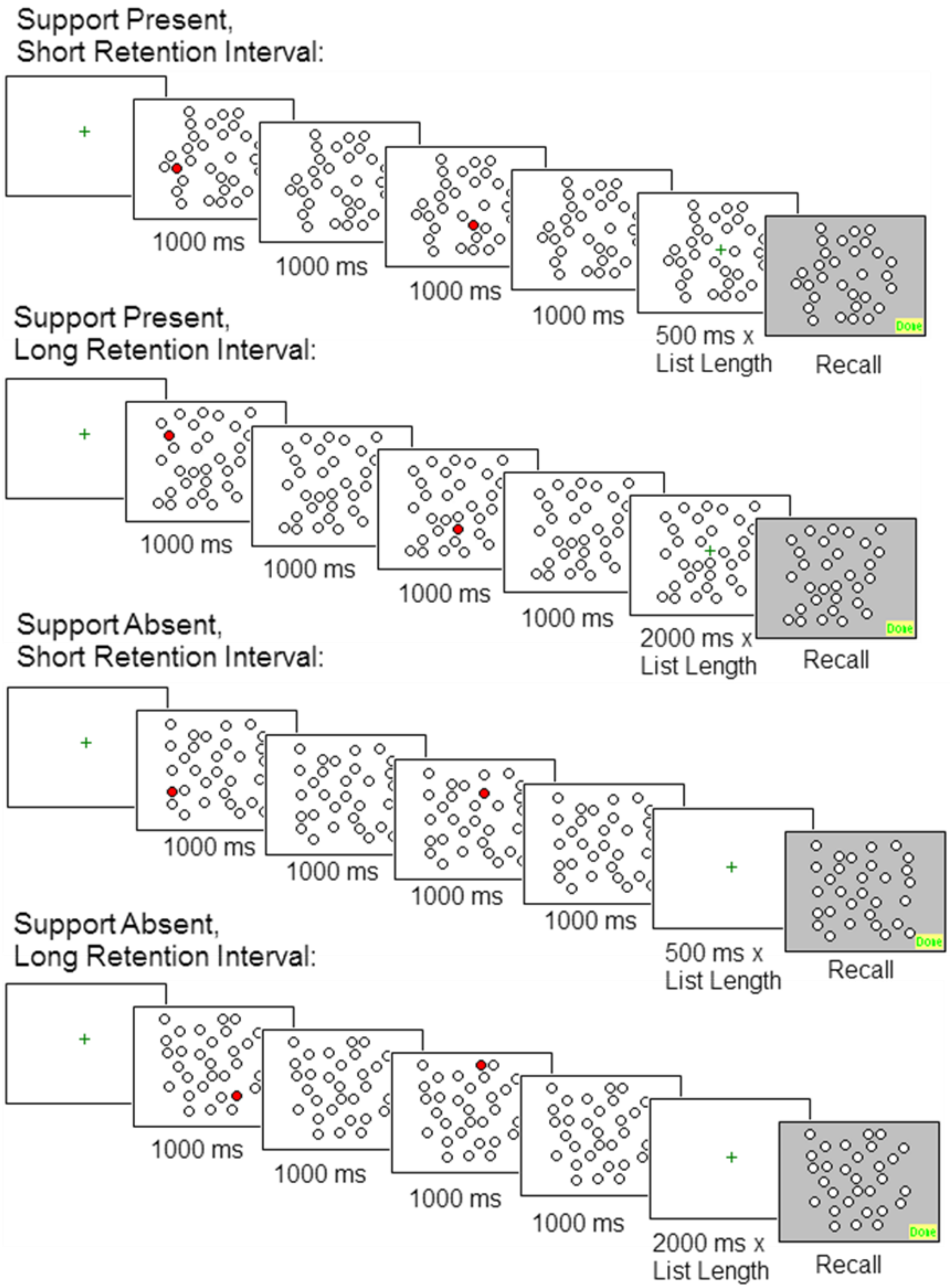

Figure 4.1: Example trials from each task condition in Experiment 3. Retention intervals (the time preceding recall, during which environmental support was manipulated) were either short or long, and participants were required to fixate on the central cross during that time.

the locations of the red circles (i.e., the to-be-remembered locations). Each red circle was presented for 1,000 ms, followed by a 1,000 ms inter-item interval during which the array of empty circles remained on the screen.

A retention interval followed the presentation of the final red circle, and as in Experiment 1, both the duration of the retention intervals and whether or not environmental support was present during that time was manipulated across the four conditions. Retention intervals were again either short (500 ms multiplied by the list length) or long (2,000 ms multiplied by the list length), and environmental support during retention intervals was either present or absent. As in Experiments 1 and 2, when environmental support was present, the array of 30 circles remained visible on the computer screen during the retention intervals, whereas when environmental support was absent, participants instead viewed a blank screen during the retention intervals; however, during the retention intervals in the present experiment, a fixation cross was presented in the center of the screen (see Figure 4.1).

Following the retention interval, participants were asked to recall the to-be-remembered locations. In order to do this, participants were presented again with the array of 30 circles, now appearing against a gray background (see Figure 4.1), and they were asked to click on the circles that had turned red during that trial using the computer mouse. Upon being clicked, the circles turned green, and this was done in order to indicate to participants which locations they already had chosen. Participants were allowed to recall the locations in any order and were given as much time as they needed to do so. They were instructed to click on an icon labeled “Done,”, located in the bottom right corner of the computer screen, when they were finished recalling.

Each of the task conditions began with four practice trials, followed by 20 test trials. As in Experiment 1, list lengths (i.e., the number of to-be-remembered locations presented on a trial) ranged from two to 11, and participants completed two trials at each length in each condition. List lengths were presented in ascending order, so that participants first performed the two list-length-one trials, followed by the two list-length-two trials, and so on. Memory performance in each condition was assessed using a span measure, scored as one less than the shortest list length at which both test trials were incorrect.

The order of the four task conditions was counterbalanced across participants so that each participant performed the conditions in one of four orders (six participants in each age group per order condition). Half of the participants completed the two conditions with environmental support first, followed by the two conditions without environmental support. The other half of the participants completed the two conditions without environmental support first, followed by the conditions with environmental support. Within each of these two groups of participants, half completed a condition with short retention intervals first, and the other half completed a condition with long retention intervals first; however, the interval duration conditions were always presented alternately (i.e., either short-long-short-long, or long-short-long-short).

Critically, participants in the present experiment were required to fixate on a central point throughout the duration of the retention intervals. At the start of each retention interval, a green cross appeared in the center of the screen; the arrays in this experiment were adjusted so as to never include a circle in that center position. Participants were allowed to move their eyes freely while the red circles were being presented, but they were instructed to move their eyes to the cross as quickly as possible when it appeared and to keep their eyes fixed on the cross until it disappeared, signaling the start of the recall test.

In order to verify that participants maintained fixation during the retention intervals, the eye tracking system used in Experiment 2 also was utilized in the present experiment. Participants' head position was fixed by a chinrest so that they viewed the computer screen from a distance of 94 cm. An infrared camera was focused on participants' right eye and the image was projected to a display visible only to the experimenter seated in the corner of the testing room. The experimenter monitored this display during retention intervals and recorded on which trials participants broke fixation[1]. Trials on which participants broke fixation were removed, and at the end of each condition participants were asked to complete make-up trials of the same list lengths so that span could be calculated normally. On average, a total of 2.1 trials (*S*D = 1.8) for young adults and 0.9 trials (*SD* = 1.2) for older adults were removed across conditions due to breaks in fixation; the average number of trials removed in each condition for each age group is presented in Table 4.1. A 2 (environmental support: present vs. absent) x 2 (retention interval duration: short vs. long) x 2 (age group: young vs. old) ANOVA conducted on the number of trials removed revealed significant main effects of interval duration, $F(1, 46) = 19.97$, $p < .001$, and age group, $F(1, 46) = 14.04$, $p < .001$, reflecting the fact that participants were more likely to break fixation in conditions with long retention intervals than in conditions with short retention intervals, and that young adults were more likely to break fixation than were older adults; no other significant main effects or interactions were observed (all Fs < 3.74, all ps > .061).

[1] In order to ensure that the experimenter could identify eye movements made by each participant, before the start of the first task condition participants completed a brief verification task on which they were asked to move their eyes to 12 fixed locations on the screen while the experimenter monitored the display. These 12 locations varied in their distance from the central fixation point, and included four locations that mimicked the positions of the to-be-remembered locations that could appear closest to the fixation point during the memory task. The experimenter was able to successfully identify these eye movements for all participants.

Table 4.1: Mean number of trials in each condition that were removed due to breaks in fixation for young and older adults (standard deviations are presented in parentheses).

	Support Absent Conditions		Support Present Conditions	
	Short Intervals	Long Intervals	Short Intervals	Long Intervals
Young Adults	0.21 (0.7)	0.58 (1.2)	0.46 (0.7)	0.83 (1.1)
Older Adults	0.08 (0.3)	0.12 (0.4)	0.04 (0.2)	0.67 (1.0)

4.2 Results and Discussion

Young and older adults' memory spans in all four task conditions are presented in Figure 4.2. A 2 (environmental support: present vs. absent) x 2 (retention interval duration: short vs. long) x 2 (age group: young vs. old) ANOVA performed on the spans revealed a significant main effect of interval duration, $F(1, 46) = 19.97$, $p < .001$, indicating that spans were smaller when retention intervals were long than when intervals were short, as well as a significant main effect of age group, $F(1, 46) = 14.04$, $p < .00$, indicating that older adults' spans were smaller than young adults' spans. There was no main effect of environmental support and no significant interactions (all Fs < 1.55, all ps > .220).

In the present experiment, participants were required to fixate during retention intervals, and thus were limited to covert rehearsal strategies (i.e., strategies relying on shifts of spatial attention in the absence of overt eye movements). If covert visuospatial rehearsal is as effective as overt visuospatial rehearsal, it was hypothesized that the same pattern of results observed in Experiment 1 also would be found in the present experiment, but this was clearly not the case

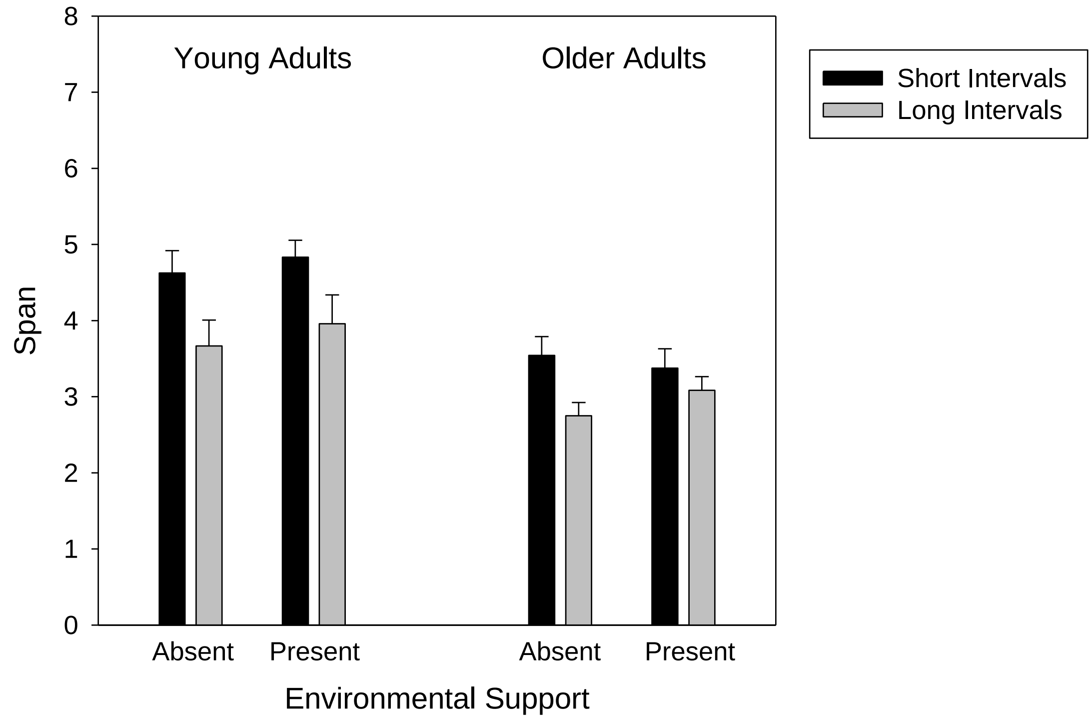

Figure 4.2: Effects of retention interval duration and environmental support on visuospatial memory spans for both young and older adults in Experiment 3.

(i.e., compare Figure 4.2 with Figure 2.2 from Experiment 1). In Experiment 1, participants' memory spans were dependent on both environmental support and retention-interval duration, in that participants forgot locations over time but only when support was absent, and in fact, young adults were able to remember more locations with more time when environmental support was present. In the present experiment, environmental support had no effect on memory spans, and instead, participants always forgot locations over time, regardless of whether or not support was present. This suggests that in the presence of environmental support, although rehearsal performed using eye movements can effectively maintain to-be-remembered locations in working memory across retention intervals, rehearsal performed using only covert shifts of spatial attention cannot. Importantly, these results are seemingly inconsistent with those reported by Godijn and Theeuwes (2012), and this will be discussed in greater detail in the General Discussion.

It is worth noting that participants in the present experiment did not receive any instructions regarding covert visuospatial rehearsal; they simply were told that they needed to keep their eyes fixated on the cross at the center of the computer screen during retention intervals, and they were not given any information about possible covert strategies. Thus, it is possible that the forgetting observed over time may have been due to participants not engaging in covert rehearsal, rather than due to the reduced effectiveness of covert rehearsal. That is, perhaps participants can rehearse effectively using shifts of attention, but they were not doing so in the present experiment. If this were the case, a different pattern of results might emerge if participants were instructed to try to shift their attention to the to-be-remembered locations while fixating during the retention intervals. The purpose of the present experiment was to investigate the effects of participants' natural behavior, and future research should examine whether instructions regarding covert rehearsal produces different effects.

In addition, the present experiment is also the first to investigate potential differences in covert rehearsal across age. As expected, older adults' memory spans were significantly smaller than young adults' spans, as evidenced by the main effect of age group, but no significant interactions involving age were observed. Although it seemed possible that older adults might have more difficulty using covert rehearsal strategies than young adults, the results of the present experiment provide no evidence in support of that idea. Instead, the present results are consistent with those obtained in spatial cueing experiments and suggest that the ability to shift spatial attention may not be influenced significantly by aging.

Chapter 5: General Discussion

Even though a substantial amount of evidence has supported a functional distinction between verbal and visuospatial working memory (e.g., Hale et al., 1996; de Renzi & Nichelli, 1975; Park et al., 2002; Jenkins et al., 2000), most of the research on working memory has focused almost exclusively on the verbal domain. As a result, there currently are many unknowns related to visuospatial working memory, and although it is likely that many processes are similar across the two domains, there also may be some processes in which the two domains differ. One such differing process may be rehearsal: Lilienthal et al. (2014b) demonstrated that whether or not participants were provided with environmental support (i.e., whether or not participants were able to view the array of possible locations during inter-item intervals) can have an important effect on participants' ability to rehearse, and ultimately remember, locations. It is difficult to imagine something analogous to this environmental support in the verbal domain.

Lilienthal et al. (2014a) investigated the effects of environmental support for rehearsal in older adults; the concept of environmental support is an important one in the field of aging research (e.g., Craik & Byrd, 1982), in that older adults tend to benefit from the presence of support more than young adults, but the concept had not been applied previously to the rehearsal of locations, and it was unclear whether the typical prediction would be confirmed. In fact, it was not confirmed: When young and older adults were provided with environmental support for visuospatial rehearsal in Lilienthal et al., it was actually the young adults who benefited more. When support was present, young adults were able to recall significantly more locations when they had sufficient time to rehearse (i.e., when inter-item intervals were long), whereas older adults' memory spans did not differ across short and long inter-item intervals. The results of

Lilienthal et al. (2014a) and (2014b) suggest that there may be important differences in rehearsal across environmental support and across age, and the purpose of the three experiments in the present study was to further investigate these potential differences.

5.1 Environmental Support During Retention

The primary goal of Experiment 1 was to determine whether the findings of Lilienthal et al. (2014a) could be replicated, in both young and older adults, using a procedure in which there was a final retention interval. Across five task conditions, the duration of retention intervals and the presence of environmental support were manipulated. This retention-interval procedure was of interest because of its potential to help isolate the effects of environmental support to maintenance and rehearsal. If the effects of environmental support observed in Lilienthal et al. were due to differences in encoding across task conditions, it was expected that such effects would disappear or be greatly reduced in Experiment 1, when conditions were equated during encoding; however, if the effects of support observed in Lilienthal et al. instead were due to differences in rehearsal across task conditions, it was expected that the pattern of results would be replicated in Experiment 1. In fact, the results of Lilienthal et al. (2014a) were replicated in Experiment 1: When environmental support was present, spans were significantly larger when retention intervals were long, whereas when environmental support was absent, spans were significantly larger when retention intervals were short. In addition, young adults again benefited significantly more from the presence of support than did older adults, suggesting that there may be important age-related differences in rehearsal.

With the inclusion of a task condition with no retention interval in addition to the conditions with short and long retention intervals, the results of Experiment 1 also provided further evidence for the decay of to-be-remembered locations over time in the absence of environmental support. Notably, participants were never required to perform a secondary task or to divert their attention from the to-be-remembered locations, and so the observed forgetting is inconsistent not only with theories of working memory that posit that information is lost from memory exclusively through interference (e.g., Oberauer & Lewandowsky, 2008; 2013), but the observed forgetting also may be difficult for some decay-based theories of working memory to explain (e.g., Barrouillet et al., 2004; Barrouillet et al., 2007). These theories have been developed primarily based on experiments examining memory for verbal information, and the fact that they cannot account for the results of Experiment 1 suggests that visuospatial information may decay from working memory in situations in which verbal information may not; more research is needed to fully understand this important difference across domain.

Future research also should investigate the potential effects of reductions in the temporal distinctiveness of to-be-remembered locations in the retention-interval procedure, but it is worth noting that controlling the temporal distinctiveness of locations across conditions did not change the results in Lilienthal et al. (2014b). Interestingly, other studies have demonstrated that when to-be-remembered items are visual (e.g., colors, complex characters), reduced temporal distinctiveness can cause significant forgetting (e.g., Souza & Oberauer, 2015; Mercer, 2014; cf. Ricker, Spiegel, & Cowan, 2014). Thus, not only is more research needed investigating potential differences in maintenance, rehearsal, and forgetting between verbal and visuospatial working memory, but potential differences between visual and spatial working memory should also be explored further (e.g., Logie, 1995).

5.2 Overt Visuospatial Rehearsal

The primary goal of Experiment 2 was to investigate potential differences in eye-movement behavior during the retention intervals of a location memory task across environmental-support conditions and across age. Eye-movement behavior was of interest because the differences in memory span observed in previous experiments (i.e., Experiment 1; Lilienthal et al. 2014a) were assumed to be due, at least in part, to differences in participants' ability to rehearse, and it has been proposed that one method through which participants can rehearse to-be-remembered locations is by moving their eyes to those locations (e.g., Baddeley, 1986; Awh et al., 1998). Therefore, young and older adults in Experiment 2 performed a location memory task similar to that used in Experiment 1, and participants' eye movements were recorded during the retention intervals, when environmental support was either absent or present. Although two previous studies have used eye-movement monitoring in regards to visuospatial rehearsal (i.e., Tremblay et al., 2006; Godijn & Theeuwes, 2012), this was the first experiment to do so across environmental support conditions, the first to include older adults, and the first to examine eye-movement behaviors typical in the visual search literature (i.e., eye-movement rate, median fixation duration, and median eye-movement distance) in the context of visuospatial rehearsal.

It was hypothesized that participants would rehearse less (i.e., have a lower eye-movement rate), and/or less precisely (i.e., have lower rehearsal-allocation correlations), when support was absent than when support was present. Although this prediction was confirmed in young adults, older adults' rehearsal rate and precision did not depend on the presence of support, and neither age group differed in their average median fixation duration or eye-movement distance across support conditions. Regarding potential differences in eye-movement behavior across age, it was hypothesized that older adults would rehearse less, and/or less precisely, than young adults.

However, the results were inconsistent with both predictions, as young and older adults' eye-movement rates and rehearsal-allocation correlations were similar; in addition, no age-related differences in either average median fixation duration or eye-movement distance were observed.

In previous experiments (e.g., Lilienthal et al. 2014a; 2014b), it was assumed that the presence of environmental support improved participants' location memory because it facilitated their rehearsal, perhaps by increasing the likelihood of rehearsal, by increasing the efficiency of rehearsal through reducing the memory load (i.e., with support, participants likely do not need to maintain an internal representation of the entire array of 30 possible locations), and/or by increasing the precision of rehearsal. The data collected from young adults in Experiment 2 at least were consistent with this idea: When environmental support was absent, not only were young adults' memory spans smaller, but their eye movements were also fewer and less precise compared to when support was present. However, although older adults exhibited the same pattern of memory results, their eye movements did not differ across support conditions. This result was unexpected, and what exactly it means cannot entirely be answered by the present experiment.

One possible interpretation of the results of Experiment 2 is that, regardless of what was observed in the young adults, the memory benefit associated with the presence of environmental support was due to something other than the facilitation of rehearsal. Alternatively, it is also possible that the results of Experiment 2 suggest that individuals' responses to the presence and absence of environmental support may differ across age. For example, because young adults have greater working memory capacities, when environmental support is absent, perhaps they try to rely more heavily on their internal representation of the array of locations and engage in maintenance strategies other than just overt visuospatial rehearsal, resulting in fewer eye movements compared to when environmental support is present; on the other hand, because older adults tend to have relatively smaller working memory capacities, they cannot rely on an internal representation in the absence of environmental support and instead continue rehearsing using eye movements. However, this does assume that these different responses to the absence of environmental support are equally ineffective, as both age groups remembered fewer locations without environmental support, and it is, of course, just one possibility.

Clearly, additional research is needed in order to more fully explain the results of Experiment 2. In addition to investigating potential effects of environmental support other than just those on rehearsal, future research also should investigate the accuracy of rehearsal using eye movements (i.e., the correspondence between the to-be-remembered locations and the locations at which participants fixated). In Experiment 2, rehearsal was examined at a relatively coarse level, as the measure of precision (i.e., the rehearsal-allocation correlations) was obtained by comparing the proportion of eye movements participants ending on the left half of the computer screen to the proportion of to-be-remembered locations presented on the left half of the computer screen, which was manipulated across trials. Although the rehearsal-allocation correlations revealed that older adults were making eye movements to appropriate general locations, it is possible that if a more fine-grain measure of accuracy were considered, age-related differences would emerge.

In addition, future research should consider the potential role of individual and age-related differences in working memory capacity in the effects of environmental support on rehearsal. For example, it is possible that high- and low-span participants engage in different rehearsal strategies, or that the presence and absence of environmental support might affect such participants differently, but no study has addressed such questions. It is also possible that the same participant might use different rehearsal strategies on different trials during the task conditions, depending on whether the number of to-be-remembered locations on that trial exceeds their memory capacity, and future research should better control for such a possibility.

Interestingly, although a number of studies have investigated age-related differences in eye-movement behavior in visual search and change detection paradigms, Experiment 2 is the first to do so during rehearsal in a location memory task. Previous studies using these paradigms have found that, compared to young adults, older adults make shorter eye movements (e.g., Scialfa & Joffe, 1997; Veiel et al., 2006; Maltz & Shinar, 1999) and may fixate for longer durations (e.g., Scialfa & Joffe, 1997; Ho et al., 2001; cf. Veiel et al., 2006; Maltz & Shinar, 1999). These results are consistent with age-related reductions in the size of the useful field of view and slower processing speed, and it seemed possible that a similar pattern of results would be observed in the present study. However, in Experiment 2, when participants' goal was to maintain to-be-remembered locations rather than search for a target, no such differences in eye-movement behavior were observed. Thus, the age-related declines may be somewhat task dependent, and Experiment 2 suggests that there may not be any age-related differences in the rehearsal of locations.

5.3 Covert Visuospatial Rehearsal

The primary goal of Experiment 3 was to investigate the effects of environmental support and age on covert visuospatial rehearsal. In the other experiments presented here, as well as in Lilienthal et al. (2014a) and (2014b), participants were allowed to rehearse the to-be-remembered locations using overt eye movements, but it has been proposed that participants also can rehearse locations in the absence of such eye movements, through covert shifts of spatial attention (e.g., Awh et al., 1998). The relative effectiveness of the two rehearsal strategies has yet to be determined conclusively, as only a few previous studies' results can speak to the issue and conclusions based on those studies have been mixed (e.g., Lawrence et al., 2004; Pearson & Sahraie, 2003; Godijn & Theeuwes, 2012). In Experiment 3 of the present study, young and older adults were required to fixate on a central point during retention intervals, and it was hypothesized that if covert rehearsal is as effective as overt rehearsal, the pattern of results observed in Experiment 1 would be replicated. This was not the case, however, as participants' memory spans in Experiment 3 always were smaller when retention intervals were long than when intervals were short, regardless of whether environmental support was present or absent. These results indicate that when asked to remember a series of locations, participants who are limited to rehearsing through shifts of spatial attention are able to successfully maintain fewer locations than participants allowed to rehearse using eye movements.

Importantly, the results of Experiment 3 are not consistent with those reported by Godijn and Theeuwes (2012), the only other study to compare overt and covert visuospatial rehearsal. Godijn and Theeuwes found that participants' serial memory for locations was similar regardless of whether they were allowed to move their eyes freely or had to fixate on a single location during retention intervals, suggesting that overt and covert rehearsal may be equally effective. In the present study, not only did the pattern of results differ across overt and covert rehearsal conditions, but in addition overall memory performance was lower when participants were restricted to covert strategies: A planned independent-samples contrast comparing memory spans in Experiment 1 to those in Experiment 3 revealed a significant effect of experiment, $t(94) = 4.27$, $p < .001$. Thus, it seems that simply being required to fixate during a retention interval can disrupt memory, consistent with the idea that covert rehearsal is less effective than overt rehearsal.

The reasons for the inconsistency between Experiment 3 and Godijn and Theeuwes (2012) are unclear. There are a number of potentially important differences in the tasks that were used in the two studies, such as the fact that participants in Godijn and Theeuwes were required to recall locations in the correct serial order, whereas participants in the present experiments could recall locations in any order. Therefore, it is possible that in the present study, strategy differences other than the form of rehearsal (i.e., overt vs. covert) existed between Experiment 1 and Experiment 3. For example, perhaps participants in Experiment 1 were re-ordering the to-be-remembered locations to make them more meaningful in ways in which participants in Experiment 3 were not. It is also worth noting again that these are the only two studies that have attempted to investigate this issue, and in areas with such little research, inconsistencies are not uncommon; additional research regarding the relative effectiveness of overt vs. covert visuospatial rehearsal is needed in order for a consensus to be reached.

Importantly, Experiment 3 was the first to investigate older adults' ability to covertly rehearse locations. Although it has not been directly addressed previously in the literature, it seemed possible that older adults might have more difficulty using a covert rehearsal strategy than young adults. However, the results of Experiment 3 do not support that idea, as no interactions involving age were significant. In addition, although participants' spans in Experiment 3 were significantly smaller overall than in Experiment 1, a 2 (age group: young vs. old) x 2 (experiment: 1 vs. 3) ANOVA conducted revealed that the interaction between age group and experiment was not significant, $F(1, 92) = 1.05$, $p = .309$, indicating that requiring participants to fixate during retention intervals did not lower older adults' spans more than young adults' spans. Thus, it seems that young and older adults did not differ in their ability to rehearse locations using shifts of spatial attention. This is consistent with what has been observed in other studies using a spatial cueing paradigm (e.g., Folk & Hoyer, 1992; Greenwood et al. 1993); these studies have found that the costs and benefits associated with voluntarily shifting one's attention to a spatial cue are relatively similar across age, and the results of Experiment 3 suggest that the preserved efficiency of visuospatial attention extends to the rehearsal of locations. However, it is also important to keep in mind that although older adults may have been able to rehearse covertly as well as young adults, this rehearsal was not enough to prevent forgetting in either age group.

5.4 Conclusions

The three experiments in the present study explored a number of questions regarding visuospatial working memory and rehearsal, some for the first time. Experiment 1 demonstrated the robustness of the effects of environmental support on location memory span, replicating previous results using a different procedure. Experiment 1 also provided further evidence for decay in visuospatial working memory, and this is inconsistent with a number of theories of working memory that posit forgetting occurs only through interference or when attention is diverted. Experiment 2 was the first to investigate participants' eye-movement behavior during rehearsal across environmental-support conditions and across age, and a number of potential differences were ruled out; although some of the results were unexpected, they are certainly intriguing and inviting of future research. Contrary to the results of Godijn and Theeuwes (2012), the results of Experiment 3 suggest that covert visuospatial rehearsal (i.e., rehearsal performed through shifts of spatial attention) is not as effective as overt visuospatial rehearsal (i.e., rehearsal performed through eye movements). Experiment 3 was also the first to investigate potential age-related differences in covert visuospatial rehearsal, and the results suggest that none exist. Overall, the present experiments offer some interesting insights into visuospatial working memory, as the results provide support for the importance of environmental support, for a role of decay in visuospatial working memory, and for differences in effectiveness between the overt and covert rehearsal of locations. The present experiments also introduce a number of additional questions, as the results suggest that age-related differences in rehearsal cannot account for the differential decline observed in visuospatial working memory in other experiments, and so other potential differences (e.g., the accuracy of rehearsal, the contributions if individual differences in working memory capacity) will need to examined in future studies.

References

Abel, L. A., Troost, B. T., & Dell'Osso, L. F. (1983). The effects of age on normal saccadic characteristics and their variability. *Vision Research, 23*, 33-37.

Alloway, T. P., Gathercole, S. E., & Pickering, S. J. (2006). Verbal and visuospatial short-term and working memory in children: Are they separable? *Child Development, 77*, 1698-1716.

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.

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

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. A. Bower (Ed.), *Recent Advances in Learning and Motivation* (Vol. 8, pp. 47-89). New York: Academic Press.

Bailey, H., Dunlosky, J., & Hertzog, C. (2009). Does differential strategy use account for age-related deficits in working-memory performance? *Psychology and Aging, 42*, 82-92.

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.

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

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, & Cognition, 37,* 1302-1317.

Brandt, J., Spencer, M., & Folstein, M. (1988). The telephone interview for cognitive status. *Neuropsychiatry, Neuropsychology, and Behavioral Neurology, 1*, 111-117.

Brooks, L. R. (1968). Spatial and verbal components of the act of recall. *Canadian Journal of Psychology, 22*, 349-368.

Brown, G. D. A., Neath, I., & Chater, N. (2007). A temporal ratio model of memory. *Psychological Review, 114*, 539-576.

Buckner, R. L., & Tulving, E. (1995). Neuroimagining studies of memory: Theory and recent PET results. In F. Boller & J. Grafman (Eds.), *Handbook of Neuropsychology* (Vol. 10) (pp. 439-446). New York: Elsevier.

Cowan, N. (1999). An embedded-processes model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 62-101). Cambridge, England: Cambridge University Press.

Craik, F. I. M. (1983). On the transfer of information from temporary to permanent memory. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 302*, 341-359

Craik, F. I. M. (1986). A functional account of age differences in memory. In F. Klix & H. Hagendorf (Eds.), *Human memory and cognitive capabilities, mechanisms and performances* (pp. 409-422). North Holland: Elsevier.

Craik, F. I. M. (1994). Memory changes in normal aging. *Current Directions in Psychological Science, 3*, 155-158.

Craik, F. I. M., & Byrd, M. (1982). Aging and cognitive deficits: The role of attentional resources. In F. I. M. Craik and S. Trehub (Eds.) *Aging and cognitive processes* (pp. 191-211). Plenum Press: New York.

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

Craik, F. I. M., & McDowd, J. M. (1987). Age differences in recall and recognition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 13*, 474-479.

Craik, F. I. M. & Rabinowitz, J. C. (1985). The effects of presentation rate and encoding task on age-related memory deficits. *Journal of Gerontology*, *40*, 309-315.

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

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, *19*, 450-466.

de Renzi, E., & Nichelli, P. (1975). Verbal and non-verbal short-term memory impairment following hemispheric damage. *Cortex*, *11*, 341-354.

Dunlosky, J., & Hertzog, C. (2001). Measuring strategy producing during associative learning: The relative utility of concurrent versus retrospective reports. *Memory & Cognition, 29*, 247-253.

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.

Folk, C. L., & Hoyer, W. J. (1992). Aging and shifts of visual spatial attention. *Psychology and Aging, 7,* 453-465.

Gathercole, S. E. (1998). The development of memory. *Journal of Child Psychology and Psychiatry, 39*, 3-27.

Geng, J. J., Ruff, C. C., & Driver, J. (2008). Saccades to a remembered location elicit spatially specific activation in human retinotopic visual cortex. *Journal of Cognitive Neuroscience, 21*, 230-245.

Gilhooly, K. J., Wynn, V., Phillips, L. H., Logie, R. H., & Della Sala, S. (2002). Visuo-spatial and verbal working memory in the five-disc Tower of London task: An individual differences approach. *Thinking and Reasoning*, *8,* 165-178.

Godijn, R., & Theeuwes, J. (2012). Overt is no better than covert when rehearsing visuo-spatial information in working memory. *Memory & Cognition, 40*, 52-61.

Greenwood, P. M., Parasuraman, R., & Haxby, J. V. (1993). Changes in visuospatial attention over the adult lifespan. *Neuropsychologica, 31,* 471-485.

Hale, S., Myerson, J., Faust, M., & Fristoe, N. (1995). Converging evidence for domain-specific slowing from multiple non-lexical tasks and multiple analytic methods. *Journal of Gerontology: Psychological Sciences, 50B,* 202-211.

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.

Hartley, A. A. (1993). Evidence of the selective preservation of spatial selective attention in old age. *Psychology and Aging, 8,* 371-379.

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

Ho, G., Scialfa, C. T., Caird, J. K., & Graw, T. (2001). Visual search for traffic signs: The effects of clutter, luminance, and aging. *Human Factors, 43*, 194-207.

Hulme, C., Thomson, N., Muir, C., & Lawrence, A. (1984). Speech rate and the development of short-term memory span. *Journal of Experimental Child Psychology, 38*, 241-253.

Jenkins, L., Myerson, J., Joerding, J. A., & Hale, S. (2000). Converging evidence that visuospatial cognition is more age-sensitive than verbal cognition. *Psychology and Aging*, *15*, 157-175.

Just, M.A. & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review*, *99*, 122-149.

Kyllonen, P. C., & Stephens, D. L. (1990). Cognitive abilities as determinants of success in acquiring logic skill. *Learning and Individual Differences*, *2*, 129-160.

Kynette, D., Kemper, S., Norman, S., & Cheung, H. (1990). Adults' word recall and word recognition. *Experimental Aging Research, 16*, 117-121.

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.

Lawrence, B., Myerson, J., & Hale, S. (1998). Differential decline of verbal and visuospatial processing speed across the adult lifespan. *Aging, Neuropsychology, and Cognition*, *5,* 129-146.

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.

Lejbak, L., Crossley, M., & Vrbancic, M. (2011). A male advantage for spatial and object but not verbal working memory using the n-back task. *Brain and Cognition, 76,* 191-196.

Lilienthal, L., Hale, S., & Myerson, J. (2014a). Effects of environmental support and age on visuospatial working memory. *Presented at the biennial Cognitive Aging Conference, Atlanta, GA.*

Lilienthal, L., Hale, S., & Myerson, J. (2014b). The effects of environmental support and secondary tasks on visuospatial working memory. *Memory & Cognition, 42*, 1118-1129.

Lilienthal, L., Tamez, E., Myerson, J., & Hale, S. (2013). Predicting performance on the Raven's Matrices: The roles of associative learning and retrieval efficiency. *Journal of Cognitive Psychology, 25,* 706-716.

Logie, R. H. (1995). *Visuo-spatial Working Memory*. East Sussex, UK: Lawrence Erlbaum Associates.

Maltz, M., & Shinar, D. (1999). Eye movements of younger and older drivers. *Human Factors, 41*, 15-25.

McCabe, D. P. (2008). The role of covert retrieval in working memory span tasks: Evidence from delayed recall tests. *Journal of Memory and Language, 58*, 480-494.

Mercer, T. (2014). The loss of short-term visual representations over time: Decay or temporal distinctiveness? *Journal of Experimental Psychology: Human Perception and Performance, 40*, 2281-2288.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., & Howerter, A. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41,* 49-100.

Multhaup, K. S., Balota, D. A., & Cowan, N. (1996). Implications of aging, lexicality, and item length for the mechanisms underlying memory span. *Psychonomic Bulletin & Review, 3,* 112-120.

Munoz, D. P., Broughton, J. R., Goldring, J. E., & Armstrong, I. T. (1998). Age-related performance of human subjects on saccadic eye movement tasks. *Experimental Brain Research, 121*, 391-400.

Myerson, J., Emery, L., White, D. A., & Hale, S. (2003). Effects of age, domain, and processing demands on memory span: Evidence for differential decline. *Aging Neuropsychology and Cognition, 10*, 20-27.

Naveh-Benjamin, M. (2000). Adult age differences in memory performance: Tests of an associative deficit hypothesis. *Journal of Experimental Psychology: Learning, Memory, and Cognition,26*, 1170-1187.

Oberauer, K., & Lewandowsky, S. (2008). Forgetting in immediate serial recall: Decay, temporal distinctiveness, or interference? *Psychological Review, 115*, 544-576.

Oberauer, K., & Lewandowsky, S. (2013). Evidence against decay in verbal working memory. *Journal of Experimental Psychology: General, 142*, 380-411.

Park, D. C., Cherry, K. E., Smith, A. D., & Lafronza, V. N. (1990). Effects of distinctive context on memory for objects and their locations in young and elderly adults. *Psychology and Aging, 5*, 250-255.

Park, D. C., Lautenschlager, G., Hedden, T., Davidson, N. S., Smith, A. D., & Smith, P. K. (2002). Models of visuospatial and verbal memory across the adult life. *Psychology and Aging, 17*, 299-320.

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

Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology, 32,* 3-25.

Postle, B. R., & Hamidi, M. (2007). Nonvisual codes and nonvisual brain areas support visual working memory. *Cerebral Cortex, 17*, 2151-2162.

Ricker, T. J., Spiegel, L. R., & Cowan, N. (2014). *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*, 1510-1523.

Salthouse, T. A. (1994). The nature of the influences of speed on adult age differences in cognition. *Developmental Psychology, 30*, 240-259.

Salthouse, T. A. (1996a). General and specific speed mediation of adult age differences in memory. *Journal of Gerontology, 51B,* 30-42.

Salthouse, T. A. (1996b). The processing-speed theory of adult age differences in cognition. *Psychological Review*, *103*, 403-428.

Salthouse, T. A. (2010). Selective review of cognitive aging. *Journal of the International Neuropsychological Society*, 16, 754-760.

Salthouse, T. A., Atkinson, T. M., & Berish, D. E. (2003). Executive functioning as a potential mediator of age-related cognitive decline in normal adults. *Journal of Experimental Psychology: General*, *132*, 566-594.

Scialfa, C. T., & Joffe, K. M. (1997). Age differences in feature and conjunction search: Implications for theories of visual search and generalized slowing. *Aging, Neuropsychology, and Cognition, 4*, 227-246.

Scialfa, C. T., Thomas, D. M., & Joffe, K. M. (1994). Age differences in the useful field of view: An eye movement analysis. *Optometry and Vision Science, 12*, 736-742.

Sharps, M. J., & Gollin, E. S. (1987). Memory for object locations in young and elderly adults. *Journal of Gerontology, 42*, 336-341.

Smith, A. D., Park, D. C., Cherry, K., & Berkovsky, K. (1990). Age differences in memory for concrete and abstract pictures. *Journal of Gerontology: Psychological Sciences, 45*, 205-209.

Smith, B. L., Wasowicz, J., & Preston, J. (1987). Temporal characteristics of the speech of normal elderly adults. *Journal of Speech and Hearing Research, 30*, 522-529.

Smith, E. E., & Jonides, J. (1997). Working memory: A view from neuroimaging. *Cognitive Psychology, 33*, 5-42.

Smith, E. E., Jonides, J., & Koeppe, R. A. (1996). Dissociating verbal and spatial working memory using PET. *Cerebral Cortex, 6*, 11-20.

Smyth, M. M., & Scholey, K. A. (1994). Interference in immediate spatial memory. *Memory & Cognition, 22*, 1-13.

Souza, A. S., & Oberauer, K. (2015). Time-based forgetting in visual working memory reflects temporal distinctiveness, not decay. *Psychonomic Bulletin and Review, 22*, 156-162.

Spooner, J. W., Sakala, S. M., & Baloh, R. W. (1980). Effect of aging on eye tracking. *Archives of Neurology, 37*, 575-576.

Tan, L., & Ward, G. (2000). A recency-based account of the primacy effect in free recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26,* 1589-1625.

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.

Unsworth, N., & Engle, R. W. (2007a). The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory. *Psychological Review, 114*, 104-132.

Unsworth, N., & Engle, R. W. (2007b). On the division of short-term and working memory: An examination of simple and complex span and their relation to higher order abilities. *Psychological Bulletin*, *133*, 1038-1066.

Vecchi, T., & Girelli, L. (1998). Gender differences in visuo-spatial processing: The importance of distinguishing between passive storage and active manipulation. *Acta Psychologica, 99*, 1-16.

Veiel, L. L., Storandt, M., & Abrams, R. A. (2006). Visual search for change in older adults. *Psychology and Aging, 21*, 754-762.

Warabi, T., Kase, M., & Kato, T. (1984). Effect of aging on the accuracy of visually guided saccadic eye movement. *Annals of Neurology, 16*, 449-454.