Grouping effects in spatial short-term memory

by

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Abstract

Spatial short-term memory is the mental system for internally representing object locations, and keeping this type of information accessible for further cognitive processing. The present research identified factors that influence people's ability to encode and retain spatial information. In a series of four experiments using a spatial span (Corsi Blocks) task, university students ($n = 116$) viewed and reproduced sequences of locations. Contrary to extant findings from verbal serial recall, increasing the retention interval did not impair accuracy (Experiment 2), and inserting a pause between groups of locations during presentation did not yield an accuracy advantage (Experiment 4). Instead, two types of grouping during the encoding phase enhanced participants' accuracy on the span task. Participants who reported that they used *strategic grouping* to encode the sequences in two or more parts scored higher on the spatial span task than those who preferred other strategies (Experiments 1 - 3). *Perceptual grouping* related to characteristics of the sequences also enhanced accuracy, and did not depend on participants' efforts to parse the sequences. Spatially separable sequences that could be represented as two, nonoverlapping shapes were better recalled than those with more complex path configurations (Experiments 3 and 4).

Three encoding strategies were identified through participants' self-reports. Strategy selection was adaptive in that it varied systematically with problem difficulty. Multiple executive processes were implicated in performance of the spatial span task. The executive processes investigated in the present research were those dedicated to

coordinating multiple tasks, maintaining serial position information, and strategy selection. As executive demands of the experimental tasks increased, participants were less able to manage task demands, made more errors in recalling serial positions, and were less able to select strategies adaptively. Cognitive models developed to explain verbal serial memory did not account for spatial memory phenomena. When performing spatial span tasks, participants recruited diverse representations and processes. Cognitive models of spatial memory will need to include processes that are flexibly recruited based on characteristics of individuals and of the problems that are presented.

Keywords: chunking, Corsi Blocks, grouping effects, spatial short-term memory, spatial span, temporal grouping, working memory

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Chapter 1

Spatial short-term memory is the mental system for internally representing object locations, and keeping this type of information accessible for further cognitive processing. People use this system when performing complex cognitive tasks, such as navigating in the world and interacting with computers. These complex cognitive tasks require people to retain and transform multiple pieces of information in a mental workspace that has often been referred to as working memory (e.g., Baddeley & Hitch, 1974). Humans are limited in the amount of information that they can simultaneously process, and these limitations affect the types of problems that can be solved in real-time. The ability to temporarily store information has been studied extensively using memory tasks in the laboratory. The bulk of memory research has been conducted with letters, digits, and other verbal items, dating back at least to the self-studies of Ebbinghaus in the 1880s (republished in Ebbinghaus, 1964). In contrast, spatial memory is a relatively young research area. This area has seen a surge of interest in the past 15 years, with the elaboration of models of specialized mental systems for spatial memory (e.g., Logie, 1995). Despite this surge of interest, the cognitive mechanisms supporting spatial memory remain poorly understood.

The goal of the present research was to explore factors that influence how people encode and retain spatial information over short periods of time. Based on a review of the literature, I hypothesized that people could augment their memory performance by chunking locations into groups. Chunking has been shown to increase the amount of information an individual can process by compressing more information into each unit that is represented in memory (Gobet et al., 2001). By using chunking,

people have been trained to process longer sequences of words, and more complex visual patterns of chess pieces (Chase & Ericsson, 1982; Chase & Simon, 1973). In the context of the present research, chunking was referred to as *strategic grouping*. A second, *perceptual grouping* process was proposed to explain how locations tend to be encoded into groups based on proximity and closure, independent of the strategies that people apply in performing spatial memory tasks. Identifying variables that affect spatial memory will contribute to our ability to train people to process spatial information, and to present information in ways that take advantage of the human cognitive system's tendencies to group visual items.

A serial recall task was selected to test hypotheses related to processes underlying spatial memory. In this task, sequences of locations were shown on a computer screen and participants reproduced the sequences by pointing. This task was originally developed by Corsi (1972) as a nonverbal analogue to Hebb's digit span test (Hebb, 1961). Corsi used wooden blocks fixed in a nonsymmetrical arrangement on a board, similar to the layout shown in Appendix A-1. The blocks could only be distinguished by their location, so verbal recoding of the items was assumed to be minimized. The Corsi Blocks test, also referred to as the spatial span task in the present paper, has been widely used in clinical assessment and to explore models of short-term memory (e.g., De Renzi & Nichelli, 1975; Hanley, Young, & Pearson, 1991; Smyth & Scholey, 1992, 1994b). In particular, the task has been used to estimate the capacity of a specialized visuospatial store. However, it should be noted that there has been lack of agreement as to what processes are tapped by the spatial span task.

For verbal span tasks, a useful distinction has been made between short-term memory (STM) and working memory (WM) tasks (Daneman & Merikle, 1996; Kail & Hall, 2001). In a short-term memory task, participants store and reproduce a series of items. In the forward digit span task, for example, participants view or hear a list of digits, and repeat them back to the experimenter. The number of digits is increased until the participant is unsuccessful on a predetermined number of trials, at which point testing is discontinued (Dempster, 1981). In a working memory task, people engage in concurrent processing while also storing a series of items. In the reading span task, for example, participants make simple judgments about sentences, and also remember sentence-final words (Daneman & Carpenter, 1980). Working memory span tasks are thought to estimate storage plus processing. They are better predictors of higher cognitive functioning than simpler, STM span tasks, presumably because complex cognitive activities, such as understanding a text, require both storage and processing (Daneman & Merikle, 1996).

In the present paper, tasks that explicitly require concurrent processing were referred to as working memory tasks, whereas tasks that do not were referred to as short-term memory tasks, consistent with the terminology adopted by many other researchers (e.g., Daneman & Merikle, 1996; Kail & Hall, 2001; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). The spatial span task used in the present research has sometimes been classified as a measure of short-term memory when included in a set of tasks that were intended to tap both spatial short-term and working memory (e.g., Miyake et al., 2001) because it does not require participants to process the locations, for

example by judging some aspect of the stimuli or transforming them. However, other researchers have used the spatial span task as a measure of spatial working memory (Kemps, De Rammelaere, & Desmet, 2000; Mammarella, Cornoldi, & Donadello, 2003). Whether the spatial span task is more like a short-term or a working memory task depends partly on how people execute the task. This issue will be revisited in Chapter 5 in light of the data on the variation in strategies reported by participants.

In this thesis, I will examine some of the factors that influence spatial short-term memory performance. The general approach was to manipulate variables that are known to affect verbal short-term memory performance, such as item familiarity and timing of presentation. To the extent that these variables have similar effects for spatial materials, verbal and spatial memory would appear to be served by common mechanisms, or parallel mechanisms within specialized subsystems. The results will shed light on the structure of working memory, on grouping processes in spatial memory, and on the role of strategies in spatial memory performance.

To establish a context for the present research, a models of short-term memory were reviewed, focusing on spatial memory and the effects of strategies and grouping on performance. I first review the evidence for multiple codes and multiple stores in memory, as my research begins from the hypothesis that spatial information is processed differently from verbal information. Second, I review the literature on chunking in memory tasks, and propose that similar mechanisms underlie chunking in verbal and spatial memory. Third, I discuss models of serial memory and their predictions related to performance on the spatial span task.

1.1 Multiple codes and multiple stores in memory

The notion that verbal and visuospatial information are coded, processed, and stored separately is fundamental to several models of memory (Baddeley & Logie, 1999; Paivio & Csapo, 1973), and is supported by a large empirical literature on memory functioning in normal adults and neurologically impaired patients (e.g., De Renzi & Nichelli, 1975; Hanley, Young, & Pearson, 1991; Logie, Zucco, & Baddeley, 1990). In the encoding stage, it is clear that visual and auditory stimuli are handled differently because these stimuli are processed by specialized sense organs. In the earliest stage of processing, termed sensory memory, representations are maintained for a short period of time during which they can be further sampled and processed. The difference in durability of visual (“iconic”) versus auditory (“echoic”) representations strongly supports the use of code-specific stores in sensory memory. Iconic representations last for approximately 150 to 250 ms (Sperling, 1960). Echoic representations last for approximately 2 seconds (Crowder & Morton, 1969) or more: parts of the auditory trace may be available for as long as 20 seconds (Watkins & Todres, 1980; Watkins & Watkins, 1980). Thus, at the perceptual level, different codes are involved in verbal and spatial memory tasks.

The present research is concerned with the codes that are used after information is extracted from sensory memory, in the system termed short-term memory (STM). This system functions to maintain representations over several seconds, and is necessary for keeping multiple pieces of information active so that they may be integrated. The short-term memory system has been conceptualized in the context of many models of

memory (Atkinson & Shiffrin, 1968; Baddeley & Hitch, 1974), and has the following general characteristics: 1) limited capacity; 2) limited duration; 3) mechanisms for keeping information active; and 4) connection to long-term memory. Whether STM handles multiple codes or a single code has been a matter of debate for several decades. STM has been investigated using a wide range of tasks that require people to keep multiple pieces of information active for a short period of time, usually in the range of 1 to 30 seconds.

According to some models of memory, such as the multicomponent model of working memory (Baddeley & Logie, 1999), human memory relies on specialized subsystems for processing verbal and visuospatial codes in two, separate short-term memory stores. There is a great deal of evidence that functionally distinct subsystems are used to process verbal versus visual information (Logie, 1995; Shah & Miyake, 1996; Smith, Jonides, & Koeppel, 1996). However, some theorists argue that separate subsystems could operate over a single type of code that is semantic or abstract (Anderson, 1983; Pylyshyn, 1973, 1981; Jones, Farrand, Stuart, & Morris, 1995). The appeal of a single-code theory is that it avoids the binding problem: whenever information about an object is split, it must later be reintegrated, for example, the location and name of an object may both be necessary for an appropriate response to be generated. In general, abstract code theorists like Pylyshyn deny that visuospatial representations retain any analog properties of the objects being represented. Although a discussion of the mental imagery debate will not be pursued here, it is worth noting that many psychologists accept that at least some analog properties of the visual scene

are mentally represented, based on the compelling data from mental scanning and rotation experiments provided by Kosslyn and his colleagues (see Kosslyn, 1994, for a review). There is some consensus that visual representations are used in conjunction with verbal information.

To assess the types of representations that are used in short-term memory, researchers have compared performance on tasks in which items were presented in different modalities, for example, visually versus auditorily. The vast majority of these studies used letters or digits, and estimated short-term memory capacity as span, the longest sequence that an individual could remember. If separate short-term stores are used to maintain verbal and visuospatial representations, then recall should be affected by the modality of the list items. For example, if lists of letters are rehearsed subvocally in a specialized “phonological loop”, a speech-based rehearsal mechanism, as proposed by Baddeley and colleagues, then errors in recall should increase when the letters are phonologically confusable. Phonological confusions are indeed the most common error type in a letter span task, even when items are visually presented to adults¹ (Conrad & Hull, 1964). The phonemic similarity effect refers to the finding that short-term memory for sequences with similar speech sounds, such as BTCVDG, is poorer than memory for dissimilar sequences, such as FKRWYQ (Conrad, Freeman, & Hull, 1965). Few studies have examined similarity effects using a visuospatial span task, but there is some recent evidence that recognition performance decreases as the similarity of the

¹ For young children, the presentation of visually similar letters also leads to confusion in STM (Walker, Hitch, Doyle, & Porter, 1994), presumably because the children (aged 5) relied heavily on visual features to temporarily store letters, as they have little practice at rehearsing the sounds associated with letters.

images in the sequence increases (Avons & Mason, 1999; Walker, Hitch & Duroe, 1993). These error patterns suggest code-specific interference in STM.

To frame the present research, a multiple-code model was adopted, with recognition that single-code models may also prove useful in understanding spatial memory performance. An example of a single-code view that was useful in conceptualizing the present research is proceduralism. The proceduralist view of memory (Crowder, 1993a; Jones et al., 1995; Kolers & Roediger, 1984; Roediger, Gallo, & Geraci, 2002), assumes that serial order is maintained by the same cognitive resources for all information types, and denies the existence of code-specific stores, buffers, or processes. According to proceduralism, recall is related to the way that items are encoded and to the cues that are present at retrieval. This general statement captures the main findings in cognitive psychology related to transfer-appropriate processing: information is more accurately retrieved when the cues at retrieval match those that were present at encoding (Fendrich, 1998; Graf & Ryan, 1990; Morris, Bransford, & Franks, 1977). Proceduralism also predicts that one way to enhance retrieval is to elaborate on the items during encoding, for example, by associating the items with stored patterns in long-term memory. When elaborative encoding is used, more pathways to the correct information are activated. Thus, “deeper processing” increases the probability of retrieval (Craik & Lockhart, 1972). In the context of the present research, proceduralism predicts that long-term memory (LTM) can be leveraged to enhance short-term memory performance, and in particular that activities during encoding of sequences will predict the probability of recall.

Proceduralism predicts that performance on a spatial span task should share many characteristics with performance on a verbal span task because the same processes operate over all information types (cf. Jones et al., 1995). For example, the serial position curves observed in memory for verbal lists should be observed for spatial sequences as well. On the proceduralist view, there is no need to posit short-term stores with limited capacity. In the context of STM and WM tasks, apparent capacity limits emerge when people try to reproduce sequences of increasing length. Despite successful encoding of a sequence, a person may be unable to retrieve the correct sequence due to various types of interference that occur within trials and over a series of trials. Interference occurs when two tasks require common processes, not common memory stores.

Although the proceduralist view is useful as a framework for relating memory performance to encoding activities, it is limited in terms of generating testable predictions. The multiple-code working memory model is much stronger in this respect. Perhaps owing much of its success to its testability, it has become the dominant model in research on short-term memory for nearly 30 years. The present research assumes a multiple-code model, similar to that elaborated by Baddeley and colleagues (e.g., Baddeley & Logie, 1999), with dedicated memory resources for handling spatial (location) information, functionally distinct from the resources that are specialized for handling verbal information. The main advantage of the working memory model is that it generates more specific predictions than those offered by a proceduralist view. Where the proceduralist view proposes that encoding activities affect recall, the

working memory model specifies how encoding activities affect recall, namely via coordinated activities in memory subsystems. It will be argued that spatial short-term memory performance must be explained in relation to the use of differentiated executive control processes, which are involved in mental imagery and are responsible for the generation, execution, and monitoring of strategies.

Code-specific memory stores are assumed in the working memory model proposed by Baddeley and Hitch (1974) and later elaborated by Baddeley (1986) and Logie (1995). The working memory model (Baddeley, 1986) comprised three components: a central executive for supervisory functions, a phonological loop (PL) for processing speech items, and a visuospatial sketch pad (VSSP) for processing visual and spatial information. Among its many functions, which will be described below, the central executive allocates attention to the two specialized subsystems. Logie (1995) proposed that the two subsystems each comprise separate storage and rehearsal mechanisms. Studies on the operation of the phonological loop support the existence of a store and a rehearsal mechanism (Baddeley, 1986). The limits on phonological STM have been related to word length and list length, presumably because the rate of covert articulation limits how many items can be rehearsed within a fixed window of time. The word length effect refers to the finding that when items are equated for meaning and word frequency, if one set takes a shorter time to pronounce, memory will be better for the shorter items (Baddeley, Thomson, & Buchanan, 1975; Ellis & Hennelly, 1980).

The process of covertly articulating letters or words is well-practiced, and occurs with little involvement of executive processes. Thus, it has been possible to devise a

task called articulatory suppression to selectively engage the phonological loop without interfering with other memory processes. In the articulatory suppression task, participants repeat a word (e.g., “the, the, the....”). This task has been widely used in research on verbal memory to test whether the phonological loop is involved in specific cognitive tasks. For example, the finding that articulation suppression impaired mental addition supported the hypothesis that people use verbal codes when performing mental arithmetic (Logie, Gilhooly, & Wynn, 1994).

Given the wealth of data available on verbal span performance, and how verbal span is affected by item-related variables (e.g., length, confusability) and secondary tasks, various researchers have tried to apply the dual-task approach to investigate the structure of a specialized store for visuospatial memory (Jones et al., 1995; Logie & Marchetti, 1991; Smyth & Scholey, 1992, 1994b). However, these efforts have been hampered in two ways: 1) the limits of the visuospatial scratch pad (VSSP) and the mechanisms for spatial rehearsal are poorly specified, and 2) no task that engages spatial memory without engaging other memory systems has been developed. Logie (1995) proposed that the VSSP includes a passive visual cache for information such as pattern and color, and a dynamic mechanism, the inner scribe, for information such as location. Movement information is also linked to the inner scribe, but it is unclear how movements are represented. Logie (1995; Logie, Zucco, & Baddeley, 1990) explicitly connected the construct of the VSSP to the visual buffer proposed by Kosslyn (1980, 1984), who elaborated a model of mental imagery processes. Logie and Kosslyn agree that mental images are maintained in a visual cache or buffer. In order to maintain

mental images over time, rehearsal processes (termed “generate/regenerate” processes by Kosslyn, 1980) operate on the contents of a visual buffer. Rehearsal processes are sequential: parts of the image are generated in a particular order (Kosslyn, Cave, Provost, & von Gierken, 1988). According to Logie (1995), “An emergent property of such a sequential process is that it could retain movement sequences” (p. 130).

According to this view, rehearsal of visuospatial information, such as locations, involves refreshing the contents of a visual cache or buffer. More recently, Logie and colleagues specified that the VSSP serves as a workspace for the transformation of spatial information (Logie, Englekamp, Dehn, & Rudkin, 2001). Other models of visuospatial cognition also posit a buffer where representations are transformed, as in Kosslyn’s (1994) visual buffer for mental images. Although there is some agreement about the properties of the visual cache or buffer, its capacity and how it represents spatial information, such as movements, are still poorly specified at this stage of research.

There is some evidence that the visuospatial system can usefully be fractionated into two systems, one that handles static and another that handles dynamic information. For example, the fractionation of the visuospatial sketch pad (VSSP) into two subsystems for visual and spatial information has been supported empirically (Logie, 1995; Logie, & Marchetti, 1991; Logie & Pearson, 1997; Vecchi & Cornoldi, 1999). The multicomponent model predicts that tasks that use common resources will interfere with each other, and that performance will be impaired on one or both of the tasks. Tasks that use separate resources can be executed concurrently with only a small

concurrency cost. In the dual-task literature, the task of interest is referred to as the primary task, and the interference task as the secondary or load task. In many dual-task studies of short-term memory, a secondary task was imposed between the presentation and recall of items. Visual tasks and primary spatial tasks were differently impaired by load tasks that varied in their visual and spatial demands (Della Sala, Gray, Baddeley, Allmano, & Wilson, 1999; Logie & Marchetti, 1991; Logie, Zucco, & Baddeley, 1990). For example, Logie and Marchetti (1991) examined the effects of a spatial tapping task and the presentation of irrelevant pictures on visual and spatial short-term memory. They found that visual memory was impaired by the viewing of irrelevant pictures, but not by a spatial tapping task. In the same experiment, spatial memory was impaired by tapping, but not by irrelevant pictures, revealing a classic double dissociation that supports the presence of functionally distinct subsystems in short-term memory.

Mechanisms for spatial rehearsal are poorly specified despite a variety of efforts over the past 15 years to explore spatial working memory using the dual-task methodology (Logie & Marchetti, 1991; Logie, Zucco, & Baddeley, 1990; Morris, 1987; Smyth, 1996; Smyth & Pendleton, 1990; Smyth & Scholey, 1994b; Zimmer, 1996). According to Baddeley (1986), rehearsal of both phonological and visuospatial items occurs via control processes that “allow the transformation of a passive perceptual store into an active memory system that enables the organism to take information out of the relevant input store and to feed it back, thereby continuously refreshing the trace and minimising forgetting” (pp. 121-122). The process of refreshing the trace is efficient for speech items. In contrast, refreshing of the visual trace is effortful and requires

executive control. There are no secondary visual tasks that do not tap into executive processes, and this situation presents some difficulty for dual-task researchers who wish to isolate relative contributions of working memory components to task performance (cf. Miyake et al., 2001).

Baddeley (1986) proposed that spatial rehearsal relied on covert movements, such as eye movements. Based on this analogy, a length effect was predicted in visuospatial STM, such that for movements over longer distances, fewer movements (and thus fewer consecutive locations) could be retained in a STM span task. However, empirical attempts to verify this hypothesis have been unsuccessful (Smyth & Scholey, 1992, 1994a). The limits of visual STM may be related not just to the number of items that can be stored, but also to the amount of information needed to represent each item (Kosslyn, 1980). In contrast to visual representations, phonological representations retain temporal properties in that the phonemes are stored in a certain order and longer words are represented in memory with a greater number of phonemes. For the location sequences that were used in the present research, it seemed likely that people would represent the sequences using visualization, and thus the complexity of the images that need to be maintained in memory would help to predict the difficulty of individual sequences.

In summary, a multiple-code working memory model was adopted in the present thesis, because there exists ample evidence for code-specific processing in short-term memory tasks, such as span tasks. Of particular interest to the present research, verbal and spatial rehearsal in short-term memory operate differently. Covert articulation of

verbal items is well-practiced and requires little executive processing, whereas spatial rehearsal requires executive control to refresh the contents of a visual cache or buffer. Longer words take longer to rehearse, whereas longer distances between spatial locations do not take more resources to rehearse. The nature of spatial rehearsal will be explored in the present research by examining how people attempt to rehearse sequences while performing a spatial span task.

1.2 Chunking in memory

Chunking items into units that contain more information than individually coded items is a way to increase the amount of information that can be processed simultaneously and is thus critical to any complex cognitive task (Gobet et al., 2001). Examples of chunking include recoding a group of letters as a word, and recoding a string of digits using a verbal code. Digits could be named in groupings, for example, “3, 5” as “thirty-five”, or associated with a meaningful label, for example “9, 1, 1” as “emergency number.” Miller (1956) introduced the notion of the chunk in his classic paper on the limits of human information processing. Miller proposed that working memory holds seven plus or minus two chunks, and what the chunks contain will depend on how the individual organizes the information. Since that time, various computational models of human information processing, such as ACT-R (Anderson & Lebiere, 1998) and CHREST (Gobet & Simon, 2000), have included mechanisms for chunking information. For example, the CHREST model represents chunks as patterns stored in long-term memory (Gobet et al., 2001). In order to maintain sequences of items in the limited-

capacity short-term memory, the STM component of the CHREST model contains pointers to chunks in longer-term memory. This model makes explicit the procedure for using “pointers to long-term memory” described by Ericsson, Kinstch, and colleagues (Ericsson & Delaney, 1999; Ericsson & Kintsch, 1995) in their long-term working memory (LT-WM) model.

According to the LT-WM model, experts show superior recall for practiced materials because they use specialized retrieval structures that have been developed through an effortful learning process. Ericsson and colleagues studied expert memory, which they previously referred to as skilled memory (Chase & Ericsson, 1981), in several domains. In one set of studies, participants received extensive practice on a verbal digit span task (Chase & Ericsson, 1982). Using prior knowledge as a base, the participants recoded the digits into groups and created associations between these number groups and running times (e.g., “408” was encoded by one participant as “8 seconds away from a four-minute mile”). The participants reported encoding relations at multiple levels, for example, the first two digit groups as mile times and the second two as marathon times. Using recoding in the digit span task, participants were able to increase their digit span from less than 10 to more than 20 after 50 hours of practice. With additional practice, two participants were able to recall sequences longer than 80 digits (Chase & Ericsson, 1982). The increase in digit span did not transfer to enhanced short-term memory for other types of materials, such as consonants. One individual in their study who learned to retain strings of 80 digits could only retain six consonants in order. When people work with specific materials, they develop memory skills for those

materials. They are better at grouping these materials at encoding, and have practiced connecting groups of items to stored patterns in long-term memory.

Ericsson and colleagues argued that augmenting memory performance requires effort: “these [memory] skills are not automatically acquired as a consequence of experience with the task” (Ericsson & Delaney, 1999, p. 277). The digit span experts improved because they leveraged an elaborate and stable semantic representation whose meaningfulness was defined by a domain of expertise (i.e., running). In the same manner, chess experts make use of a well-developed retrieval structure, a stored representation of the board. When presented with patterns of pieces, items are encoded into the retrieval structure. Chase and Simon (1973) studied the effects of expertise on short-term memory for configurations of chess pieces. Chess experts can remember approximately 20 positions if the pieces are arranged in configurations found in actual games, also show some memory advantage for randomly placed positions (Gobet & Simon, 1996). Experts show a significant memory advantage over novice players, who can only remember about 5 positions in the context of a visual STM task. For both digit span and chess experts, what is critical to the expert’s memory advantage is the time spent learning retrieval structures and the time spent encoding the stimuli with elaborative cues (Chase & Ericsson, 1982; Staszewski, 1990).

In single-session tests of memory span for digits and words, participants have also been successfully trained to increase their span by applying strategies (Hockey, 1973; McNamara & Scott, 2001), though with much smaller gains than those obtained via extensive training. McNamara and Scott (2001) tested memory span for words that

were presented on a computer screen, one at a time. Participants in one condition (Experiment 1) received three training sessions in which they practiced chaining the words. They were asked to create stories with interrelated sentences, and subsequently, to produce the target words in the correct order. The story-chaining strategy led to increases in STM performance. Participants who were tested on the same word lists an equal number of times but without story-chaining instructions showed no improvement in memory span.

Hockey (1973) showed that instructing participants to use a grouping strategy for digits helped when participants were given longer encoding times. He tested memory for auditorily presented digit sequences. He instructed half of the participants to try to group the digits during encoding, and varied the rate of presentation (1, 2, or 3 items per second). There was no overall effect of strategy group due to a crossover interaction between strategy group and presentation rate. For participants who were instructed to group the digits, accuracy decreased as rate of presentation increased (i.e., trying to group the digits resulted in worse performance when the digits were presented rapidly). For those who were instructed to listen passively, accuracy increased as presentation rate increased. Thus, longer encoding times enhanced recall when participants were instructed to group the stimuli. Fischer (2001) used a between-subjects design to compare performance on the Corsi Blocks test in two conditions: each location was presented for 1 second or for 3 seconds. He found that longer encoding times of 3 seconds per item produced better recall than the standard, 1 second

per item. Participants may be able to group locations given additional time during encoding, perhaps by associating the groups with familiar shapes.

Kemps (2001) also provided evidence that long-term memory was leveraged in the spatial span task. She compared recall of spatial sequences that were structured versus “complex” (i.e., less structured), and found that recall was more accurate for structured sequences. One feature of the structured sequences was that they sometimes comprised two symmetrical parts when visualized, with the second part rotated. By coding the information that the sequence was symmetrical, participants may have been able to correctly reproduce the sequence without remembering all the locations. Instead, they could remember the first part, that the sequence was symmetrical, and the spatial orientation of the second part. Thus, they could potentially reconstruct the sequence using a set of pointers stored in short-term memory, rather than individual locations stored in short-term memory, resulting in decreased memory load and an increase in memory span.

In sum, an effortful process of chunking has been shown to benefit short-term memory performance for verbal materials, such as digits, and for visual patterns, such as chessboard configurations. It is proposed that people can develop specialized retrieval structures for locations, and that by encoding locations into stored retrieval structures, they will be able to augment their spatial span. This hypothesis related to strategic grouping was tested in Experiment 1.

1.3 Memory for serial order

The study of how we remember the order of events has a long history in psychological research. Many computational models (Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1999; Lewandowsky & Murdock, 1989; Nairne, Neath, Serra, & Byun, 1997) have been developed to explain aspects of serial memory performance, such as the primacy and recency effects, which refer to enhanced recall for events or items near the beginnings and ends of sequences, respectively. These models were developed based on data from verbal tasks, and some attempts have been made to extend these models to memory for locations (e.g., Smyth & Scholey, 1996a). The perturbation model developed by Estes (1972, 1997) accounts for a wide range of data (see Brown, 1997, and Neath & Surprenant, 2003, for reviews of models of serial order) and will be described in some detail in order to generate predictions about spatial serial recall. Studies that focused on how grouping influences recall will be reviewed, as these are of particular relevance to the present research.

Models of serial memory seek to explain how we keep track of the order of events. The present discussion will be limited to memory for items presented in rapid succession in the laboratory, and will not include a discussion of memory for the order of events in autobiographical memory. Serial memory experiments have traditionally used verbal items, such as words, letters, or digits. The probability of recalling an item at its correct serial position depends on many variables, including task characteristics such as recall requirements (e.g., report the whole sequence vs. probed recall for a single position). The extant data are complex and none of the proposed models

correctly predict the range of effects that have been observed, for example, the effects of continuous distractors that will be described below.

One class of models proposes that sequences are stored as chains of associations between successive items, such that retrieval of one item triggers retrieval of the next item. An example is the chaining model called TODAM (Theory Of Distributed Associative Memory) outlined by Lewandowsky and Murdock (1989). However, it seems clear that chaining mechanisms cannot explain the basic finding that retrieval of an item can occur without successful retrieval of the preceding item (Ladd & Woodworth, 1911). Modifications to chaining models have been proposed to deal with this problem. Lewandowsky and Murdock (1989) suggested that for the sequence A B C, A might lead to the retrieval of a partial representation of B, and even if B was not successfully output, this partial representation of B could be used as a probe for the correct retrieval of C. Notwithstanding these modifications, TODAM and other chaining models make predictions that have been disconfirmed experimentally (e.g., Henson, Norris, Page, & Baddeley, 1996), and so have been less developed than other classes of models.

A second class of models proposes that sequences are represented as associations between items and their temporal positions. In some models, items are encoded with temporal tags (Brown, Vousden, McCormack, & Hulme, 1999). Early proposals suggested that temporal tags used verbal codes (e.g., Healy, 1974), but it is currently believed that temporal tags can be implemented in diverse ways, and that the codes used vary with the type of information in the sequence, such that codes for letters

and musical tones would be implemented and organized differently (McNicol & Heathcote, 1986). Examples of models that propose some type of temporal tagging are OSCAR (Brown et al., 2000) and the perturbation model (Estes, 1972, 1997).

Computational models have specified how an item could be associated with its temporal position. Brown et al. (2000) described an oscillator mechanism that provides a context signal that varies over time. Brown et al. compared the context signal to the hands of a clock moving over time. In a serial memory task, each presented item is associated with the positions of the clock hands at the time of presentation. At recall, participants run the clock forward from its starting point and items associated with the different temporal positions are retrieved in the correct order. Associations are learned via a simple, Hebbian-type learning mechanism. Recall involves reinstatement of successive states of the context signal. In OSCAR, the context signal is implemented using an array of oscillators of different frequencies. In modeling development of verbal memory span, Brown et al. proposed that adults exhibit greater precision in encoding items as temporally distinct (i.e., their oscillators have higher frequencies), whereas children are less able to represent temporal information precisely. OSCAR predicts that swapping of adjacent items will be the most common error type, because when the third context signal is activated, for example, the items associated with the second and third context signals will also receive partial activation (Brown, 1997). Similarity between items increases the probability of confusion due to the overlap in features between list items.

Estes (1972, 1997; Lee & Estes, 1977, 1981) also proposed that events are associated with their temporal context during encoding. People encode associations between items and positions, and these associations are rehearsed in order. Due to random variations in the timing process, like “noise” in the system, on each cycle of rehearsal, there is some probability that the rehearsals will occur in an incorrect order, and that neighboring associations will be swapped. This process of swapping was named “perturbation.” According to the perturbation model, both primacy and recency are attributed to the fact that the first and last associations can only perturb in one direction, and so the probability of error is smaller for these two positions. Primacy and recency are modeled in a very simple way as emerging from a perturbation process that is not consciously controlled. However, there is no reason that the basic perturbation model cannot be expanded by positing conscious rehearsal processes. Cunningham, Healy, and Williams (1984), in their interpretation of an early version of the perturbation model (Lee & Estes, 1981), claimed that active rehearsal “crystallizes the memory structure and makes perturbations less likely” (p. 575). According to the interpretation of the model provided by Healy and colleagues (e.g., Healy, Cunningham, & Parker, 2002), the codes for item-position associations undergo repeated activations, and these activations (i.e., rehearsals) continue throughout the output process. In the context of the present research, I hypothesized that repeated activations would benefit recall, but noted that they also engender more opportunities for perturbations to occur.

The perturbation model nicely accounts for much of the performance data in serial recall (Neath & Surprenant, 2003). The model predicts that the most common

confusions will be between items that are presented consecutively. Error patterns in verbal serial recall show that when items appear at an incorrect location in the sequence, they most frequently appear at an adjacent location (Cunningham et al., 1984). The probability of recall of a particular item is highest at its input position and declines as a function of distance from the input position (Cunningham et al., 1984; Healy, 1974).

The model proposed by Lee and Estes (1977) was developed to account for data on serial recall of verbal materials. Their model has recently been used to generate predictions about spatial serial recall (e.g., Smyth & Scholey, 1996a), on the assumption that maintaining serial order relies on general-purpose (i.e., not code-specific) processes. One prediction was that the most common errors should be those in which two items are transposed, that is, one perturbation occurs. Smyth and Scholey (1996a, Experiment 1) confirmed this prediction using spatial sequences of 6 and 7 locations. Smyth and Scholey noted that transpositions of consecutive items were the most common error type, constituting more than 50% of errors. In another experiment, they tested the relative contributions of item and order information using a probed recall task with sequences of length 6. On each trial, 6 locations in a 4 x 4 grid were marked, one at a time. At the time of recall, a single location was marked and participants were asked to judge whether it had been part of the sequence, and then what serial position it occupied. Participants were equally accurate at judging the presence versus absence of target locations at the various serial positions, suggesting that item information was preserved for all 6 locations. Accuracy at reproducing the serial position (e.g., “This location was presented third”) showed the typical, bow-shaped curve, suggesting that it is order

information that produces primacy and recency effects, as shown in early work by Healy (1974). The results from the studies by Smyth and Scholey using a spatial span task demonstrate similarities in recall characteristics for verbal and spatial information. Pickering, Gathercole, and Peaker (1998) reported that verbal and spatial serial recall in children ages 7 to 15 showed similar error distributions, with decreasing selection of an item as the distance from the input position increased. These studies on spatial serial memory suggest that verbal and spatial serial recall rely on common cognitive processes, and suggest that the perturbation model may be usefully applied to the study of spatial short-term memory.

Position effects

Two effects will be discussed, the primacy effect and the recency effect. One of the robust findings in serial memory research is the primacy effect: items presented at the beginning of a sequence are better recalled than those presented in the middle of the sequence. The primacy effect is attributed to various sources. One source of primacy is the development of a representation in long-term memory for the early part of a sequence. According to some explanations (e.g., Atkinson & Shiffrin, 1968), items that are presented early may be successfully rehearsed and activated in long-term memory (LTM), such that they still have high levels of activation and are easy to retrieve when the recall cue is presented. When items in the middle of the sequence are presented, there may be insufficient resources to rehearse the items and activate them in LTM. Items presented earlier in the list are rehearsed more times, and the effectiveness of rehearsal during list presentation declines as a function of increasing serial position

(Fischler, Rundus, & Atkinson, 1970; Wixted & McDowell, 1989). An encoding gradient, according to which successive list items are encoded with decreasing strength, is assumed in several models of serial memory (Lewandowsky & Murdock, 1989; Page & Norris, 1998). The hypothesis that early items are better recalled due to use of LTM is supported by evidence that features of long-term memory organization influence the primacy effect. The primacy effect is sensitive to word familiarity and lexicality (Hulme, Maughan, & Brown, 1991; Hulme, Roodenrys, Brown, & Mercer, 1995). When an articulatory suppression task is imposed during list presentation, the primacy effect is reduced (Nairne et al., 1997), presumably because transfer of items to long-term memory is blocked.

Another source of primacy is that items that are presented early are recently activated in memory because they are rehearsed close to the time of recall (Tan & Ward, 2000). Tan and Ward (2000) asked participants to rehearse aloud while performing a short-term memory task to see when and how often people rehearsed each word in a list. They found that people continued to intersperse rehearsals of the first few items while hearing the rest of the list. They argued that the primacy effect was partly attributable to the recency of rehearsal, and thus that recency is a general mechanism that produces serial position effects at both ends of the list (Ward, 2001). Thus, strategies may play a role in the primacy effect. In the present research, the primacy effect in visuospatial memory will be examined. In particular, I will test the role of deliberate rehearsal in enhancing memory for locations that are presented early in the sequences.

The recency effect was originally interpreted as a signature of a short-term memory system, distinct from long-term memory. Brown (1958) and Peterson and Peterson (1959) conducted a set of classic experiments that showed that distractor tasks imposed at the end of list presentation selectively impaired the recency effect, and that longer filled intervals resulted in greater loss of information (e.g., 3 seconds vs. 18 seconds, Peterson & Peterson, 1959). Items at the beginning of the list, which were presumably supported by activation in long-term memory, were unaffected by the distractor task, or by increases in retention interval (Glanzer & Cunitz, 1966). These classic studies inspired investigations of serial verbal memory in which many task variables were manipulated, including recall requirements (e.g., free recall, serial recall, probed recall, recognition), item characteristics (e.g., familiarity, similarity), and list characteristics (e.g., semantic categories within lists). The result was a wealth of data that did not fit together in an easily interpretable way. At the very least, it is safe to conclude that the recency effect for verbal items cannot be attributed to the output of a short-term memory system. Most damning for the simple output-of-STM account was the effect of continuous distractors on serial recall (Bjork & Whitten, 1974; Tzeng, 1973). Tzeng (1973) found that when a distractor task was imposed after presentation of every item, rather than at the end of the list only, recency effects were observed. Interspersed distractors should not have advantaged the retention of the last few items in a short-term memory system; the recency effect should have been wiped out by the 20 seconds of distractor task at the end of the list. Long-term recency effects, such as the finding that rugby players had better recall for the names of more recently played teams

(Baddeley & Hitch, 1977), are also inconsistent with attribution of the recency effect to the output of a short-term store, which operates over seconds, not days or weeks.

Although a great deal of data on the recency effect were generated, they were not successfully integrated into a single model of serial memory. According to Baddeley's (1990) review of serial memory research, interest in the recency effect waned in the 1980s, apparently with no satisfactory explanation of its source. Given that the recency effect in verbal memory has resisted analysis, it is unsurprising that the less-studied visual recency effect is poorly understood. For visual items, some theorists have proposed that recent items are maintained in some type of short-term store. Logie (1995) referred to the visual short-term store as a "visual cache"; Kosslyn (1980) referred to a "visual buffer" with similar characteristics, including limited capacity and representations that retain some analog properties. The size of the recency effect has been of particular theoretical interest because it may reflect the capacity of a visual short-term store. Logie (1995) cautioned against interpreting the recency effect as evidence for a short-term store, noting problematic findings such as long-term recency, but did not give an alternative account of the recency effect. Interestingly, Baddeley and Hitch (1993) also tried to exclude the findings related to the recency effect from their model of working memory, claiming that recency was to be attributed to general cognitive mechanisms that operate on a system-wide basis, unrelated to specific working memory systems. Essentially, they claimed that more recent items are better remembered because they are easier to reactivate at the time of recall.

In general, cognitive psychologists have shifted away from attributing the recency effect to a short-term store. This shift has been perhaps related to the development of computational models of serial recall such as OSCAR and the perturbation model. These recent models do not posit separate memory systems that handle early and late list items differently. Rather, serial position effects emerge from processes, such as perturbation, that affect the memory representation over time. Nairne et al. (1997) tested some predictions of the perturbation model. They proposed that recall depends on an item's distinctiveness relative to the occurrence of other items presented in time. Items further apart in one's episodic memory space will be easier to discriminate. They assumed that perturbations occur over time as proposed by Lee and Estes (1977), and that there is more positional uncertainty for items presented early because there is more time for perturbations to occur. In a series of experiments, they tested memory for visually presented letters, and manipulated the ratio of inter-item presentation interval (IPI) and retention interval (RI). They found that as the ratio decreased from 1:1 (1 second between list items and 1 second RI) to 1:12 (1 second between list items and 12 second RI), recall of the final letter in the list decreased from 95% to 63%, suggesting that increasing the interval between presentation and recall affected the recency portion of the list. Memory for items in earlier serial positions was less affected by increasing the retention interval. As predicted by the perturbation model, increasing the RI while holding the IPI constant (i.e., decreasing the ratio) led to a decrease in the recency effect. Nairne et al. extended these findings over a wide range

of IPI:RI ratios and found that the recency effect, as measured by the slope of the best-fitting regression line for the last three serial positions, decreased as the ratio decreased.

Other studies using verbal items have also shown that as the IPI:RI ratio decreases, the magnitude of the recency effect decreases (Glenberg, Bradley, Kraus, & Renzaglia, 1983; Glenberg & Swanson, 1986). When the IPI is constant across list presentation, increasing the retention interval leads to a smaller ratio and a smaller recency effect. Few studies have examined the relation between RI and the recency effect for sequences of locations. There has thus far been no demonstration that manipulating the IPI:RI ratio affects the recency effect for visual items the way it affects recency for verbally encoded lists. Jones et al. (1995, Experiment 1) tested recall of spatial sequences after 0, 10, 20 or 30 seconds of delay. They reported main effects of serial position, with bow-shaped curves that had a significant quadratic component. They did not report any interactions between delay interval and serial position. Such interactions may have been present but not tested (Jones, personal communication, February 17, 2004). In the present research, the recency effect in visuospatial memory will be examined. One factor that is predicted to influence the recency effect, the IPI:RI ratio, will be manipulated in Experiment 2.

Farrand, Parmentier, and Jones (2001) investigated a hypothesized similarity between verbal serial and spatial serial recall. In verbal recall, the recency effect is smaller when both order and items must be remembered. Farrand et al. hypothesized that for spatial stimuli, the items are the locations, and thus when the locations had to be remembered more precisely, the requirement for item information would be greater and

the recency effect would be reduced. They increased the requirement for item (spatial) information by adding distractors to the layout of dots that was presented at recall. Seven dots were presented in a sequence. At the time of recall, 7, 9, or 12 dots were presented. Overall accuracy was lower when the distractor dots were added, but the advantage for the last location was preserved. Farrand et al. found no interaction between layout (7, 9, 12 dots) and position (penultimate vs. last), suggesting that the distractor dots at recall did not affect the recency slope. The distractor dots did not affect the discriminability of the last location from the penultimate location, but increased the probability of making errors overall, displacing the entire serial position curve while maintaining its shape. Thus, when item information was operationalized as spatial position, Farrand et al. did not find that increasing the demand for item information diminished the recency effect, contrary to findings with verbal items. Either the recency effect in spatial memory is not affected by the demand for item memory, or item information needs to be operationalized differently to obtain effects analogous to those obtained in studies of verbal serial recall.

Summary. Despite the consensus that recency effects are not a definitive signature of STM, the notion that recently presented items are maintained in a short-term store has remained a critical component of models of working memory. The source of the recency effect remains an important puzzle. There is a good deal of evidence that recency is related to general properties of human information processing that make recently activated items easier to reactivate. However, active rehearsal may also contribute to both primacy and recency effects, as argued by Ward (2001; Tan &

Ward, 2000). There is evidence that verbal and spatial serial memory rely on some common processes for maintaining serial order in that bow-shaped serial position curves were obtained in a spatial span task (Farrand et al., 2001; Jones et al., 1995). In the present study of spatial short-term memory, it is expected that bow-shaped serial position curves will be observed. The available data on the recency effect were inconsistent with respect to the size of the effect and the variables that influence memory for the most recently presented locations. However, it seems likely that the recency effect will be sensitive to changes in retention interval, as found for verbal items (Glenberg et al., 1983; Nairne et al., 1997).

Grouping effects

The *grouping effect* refers to enhanced sequence recall when the sequence is divided into subgroups by pauses, stresses, or other marker signals. Recall of auditorily presented sequences is enhanced by inserting pauses in between groups of digits (Ryan, 1969) or letters (Hitch, Burgess, Towse, & Culpin, 1996). Even brief pauses can enhance recall: the grouping effect “probably arises as a result of the underlying auditory memory system being specifically evolved to detect and use the rhythmic and prosodic aspects of speech” (Baddeley, 1990, p. 40). Hitch et al. (1996) tested the effects of temporal grouping on serial recall of letters that were presented auditorily or visually. Nine-letter lists were presented with evenly spaced pauses in the ungrouped condition, or with longer pauses after the third and sixth letters in the grouped condition. For both auditory and visual presentation types, the serial position curve for ungrouped lists showed a single bow shape. Grouped lists showed multiple bowing corresponding

to the three-item stimulus groups, with small primacy and recency effects for each group. Thus, the benefit for grouped lists was related to higher accuracy for the items on the edges of the groups when verbal items were used.

Hitch et al. (1996) also tested the effects of articulatory suppression on recall for each presentation type. They found that grouping effects persisted under conditions of articulatory suppression for auditorily presented lists, but were diminished for visually presented lists. They argued that articulatory suppression prevented the use of verbal recoding for the visually presented digits, and provided some evidence that the grouping effect for verbal items is related to reliance on the phonological loop, consistent with Baddeley's (1990) statement.

Based on the grouping effects found for verbal items, researchers have proposed that grouping may occur for spatial items as well. This hypothesis has been tested using verbal materials presented in different locations on the screen, creating spatial clusters instead of inserting temporal pauses (Bowles & Healy, 2003; Cowan, Saults, Elliott, & Moreno, 2002; Sinclair, Healy, & Bourne, 1997). Bowles and Healy (2003) reported that participants learned the spatial arrangement of an 18-word list faster when the words were clustered on the screen in groups of three. Grouping effects may arise via different processes for different information types (McNicol & Heathcote, 1986). Grouping of verbal items appears to be linked to patterns in the way that stimuli are presented (e.g., temporal pauses), whereas grouping of visually presented items is more related to the strategies that people use (Cowan et al., 2002).

Cowan et al. (2002) compared grouped vs. ungrouped presentations of nine-digit sequences. Auditorily presented sequences were grouped by inserting pauses in between three-digit clusters. Visually presented digits appeared individually from right to left, and were grouped by increasing the space between three-digit clusters. Consistent with previous research (Frankish, 1989), Cowan et al. found that grouping by inserting temporal pauses enhanced recall for auditorily presented digits. In contrast, spatial grouping of visually presented digits conferred no benefit. The serial position curves for recall of visually presented digits showed a scalloped pattern for both grouped and ungrouped lists: for each three-digit cluster, recall was slightly better for the digits on the visual edges (first and third) than the middle digit.

Based on these patterns, Cowan et al. suggested that grouping of the visually presented digits was strategic, and not dependent on whether the stimuli were grouped on the screen. For auditory stimuli, the grouping manipulation helped because processing of auditory material is more automatic and more sensitive to features of the stimuli. Thus, Cowan provides some indirect evidence that serial memory operates differently over auditory versus visual codes, and more generally that verbal and spatial codes are processed differently. Auditory codes have obligatory access to a phonological store or auditory trace (Salamé & Baddeley, 1982), and this trace is long-lasting compared to that maintained in visual memory. Grouping is more automatic for speech than other types of stimuli. As noted above, Hitch et al. (1996) found that temporal grouping effects survived an articulatory suppression task better for auditorily than visually presented letters. Cowan interpreted this finding as supporting evidence

that the grouping effect is stimulus-linked for auditorily presented stimuli. People have little control over the processing of auditorily presented letters or digits, and may have greater influence over the processing of visually presented items, even though letters and digits are so familiar that they can be recognized in less than 50 ms.

Summary. When people remember sequences of verbal items, aspects of stimulus presentation that are linked to the timing affect memory performance. In particular, memory for recently presented items is affected by the ratio between the time between list items and the time from the last item to the recall cue. Sensitivity to the IPI:RI ratio has not been demonstrated for visuospatial items. Temporal grouping of verbal stimuli also affected memory performance, but such effects have not been investigated using location sequences. Further investigations are needed to determine the effects of temporal pauses and visual spacing on serial memory for locations.

In this chapter, I described a model of working memory that has been used to frame a great deal of research on memory for locations. According to the multicomponent model, the visuospatial scratch pad has an architecture similar to that of the verbal subsystem. The verbal subsystem is comprised of a passive store connected to an active, response-based rehearsal mechanism. Although the activities of both subsystems are regulated by an executive control system, greater executive control is required to perform spatial memory than verbal memory tasks. When people perform spatial short-term memory tasks, many executive processes are engaged. I have proposed that strategic grouping processes for chunking of locations requires executive resources, and that strategic grouping can augment short-term memory performance by

decreasing memory load. To explore similarities between verbal and spatial serial memory, the familiarity, serial position, and grouping effects that are prevalent in verbal memory were investigated using variants of the spatial span task.

Chapter 2

In this chapter, I will establish the context for my empirical research. I will first review the literature on cognitive mechanisms for processing spatial information. I will then review the studies that have employed the spatial span task selected for the present research. Finally, I will propose a model of spatial processing and develop hypotheses to be tested.

2.1 Processing of spatial information

There are two main approaches to investigating whether spatial information is processed by domain-general or code-specific mechanisms. In the experimental approach, task requirements are manipulated and memory performance is compared across conditions. In the correlational approach, participants complete a number of tasks, and the variance shared among performance measures is used to make inferences about the processing resources and memory systems that underlie performance. The data pertaining to spatial short-term memory from these two approaches are reviewed below.

Experimental research

Dual-task studies have been used to demonstrate interference between spatial span and other spatial tasks. When people are required to perform spatial secondary tasks, the number of locations that they can recall in the correct order decreases. Spatial span is impaired by tasks that require movement planning, such as continuous tapping to a square arrangement of pegs, or pointing to a sequence of locations on a computer monitor (Smyth & Pendleton, 1989; Smyth & Scholey, 1994b). Smyth and Pendleton (1989)

found that Corsi span decreased when participants tapped in a pattern during encoding of the test items.

Smyth and Scholey (1994b) found that performing a serial reaction time (SRT) task during the retention interval impaired spatial span. Participants were required to point at locations as they were marked on a screen, which could have impaired spatial memory in two possible ways. One is that pointing to a new set of targets prevented people from rehearsing a motor program or a sequence of eye movements corresponding to the test sequence. Alternatively, viewing and pointing to target locations could have interfered with the representation of the spatial sequence by updating the contents of short-term memory. The role of rehearsal in spatial memory requires further study to differentiate between these two possibilities. In general, these results suggest that spatial tasks compete for the limited resources of a fixed-capacity spatial memory store. The impairment of spatial span is specific to tasks that require participants to retain movement or location information (see Logie, 1995, for a review). Spatial span is not impaired by tasks requiring retention of static visual information, such as color (Logie & Marchetti, 1991; Smyth & Pendleton, 1989), nor by articulation of words during a retention interval (Klauer & Stegmaier, 1997; Smyth, Pearson, & Pendleton, 1988; Smyth & Scholey, 1994a).

Some researchers have argued that concurrent spatial tasks compete not for code-specific storage, but for common processing mechanisms, such as those required for spatial attention (Smyth & Scholey, 1994b) or maintenance of order information (Jones et al., 1995). Based on their model of spatial attention, Smyth and Scholey (1994b)

predicted that spatial span task performance would be impaired by any task that engages spatial attention, regardless of presentation modality. Consistent with this prediction, they found that a variety of tasks interfered with performance on the Corsi Blocks task, whether the secondary tasks were visual, auditory, perceptual, or motor in nature. For example, spatially presented tones heard during a retention interval impaired performance, even when subjects did not have to respond to these tones (1994b, Experiment 2). According to Smyth and Scholey, “These findings suggest that interference is spatial, not visual, and that it is related to covert spatial attention rather than to overt manual responses” (p.6).

Consistent with Smyth and Scholey (1994b), Jones et al. (1995) reported that presentation of auditory stimuli disrupted recall of spatial sequences. However, Jones et al. argued that the interference was caused not by shifts of spatial attention, but by concurrent demands on a unitary system that maintains representations of serial order. Jones et al. used a modified version of the spatial span task that will be referred to as the dot sequence task. Dots appeared in one location at a time on the screen. Locations were changed on each trial to prevent verbal recoding. At the time of recall, all locations presented on that trial appeared simultaneously, and participants selected the locations to reconstruct the order. In four experiments, Jones et al. tested the effect of secondary tasks on dot sequence recall. Each experiment included three conditions: control (no secondary task), steady state secondary task, and changing state secondary task. Steady state tasks required repeatedly producing a single response, such as pressing a key or articulating a syllable (e.g., “ay”). Changing state tasks required producing a cycle of

responses, such as tapping in a 12-key pattern or articulating a sequence of letters (e.g., “ay, bee, see, dee, ee, eff, gee, ay...”). Secondary tasks were imposed both during encoding of the dot locations and during the 10 second retention interval. In all four experiments, they found that changing state tasks interfered with serial memory performance, whereas steady state tasks did not. Importantly, three of the four experiments included both verbal and spatial span tasks. They found that verbal changing state tasks impaired spatial span, and a spatial changing state task impaired verbal span. Based on these patterns of mutual interference, Jones et al. argued that what causes the interference is that the “changing state” of the secondary task: the pattern of stimuli contained information about serial order. The disruptive effects of the interference tasks (spatial tapping, reciting letters, and listening to letters) appeared to be of similar magnitude, but cross-experiment analyses were not reported, so direct comparisons were not possible.

In their final experiment, Jones et al. found that presenting a list of ordered, irrelevant letters interfered with spatial span. This finding was inconsistent with previous studies showing that hearing irrelevant words during the retention interval did not impair spatial span (Smyth & Scholey, 1994b, Experiment 3). It is unclear whether the interference effect obtained by Jones et al. in the irrelevant speech condition was due to the ordered nature of the stimuli, the presentation of the speech stimuli during encoding, or the differential demands of the dot sequence versus the standard spatial span task. Although none of these possibilities were ruled out, it seems likely based on extant research that ordered stimuli engage cognitive resources that are also tapped by the

spatial span task. Quinn (1994) reported that visuospatial memory was impaired when an experimenter moved the participant's hand in a predictable pattern, but not when the participant could not predict the pattern. Thus, the presentation of predictable and ordered locations interferes with spatial memory in a way that presentation of unpredictable locations does not, and similarly, alphabetic sequences may engage resources that are used in serial memory tasks more than random letter sequences.

The finding that spatial memory can be engaged by auditory stimuli seems inconsistent with code-specific resources for visuospatial information. However, Smyth and Scholey argued that auditory targets that are presented from different locations in space can trigger shifts in spatial attention (Smyth & Scholey, 1994b). They found that participants were impaired on the spatial span task even when they were told to ignore tones that were presented from varying locations (1994b, Experiment 2). However, Klauer and Stegmaier (1997, Experiment 2) reported that merely listening to tones presented from different directions did not impair spatial span. The participants in the studies of Klauer and Stegmaier were only tested in a no-response condition, whereas the participants in the studies of Smyth and Scholey (1994b) were tested in both overt and no-response conditions. Klauer and Stegmaier argued that testing in the overt response condition may have led participants to covertly respond (i.e., practice responding) even when they did not have to, leading to carryover effects in the no-response blocks. Smyth (1996) reported that auditory targets did not impair spatial span when no response was required, and argued that auditory targets interfere only when they are spatially salient. Thus, the extent to which spatial attention is automatically engaged by auditory targets

that originate from multiple locations depends on task conditions that make the location of the targets more or less salient to the participant. When people had to respond to the tones, for example, by pointing to their locations, they were clearly impaired on a spatial span task. Interference related to pointing could arise from multiple sources, including competition for specialized working memory resources and general load from decision-making requirements. When people did not have to respond to auditory targets, their spatial span was not impaired unless the location of the targets had been made salient by task requirements, such as responding to the targets in another experimental condition.

Overall, the dual-task literature supports the existence of specialized mechanisms for spatial short-term memory and rehearsal, functionally distinct from mechanisms for verbal and visual short-term memory, as proposed by Logie (1995). However, there was also some evidence that spatial short-term memory relies on domain-general mechanisms. Spatial span performance was disrupted by a changing-state verbal task (Jones et al., 1995), and auditory tones can disrupt spatial memory under some task conditions (Smyth & Scholey, 1994b). The interference in spatial memory from nonspatial tasks has been sometimes been attributed to executive requirements of the nonspatial, secondary tasks, and this link has been further supported by studies that combined spatial and executive-requiring tasks.

The spatial span task is impaired by tasks that require central executive resources (Klauer & Stegmaier, 1997; Smyth & Pelky, 1992). Some examples of secondary tasks that have been designed to tap the central executive are decision-making, mental arithmetic, and random letter generation. Klauer and Stegmaier (1997) found that spatial

span performance was impaired by a variety of tasks that required participants to make a simple decision during a retention interval. In one condition, participants judged an auditory tone as high- or low-pitched. This task impaired spatial span as much as judging whether the tones had originated from the left or right and pointing in the appropriate direction. Klauer and Stegmaier concluded that the spatial span task requires general-purpose, central executive resources that are used in decision making. Smyth and Pelky (1992) showed that central executive resources are required for encoding of spatial sequences that consisted of three locations. Their secondary task was counting backwards aloud, which requires central executive resources (Vallar & Baddeley, 1982). Smyth and Pelky reported that backwards counting during encoding and maintenance resulted in greater decrements in spatial span than backwards counting during maintenance alone. This suggests that central executive resources are required for encoding, even for short, three-item sequences.

Central executive resources are needed for retaining information about serial order (Jones et al., 1995). Jones et al. found that serial spatial recall was disrupted by each of the changing-state tasks as compared to steady state tasks, regardless of whether the distracting materials were verbal or spatial. They argued that the common factor in the changing-state interference tasks is the presence of order information, which interferes with the order information that people are trying to maintain for the spatial span task. They claimed that when two sets of stimuli contain cues to serial order, memory for one of the sets would be disrupted by presentation of the other set. Although these results do not directly test whether the central executive is involved in maintaining serial

information, the central executive has been implicated in tasks that require representation of order information, such as random generation of numbers or letters (Baddeley, Emslie, Kolodny, & Duncan, 1998; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). In the random number generation task, participants are asked to generate sequences of numbers aloud that are as random as possible. They are instructed to avoid patterned sequences such as “1-2-3” or “2-4-6.” The random number generation task requires keeping track of which numbers were recently used. It is likely that the central executive is involved in maintaining a representation of the sequence order in the spatial span task. The VSSP, conceptualized as a set of storage and rehearsal mechanisms, is not believed to be capable of maintaining this information without extensive executive control (Miyake et al., 2001).

In summary, the spatial span task requires central executive resources for encoding spatial locations (Smyth & Pelky, 1992; Morris, 1987), and for retaining information about serial order (Jones et al., 1995). The central executive is also required for adapting to task demands by selecting strategies and monitoring their effectiveness (Rabbitt, 1997) but the contribution of these executive functions to spatial span task performance has not been studied. It seems likely that some strategies will require more central executive resources than others. I hypothesized that strategic grouping of locations will require central executive resources.

Correlational research

In large-scale correlational studies, sample sizes are usually greater than 100, and each participant completes many tests, usually over several hours. This methodology

uses a variety of tests that have been shown to tap specific cognitive abilities, and examines the covariation among measures of performance. To the extent that measures share variance, the tasks are inferred to rely on common cognitive processes.

Performance measures are often subjected to factor analysis to determine how many kinds of abilities or processes are used. Such large-scale studies have revealed a spatial factor separate from verbal ability (Ichikawa, 1983; Shah & Miyake, 1996), supporting the existence of functionally distinct systems for spatial short-term memory tasks. These studies did not focus on the spatial span task used in the present research, but included tasks that required various kinds of spatial processing, such as remembering visual patterns, integrating or rotating mental images, and solving spatial analogies.

Many large-scale correlational studies have included one or more spatial memory tests (Ackerman, Beier, & Boyle, 2002; Miyake et al., 2001, Oberauer, Süß, Schulze, Wilhelm, & Wittman, 2000). Oberauer and colleagues and Miyake and colleagues have been especially interested in connecting executive functioning to spatial memory performance. Oberauer (1993) found that performance on a spatial memory task was a good predictor of reasoning ability, in contrast to verbal memory (digit span), which generally does not predict higher-level cognitive abilities such as reasoning. Spatial span tasks are likely to require control of processing in a way that verbal span does not. Oberauer et al. (2000) followed up on this finding with a large-scale study. They chose 23 tasks that were differentiated along 2 proposed dimensions: content and functions. The three types of task content were spatial, verbal, and numerical. The three task functions were coordination, supervision, and storage-transformation. One problem with

this study was that some of the tasks could be placed in multiple categories, such as a task that required both memory for locations (spatial) and mental arithmetic (numerical). Spatial short-term memory tasks required memory for static visual patterns, whereas spatial working memory tasks required processing in that visual patterns had to be mentally rotated. Reasoning ability was measured as part of an intelligence test battery. Oberauer replicated his previous finding that spatial short-term memory and spatial working memory were not differentiable. When the two measures were combined into a working memory factor, this factor was highly correlated with reasoning ability ($r = 0.56$), supporting the link between spatial ability and executive processes, as these processes are critical to reasoning skill and complex problem solving.

Miyake et al. (2001) used the large-scale correlational method and factor analytic techniques to determine whether spatial working memory could be differentiated from spatial short-term memory. Verbal short-term memory and verbal working memory had previously been differentiated using factor analytic techniques (Engle, Tuholski, Laughlin, & Conway, 1999). Miyake et al. chose two tasks to represent the visuospatial working memory (VS WM) variable, and two to represent the visuospatial short-term memory (VS STM) variable. One of the spatial working memory tasks was a letter rotation task. Letters such as F and R were presented sequentially in one of seven possible orientations, and were presented either normally or mirror-imaged. As each letter was presented, participants had to process the letter to report “Normal” or “Mirror” aloud, and then remember where the top of each letter was pointing. At the end of the trial, they reported the spatial orientations of the letters in order. One of the spatial short-

term memory tasks was a computerized spatial span task. Participants did not have to make judgments about the stimuli, but watched as squares on the screen were marked, and then clicked on the squares in the order that they had been marked. Miyake et al. used confirmatory factor analysis to show that the Executive Functioning variable, measured using tasks that included problem solving (i.e., Tower of Hanoi), was equally correlated with the VS WM variable ($r = .55$) and the VS STM variable ($r = .56$). These results suggested that, in the visuospatial domain, WM and STM span tasks may not differ in the degree to which they implicate executive functioning and may measure the same construct.

Ackerman et al. (2002) also investigated the relation between working memory measures and higher level cognitive functioning or general intelligence. They measured general intelligence using Raven's Progressive Matrices test, and working memory with span tests that varied in content (e.g., digits, figures). Ackerman et al. reported many simple correlations of interest to the present research. The task most similar to the spatial span task was called "Spatial Span", but was a working memory task in that concurrent processing was required. Participants saw a series of grids with Xs and Os. They had to judge whether the number of Xs was even or odd, and remember the position of the O. They were required to remember the position of each O, and to compare the pattern of the Os in a four-choice recognition task at the end of the trial. For example, if there were four grids in the series, they would have to recognize the correct configuration of four Os. Spatial span was moderately correlated with Raven's Progressive Matrices test, $r = 0.38$, again supporting a link between spatial processing and higher-order cognitive functioning.

Other studies of spatial ability have shown that performance on complex spatial tasks is a good predictor of general intelligence (Lohman, 1996).

Developmental studies, which tend to use smaller samples and fewer measures, have also been used to examine dissociations between verbal and spatial memory systems. If spatial and verbal memory develop at different rates, this would support functionally distinct systems. Isaacs and Vargha-Khadem (1989) reported a dissociation between verbal and spatial spans in their studies of children aged 7 to 15 years. Logie and Pearson (1997) also found developmental fractionation using two memory span tests. Block sequence span developed more slowly than visual pattern span, and the two spans correlated poorly within each age group (ages 5-6, 8-9, and 11-12 years). They interpreted their results as supporting the fractionation of visuospatial working memory into a temporary visual cache for storing visual patterns and an inner scribe for temporary retention of spatial information. Pickering, Gathercole, Hall, and Lloyd (2001) administered multiple visuospatial memory tests to children of ages 5, 8, and 10. Based on the developmental dissociation that they observed, they also argued for two separable subcomponents in the VSSP, one for static and one for dynamic visuospatial information. The developmental research supports functionally distinct working memory subsystems for verbal and visuospatial information, and a further fractionation corresponding to visual and spatial subsystems. Luciana and Nelson (1998) studied administered several working memory tests to children ages 4, 5, and 7. On the spatial working memory task, children were asked to search in boxes on the screen for tokens, and to avoid searching locations where tokens had been previously found. The authors suggested that an

effective search strategy was key to performance on this task. As task difficulty increased, children were less able to use an effective search strategy, and thus the authors attributed the increased search errors on the more difficult problems to “executive failures” (p. 285). As with adults, spatial working memory in children appears to be tightly connected to executive function and to strategy use.

In sum, several lines of research have supported the connection between spatial processing and executive control. Performance on complex spatial tasks is moderately correlated with performance on tests involving reasoning. The shared variance in these measures is likely to be attributable to the use of executive processes. However, further research is needed to determine how various executive processes contribute to performance on spatial memory tasks. In addition to the executive functions identified via latent variable analysis (e.g., shifting, inhibition, updating, as identified by Miyake et al., 2000), strategy selection also demands executive control (Rabbitt, 1997), and so will play a role in spatial memory performance to the extent that multiple strategies are used to perform spatial tasks. The connection between strategy selection and executive processing will be explored throughout the present research.

2.2 Extant literature on the spatial span task

In the previous section on dual-task research, I described secondary tasks that have been used to impair spatial memory performance. Relatively few studies have explored how spatial memory can be enhanced (De Lillo, in press; Fischer, 2001; Kemps, 1999, 2001). There were no studies in which participants received training to enhance

their spatial span. However, there is some evidence that long-term memory affects performance on the spatial span task. Practice with specific sequences leads to better recall (Crawford, Dickson, & Baños, 2000; Kemps, 2001). Corsi (1972, as described in Kolb & Whishaw, 1990) measured a person's span and then examined whether the person could learn a sequence that was one greater than span. Corsi found that normal participants were able to learn a supraspan sequence when it was repeated every third trial, in contrast to brain-damaged patients with temporal lobe excisions who were unable to learn the repeated sequence. Kemps (2001) found that people could improve their performance on specific block sequences when the same sequences were repeated over 8 trials.

Kemps (1999) showed that performance was better when blocks were arranged in a 5 x 5 grid than in a standard, pseudorandom layout (Appendix A-1). This suggests a role for long-term memory (LTM) in supporting spatial span performance: the pseudorandom layout has no connections to LTM, whereas the grid layout is supported by existing representations that people have practiced using in other cognitive tasks, such as playing games or memorizing phone numbers. Existing representations can be activated with relative ease and can provide a structure for integrating new information. Working memory research has shown that long-term knowledge contributes to immediate recall for verbal items: memory spans are greater for words than nonwords (Hulme et al., 1995), and for high-frequency than low-frequency words (Gregg, Freedman, & Smith, 1989). The work of Kemps (1999) is a first step toward demonstrating parallel findings for spatial items.

In a subsequent study, Kemps (2001) investigated three stimulus characteristics: symmetry, continuation, and repetition. Structured sequences had one or more of these characteristics. For example, a structured path might have two symmetrical parts and good continuation (i.e., the path did not cross itself); a complex sequence had no symmetry and crossed itself at least once. Structured sequences were more accurately recalled than complex sequences. As in Kemps (1999), a 5 x 5 grid was used to present the spatial sequences. In addition to providing a familiar structure, a grid layout may have created more affordances for the participant, enabling her to use strategies that are difficult to use on the standard pseudorandom layout. For example, when a structured sequence was presented, participants could potentially encode the first four locations and the information that the second part was symmetrical and transposed. This procedure would reduce memory load for the spatial items because the second set of four locations would not have to be retained in memory, as they could be reconstructed from the first four locations plus additional, verbal cues. Kemps (2001) also suggested that reconstructive processes might have played a role in span task performance. However, strategy reports were not collected by Kemps (1999, 2001), so the hypothesized effect of encoding additional information about the sequences during encoding remains speculative. Support for this hypothesis would argue for a role of long-term memory in spatial performance, and also support the extension of Ericsson's long-term working memory model (e.g., Ericsson & Kintsch, 1995) to spatial stimuli.

De Lillo (in press) proposed that memory representations used in the spatial span task are hierarchically organised. He tested performance on three types of spatial

sequences of 9 locations. Two types (A and B) were structured so that each group of three movements occurred within a group of targets that were clustered on the screen. For sequence A, the same movement pattern (e.g., clockwise) was repeated three times within the 9-location sequence. In the second type of sequence (B), different movement patterns were presented for different clusters. In the third type of sequence (C), consecutive targets were from different spatial groups. De Lillo found that people were more accurate when parts of the sequence were within spatial clusters (A and B better than C), and that accuracy was further increased when movement patterns were repeated over the groups (A better than B), consistent with the accuracy advantage reported by Kemps (2001) for symmetrical sequences. De Lillo also found that response times were slower at chunk boundaries (i.e., responses for the fourth and seventh locations) when the sequences were structured into spatial groupings (types A and B). He noted that the pattern of latencies suggested chunk boundaries in the memory representation, but that further research was needed to partial out the effects of motor processes, which are also thought to rely on hierarchically organised programs (Rosenbaum, 1987).

Fischer (2001) reported that recall was more accurate when people had 3 seconds to encode each location as compared to 1 second per location. This result is consistent with the general finding in serial memory research that when items are presented further apart in time, they are more temporally discriminable and thus their relative order is more accurately recalled. Alternatively, extra time between items may have allowed participants to better encode each item, or to strategically group parts of the sequences. Again, strategy reports would be useful to differentiate between these possibilities.

To the extent that verbal and serial memory rely on shared mechanisms, the effects of serial position and timing manipulations reviewed in section 1.3 should be observed when people perform spatial span tasks. Several studies have reported serial position effects in visuospatial memory performance, but with somewhat inconsistent results (Crawford et al., 2000; Farrand et al., 2001; Fisk & Sharp, 2003; Jones et al., 1995; Pickering et al., 1998). Jones et al. (1995) tested memory for sequences of dot locations, and claimed to find an accuracy advantage for the last two locations over the middle locations. Fisk and Sharp (2003) also noted a two-item recency effect when people viewed up to ten locations but were required to reproduce the last four only. Phillips and Christie (1977) tested recognition of abstract visual patterns, and found an advantage only for the pattern presented last. Crawford et al. (2000) tested participants on the same, 8-location sequence on nine consecutive trials. They reported no recency effect: accuracy decreased across serial position. The presence and size of the recency effect in serial spatial memory appears to vary with task requirements.

Few studies of spatial span have included manipulations of the duration of an unfilled retention interval. Fischer (2001) found that people who retained spatial sequences for nine seconds were more accurate than those who had a one-second retention interval. He argued that the benefit was due to spatial rehearsal. Jones et al. (1995) compared spatial span at four retention intervals (0, 10, 20, and 30 seconds). As retention interval increased, there was a small increase in errors. In a series of four experiments, Smyth and Pelky (1992) tested spatial span using three retention intervals (0, 5, and 15 seconds) in combination with various secondary tasks that were imposed during

encoding, or during both encoding and the retention interval. There were a large number of experimental conditions, and the effect of retention interval was inconsistent across their four experiments. There was some tendency for more errors as the retention interval increased.

In sum, there was some evidence for a role of long-term memory in performance on the spatial span task (De Lillo, in press; Kemps, 1999, 2001), which indicates a similarity in how verbal and spatial span tasks are performed. In other respects, spatial short-term memory did not appear to be affected by the same variables as verbal short-term memory. For example, the few studies that involved manipulations of the retention interval did not reveal a consistent effect of IPI:RI ratio on the recency effect.

2.3 Model of spatial working memory

The model in Figure 1 describes the memory structures and control processes involved in maintaining spatial information over short periods of time. The two memory structures are long-term memory and the workspace. Long-term knowledge contains many types of information. However, only retrieval structures are specifically indicated, as these were the focus of Experiment 1. The workspace supports the activation of the items currently in use. The workspace can retain both representations of items (i.e., images in the case of visuospatial information), or pointers to items in long-term memory. To the extent that presented visuospatial items are novel and representations are unavailable in long-term memory, images are generated and maintained in the workspace. Executive processes that impact the two memory structures are indicated in italicized font. The model

assumes that limited resources are available for executive functions, and must be shared among all the functions.

Figure 1. Model of spatial short-term memory system.

The proposed model is largely consistent with the view of working memory recently presented by Logie et al. (2001): “[Working memory] must deal with the product of activated representations in long-term memory (Logie 1995, 1996). Where the activated information is incomplete, working memory acts as the workspace to manipulate the information and seek some means to resolve ambiguities or generate new knowledge.” (p. 178). However, the model does not adopt Logie’s (1995) proposal for a functionally distinct subsystem, which he termed the “inner scribe,” that processes spatial

information, such as movement. For spatial information, no storage or rehearsal systems are posited that can operate without executive control.

With respect to the memory task used in the present research, two of the executive functions are active primarily during encoding of spatial sequences, and two during the retention interval. During encoding, *strategic grouping* is used to divide the sequence into parts. When this strategy is used, the representation in the workspace will contain additional features, such as “first part” vs. “second part”, and information about the relations between the groups (e.g., symmetrical, rotated) are encoded. The addition of these features to the representation is predicted to enhance recall. A related process referred to here as *recoding* (similar to the “elaborative encoding” described by Ericsson and colleagues, e.g., Chase & Ericsson, 1982), connects the contents of the workspace to units of long-term knowledge. Through recoding, pointers are activated in the workspace to larger units in long-term knowledge. These larger units are words or stored movement patterns that are familiar to participants based on their individual experiences.

During maintenance of spatial information, as imposed by a retention interval between presentation and recall, two executive-requiring functions are active: *rehearsal* and *keeping track*. Rehearsal works to preserve the fidelity of the representation in the workspace by taking the contents of the workspace and feeding them back into memory. The keeping track function marks the order of events and maintains serial information over time. When these two functions are inhibited, the representation decays over time, resulting in loss of order information.

The proposed model makes certain predictions regarding the amount of information that can be accurately recalled after being maintained in the workspace. The following hypotheses were generated:

- 1) Strategic grouping will enhance span because chunking allows more information to be retained. Strategic grouping affects the characteristics of the representation that is maintained in the workspace by adding features that could enhance recall. For example, six locations could be recoded as two groups of three locations each, and the relations of the two groups (e.g., symmetrical, rotated) could be encoded as added features.
- 2) Spatial span will increase to the extent that retrieval structures are developed and pointers used in the workspace. For example, a sequence of four locations could be recoded as a familiar movement pattern (e.g., two pen strokes involved in writing a Chinese letter).
- 3) Secondary tasks that compete for executive resources during the retention interval will detract from the efficiency of rehearsal and keeping track, and thus impair accuracy on the spatial span task.

The first study was designed to investigate the contributions of recoding and strategic grouping to spatial memory performance. Participants attempted to remember sequences of locations that appeared sequentially in a nonsymmetrical layout (Appendix A-1). Given that the task and the layout were novel to the participants, it was assumed that none of the participants would possess a retrieval structure in long-term knowledge that

would be recruited to support short-term memory performance. The main hypothesis of this study was that providing exposure to a layout of locations would help participants improve their memory performance. An additional hypothesis was that strategic grouping would enhance memory performance.

Chapter 3

The goal of the present research was to investigate the cognitive mechanisms that support spatial short-term memory. In particular, the role of long-term memory in supporting short-term memory performance was explored. The finding that familiarity with spatial items, such as locations, can enhance memory span, would extend the long-term working memory model to spatial items. Chunking has also been proposed as a cognitive mechanism that can increase span by increasing the amount of information stored in each chunk. Chunking could occur through the strategic recoding process that was proposed above. The first two experiments will be reported in this chapter. Experiment 1 tests the hypothesis that spatial short-term memory performance can be enhanced through familiarization with a set of locations. Experiment 2 uses a dual-task methodology to test the impact of concurrent executive demands on spatial memory performance.

Experiment 1

Rationale

This study used a pretest-posttest design. In between the two tests of spatial short-term memory, which were identical, participants performed either a spatial or a nonspatial task for approximately 35 minutes. The spatial task was a reaction time task in which participants pointed to screen locations that were marked in rapid succession. For participants who performed a spatial task, they either interacted with the same layout as used on the spatial short-term memory task, or a different layout. People who interacted with the same layout were predicted to develop a retrieval structure (i.e., a visuospatial

representation of the layout) that would facilitate encoding and recoding of spatial items, yielding greater accuracy on the posttest. According to the long-term working memory model, when people are familiarized with a specific spatial layout, they will build up a retrieval structure, which is a representation of the layout in long-term memory. When encoding items, people are thought to make use of a retrieval structure that has been developed for those items.

Method

Participants. Twenty-eight undergraduate students were recruited from an introductory psychology course at Carleton University. A brief description was posted on a departmental bulletin board, along with descriptions of other studies. Participants chose to be contacted to participate in the present study, and received extra academic credit for their participation. Fourteen males and fourteen females participated, reporting normal or corrected-to-normal vision. The mean age was 20.4 years ($SD = 2.8$). Participants were randomly assigned to one of the four training conditions that are described below, with the constraint that an equal number were assigned to each condition.

Apparatus. Stimuli for the spatial memory task were presented on a 16-inch colour monitor (Dell E770s) set to 800 x 600 resolution, connected to a Pentium III processor running Windows ME. The viewable area of the screen measured 236 mm in height and 306 mm in width. Experiments were programmed in E-Prime 1.0 (Psychology Software Tools), which controlled timing of presentation and recording of

responses. Responses were collected using a standard mouse and response times were recorded in milliseconds (ms) with ± 92 ms accuracy.

Materials. Nine target locations in a nonsymmetrical arrangement were defined as squares on the computer screen, 28 mm in height and 28 mm in width. White squares were outlined in black on a white background. The relative positions of the squares are illustrated in Appendix A-1. The location numbers shown in Appendix A-1 were not visible to participants. Sequences were selected from a pool provided by Schellig and Hättig (1993), who used the same location layout as shown in Appendix A-1. These sequences had been tested to ensure that all sequences of a given length were more difficult (i.e., recalled less accurately) than those of shorter lengths. The 21 sequences used in this study are listed in Appendix B-1. The sequences were presented in increasing order of sequence length (e.g., three sequences at length 3, followed by three sequences at length 4, and so on) and the same order of sequences was used in the pretest and posttest.

For the serial reaction time (SRT) task, targets (“X”s) appeared inside the squares in one of three layouts: *same-9* (same layout as used in the spatial memory task; Appendix A-1), *different-9* (9 locations with a different configuration from the spatial memory task; Appendix A-2), or *different-4* (4 locations that were a subset of the 9-different locations; L1, L3, L4, and L9, in Appendix A-2). In the two conditions that used nine-location layouts, participants responded to 1,752 targets in 12 blocks of 146 trials each. In the four-location condition, participants responded to 1,716 targets in 12 blocks of 143 trials each. The difference in number of total targets resulted from

counterbalancing the number of movements to each location within each block. Each possible move (e.g., L1 to L2, L2 to L3,..... L9 to L1) was required an equal number of times over the SRT portion of the experiment, and no location appeared twice in succession. Four lists meeting these criteria were generated in advance for each of the layout conditions. Lists were randomly assigned to participants who performed the SRT task.

Procedure. Participants were tested individually in a quiet room. They seated themselves at a comfortable viewing distance from the monitor and rested their right or left hand on the mouse, based on their own preference. Participants initiated each trial of the spatial memory task by pressing a mouse button. Each item in the sequence was signaled by the appearance of an “X” (8 mm in height) in one of the squares. Each item (“X”) in the sequence appeared for 1 second and was followed by a 1-second delay. All nine empty squares remained on the screen during the retention interval. The cursor was invisible during sequence presentation and during the retention interval. At the end of the retention interval, a blue frame (width of 3 pixels) appeared at the perimeter of the screen, cuing participants to begin recall.

Participants attempted to reproduce the sequence that they had just seen by using the mouse to point and click on the screen locations in the correct order. Each time a square was selected, it turned grey for 300 ms to indicate that the participant’s response had been registered. If the participant clicked outside the nine defined squares, the background of the display turned grey for 300 ms. During the instructions, the experimenter explained that if this error occurred, or if participants were aware that they

had made other errors on that trial, they would be unable to undo the error and should continue producing the rest of the sequence. They were asked to try to remember as many locations in the correct order as possible, and had an unlimited amount of time to respond. Thus, accuracy was emphasized and speed de-emphasized. The trial terminated when participants had given the correct number of responses or when they clicked an icon in the lower right corner of the screen labeled “Skip to Next Trial.” Following each trial, a text message on the screen provided feedback about accuracy, for example, “3 out of 5 correct.”

Prior to the start of the experimental trials in the pre-test, participants were familiarized with the procedure and performed four trials at sequence length 4. None of the practice sequences were used in the experimental trials. After the pretest, three groups of participants performed the serial reaction time task and one group of participants performed a nonspatial task. For the serial reaction time task, participants used the mouse to point and click on screen locations that were marked in rapid succession. They were asked to click on the marked locations as quickly as possible. Targets appeared at a fixed interval of 1200 ms, and disappeared as soon as the participant clicked, regardless of whether they selected the correct location. After each block, participants viewed a text message indicating how many locations had been selected correctly. They were asked to maintain an accuracy level of at least 130 locations correct per block, out of 146 or 143 depending on layout condition. Given the random nature of the sequences, participants were not expected to learn spatial sequences during the serial reaction time task. However, it was expected that participants who

interacted with the same-9 layout would benefit on the posttest from the layout's familiarity. Participants initiated each block by pressing a mouse button, and were encouraged to take brief rest periods between blocks. For the nonspatial task, participants read short text passages on the screen and made similarity judgments for descriptions of real and imaginary creatures. Responses were made by selecting number keys on the top row of the keyboard. Although the classification task required pressing keys, and may have involved visualization of the creatures described, the task had no spatial demands related to locations on the screen. It was expected that performing the nonspatial task would have no effect on posttest performance.

Testing was completed within a single session of approximately 80 minutes. At the end of the experiment, participants completed a questionnaire on demographics, history of visual and neurological problems, and self-rated level of computer use (Appendix C). The purpose of this questionnaire was to ensure that participants with specific visuospatial impairments or insufficient experience with computers were not included in the study. After completing the questionnaire, participants were asked, "How did you try to remember the sequences?" The experimenter manually transcribed descriptions of the reported strategies. The experimenter concluded the session by verbally disclosing the purposes of the study and issuing a standard, written debriefing.

Results

Questionnaire. All participants reported normal or corrected-to-normal vision. No participants reported known neurological problems. Seven of the 28 participants reported one or more head injuries, but none reported subsequent memory problems.

Based on responses to the 7-point Likert scale questions, all participants had adequate experience with using desktop computers (mean of 5.1 on self-rated expertise), and using the mouse (mean of 6.0 on frequency of use of mouse). Thus, all participants that were tested were retained in the final sample.

Spatial memory task.

Effects of sequence length and training group. Accuracy was defined as percent of locations recalled in the correct serial position. Thus, percent correct at each sequence length was calculated as locations correctly recalled divided by the number of locations tested at that length. For example, if an individual scored 3/5, 4/5, and 4/5 on three pretest trials, her score would be $11/15 = 73\%$ on the pretest at sequence length 5. This partial credit measure has recently been advocated (e.g., Fischer, 2001) as an alternative to traditional span measures, in which points were awarded only for sequences that were recalled perfectly. Span measures are appropriate for evaluating how many spatial locations people can remember under dual-task conditions (Smyth & Scholey, 1992, 1994) or with changes in age (Vecchi & Cornoldi, 1999). However, span measures do not permit testing of hypotheses related to performance at different levels of sequence length and serial position. Span measures were not analysed, but were reported in Appendix D to allow comparison with other studies that used a Corsi-type task. Mean percentages correct will be used as the primary dependent measure throughout the present research.

Percentages correct were first calculated as the number of locations recalled in the correct serial position, divided by 126, which was the number of locations tested over the

21 trials in each session. Mean percentages correct were entered into a 2 (session: pretest vs. posttest) x 7 (length: 3 to 9) x 4 (training group) ANOVA² with repeated measures on the first two factors. ANOVA results are presented in Table 1. All reported differences were significant at the 0.05 level. Participants were more accurate on the posttest (79%) than the pretest (75%). There was no effect of training group and no interaction between training group and session. Thus, there was no support for the hypothesis that interacting with the same9-location layout enhanced accuracy on the posttest. All groups improved from pretest to posttest, and in fact the group that interacted with the different-9 layout improved slightly more than the group that interacted with the same-9 layout (5% vs. 3%). Differences in characteristics of the groups will be further considered in the Discussion.

Accuracy decreased as sequence length increased. Pairwise comparisons (Fisher's Least Significant Difference test) showed no differences in accuracy between lengths 3 (98%), 4 (98%), and 5 (91%). Accuracy at length 6 (80%) was lower than at any of the three shorter lengths, but higher than at the longer lengths. There was no difference between accuracy at lengths 7 (63%) and 8 (59%). Accuracy at length 9 (53%) was lower than at length 7 but not different than that found at length 8. In summary, there was a significant drop in performance between lengths 5 and 6, consistent with previous research showing that people can remember 5 or 6 locations in order. The drop

² The distributions of percent correct scores were negatively skewed, especially at shorter sequence lengths where some perfect scores were obtained. To address the non-normality of the data, proportions correct (values ranging from 0 to 1) were transformed using arcsin and arcsin(square root) transformations. However, the transformations did not improve the normality of the data according to the Kolmogorov-Smirnov and Shapiro-Wilks statistics. Untransformed data were used in all reported analyses.

in accuracy at length 9 suggests that participants continued to try to remember all the locations that were presented as task difficulty increased.

Table 1: ANOVA for percentages correct (4 training groups), Exp. 1

	<i>df</i>	<i>F</i>	η^2
Training group	3	1.11	.12
Error	24	(790.16)	
Session	1	12.76**	.35
Session x Training group	3	0.72	.08
Error	24	(124.32)	
Length	6	96.43**	.80
Length x Training group	18	2.00*	.20
Error	144	(210.83)	
Session x Length	6	1.92	.07
Session x Length x Training	18	0.73	.08
Error	144	(155.70)	

Note. Values enclosed in parentheses represent mean square errors.

* $p < .05$; ** $p < .01$

The interaction between length and training group was significant, as shown in Figure 2. To assist in interpretation of figures, 95% confidence intervals (CIs) were calculated as outlined by Loftus and Masson (1994; Masson & Loftus, 2003). Instead of using different error terms for different comparisons in a repeated measures design, a single interval was calculated using the mean square error term for the most complex interaction in the analysis of variance. Error bars on figures represent 95% confidence intervals. When the error bars overlap by less than half the distance on one side of the interval, the means will be significantly different as measured by significance tests such

as Fisher's Least Significant Difference test. For some figures, such as Figure 2, the confidence intervals were numerous and so were replaced by a single reference bar that represented the critically significant difference between any two means in the figure. The critically significant difference (CSD) was calculated as CI times $\sqrt{2}$ (Loftus & Masson, 1994).

Figure 2. Accuracy for the four training groups, Exp. 1.

As shown in Figure 2, at the shortest lengths (3 and 4), performance was very similar for all groups of participants. However, the group that performed the nonspatial intervening task showed a significant decline at length 5, whereas the three other groups showed their first substantial decline at length 6. From lengths 6 through 9, the nonspatial group performed similarly to the two groups who practiced pointing to 9-location layouts. In

contrast, the group that pointed to four locations maintained near-perfect performance at length 5 (97%) and then a steep decline at length 6 (69%) and again at length 7 (55%). To evaluate whether the interaction between training group and length was driven by differences in the way that groups responded when sequence length increased from 4 to 6, mean accuracies at lengths 6 through 9 were analyzed in a 2 (session) x 4 (length) x 4 (training group) ANOVA. As expected, the interaction of training group and length was no longer significant, $F < 1$. Performance varied more as length increased from 4 to 6 than it did at the longer lengths. The results suggest that variations in performance on the spatial span task are critical between lengths 4 and 6. Some individuals were able to maintain high levels of accuracy at lengths 5 and 6, whereas others were not. Additional data are needed to determine what characteristics of an individual are relevant to maintaining accuracy as length increases in this critical range. It is likely that strategy selection will be important in explaining the variability in participants' performance.

Serial position effects. Consistent with other proposals for domain-general mechanisms in serial memory, I had predicted that performance on the spatial task would show similarities to performance on a verbal span task. In verbal short-term memory research, researchers have interpreted primacy effects as indicative of the use of rehearsal and transfer of early items to long-term memory, whereas recency is taken to reflect the use of a short-term store. To examine whether these two components of performance were observed in the present data, serial position curves were generated (Figure 3). The data from the pretest and posttest were combined to provide more stable estimates of accuracy at each serial position (i.e., six data points per position rather than three). The

serial position curves generated separately for the pretest and posttest data showed the same patterns as those shown in Figure 3.

Figure 3. Serial position effects for each sequence length, Exp. 1.

Percent correct at any input position was calculated as the number of times that location was correctly recalled, divided by the number of trials for each length. Trend analyses were used to evaluate primacy and recency, as recommended by Farrand et al. (2001), and Avons and Mason (1999). Curves with a bow shape characteristically have a significant quadratic component. To test for serial position effects at each length, an ANOVA was conducted on accuracy across serial position for each sequence length (e.g., for length 7, there were seven levels of position). These analyses revealed a quadratic component to the position effect for lengths 5, 6 ($p = .062$), 7, 8, and 9. The significant quadratic component suggests that both primacy and recency effects were obtained at

lengths greater than 4, suggesting an underlying similarity in verbal and spatial serial recall, consistent with Jones et al. (1995).

Previous research on serial memory using abstract visual items, such as dots or half-filled grids, had yielded inconsistent results with respect to the size of the recency effect. Phillips and Christie (1977) found an advantage for the last item only, but Jones et al. (1995) reported that the recency effect for spatially presented dots extended over the last two or three locations when the demand for spatial information was decreased. Visual inspection of the curves shown in Figure 3 suggests that, in the present data, the recency effect was confined to the last location. The accuracy advantage for the final location was assessed by comparing accuracy at the last to the penultimate position, as recommended by Farrand et al. (2001). Mean percentages correct were entered into a 7 (length) x 2 (position: penultimate vs. last) ANOVA with repeated measures on both factors.³ Accuracy decreased as sequence length increased, $F(6, 162) = 63.07$, $MSE = 430.03$, $\eta^2 = .70$. Accuracy was higher on the last (79%) than the penultimate (70%) position, $F(1, 27) = 24.80$, $MSE = 291.50$, $\eta^2 = .48$. The interaction between length and position was significant, $F(6, 162) = 7.88$, $MSE = 150.66$, $\eta^2 = .23$.

³ When session (pretest vs. posttest) was included as a variable, neither session nor any interactions involving session were significant.

Figure 4. Accuracy advantage for recall of last location, Exp. 1.

As shown in Figure 4, there was no accuracy advantage for lengths 3 through 6, and a significant advantage for lengths 7, 8, and 9, with the largest differences obtained for lengths 7 and 8 (20.8% in each case). For lengths 7 through 9, the two measures of recency produced consistent results: the quadratic component of the position effect was significant and accuracy on the last item was significantly greater than on the penultimate item. For lengths 5 and 6, trend analyses showed a quadratic component, but accuracy on the last location was not higher than on the penultimate location. A significant quadratic component will be taken to reflect that the position effect showed some curvature and that a recency effect was obtained; the difference between accuracy on the last and penultimate locations will be taken as an estimate of the size of the recency effect.

In summary, as length increased, changing the spatial span task from relatively easy (3 locations) to moderately difficult (5 locations), people began to make errors in the middle of the sequences, and the recency effect emerged. The recency effect at lengths 5 and 6 was small, as indicated by a nonsignificant difference in accuracy between the last and penultimate locations. The recency effect at lengths 7 through 9 was large. In contrast, the primacy effect was evident at all lengths greater than 4, suggesting that the primacy and recency effects in visuospatial memory have distinct sources related to the way that items are processed during encoding. The effects of encoding-related variables on serial position effects will be further explored in subsequent experiments.

Strategy effects. I had predicted that strategic grouping would enhance spatial short-term memory performance. Strategy reports collected at the end of the experiment were examined to explore the cognitive processes that contributed to task performance. Participants reported the use of many different strategies. Seven out of 28 participants spontaneously noted that they had used more than one strategy over the course of the study, but all participants were able to identify a strategy that they used predominantly. Based on their reports, participants were assigned to one of three strategy groups:

- Parse: Group the items into shapes ($n = 10$). Examples of typical responses were “Tried to use groupings of three,” and “Visualized shapes such as triangles.”
- Path: Connect the boxes by visualizing lines or picture a moving object ($n = 9$). Typical responses were “Traced a line between the boxes,” and “connected the dots.”

- Verbal/Other: Recode the boxes with numbers, hum a tune, other idiosyncratic strategies ($n = 9$). Examples included verbal rehearsal of words, such as “up, down, middle”, visualizing digits corresponding to serial position inside the boxes, guessing, and trying to ignore the middle locations of longer sequences.

Mean percentages correct were analyzed in a 2 (session: pretest, posttest) x 7 (length) x 3 (strategy group) ANOVA with repeated measures on the first two factors. ANOVA results are presented in Table 2. The main effect of strategy group was significant: participants who used the parse strategy were more accurate (82%) than the path (75%), and verbal/other groups (75%). Accuracy improved from the pretest to the posttest. All three groups improved with practice, so there was no strategy by session interaction, $F < 1$.

Table 2: ANOVA for percentages correct (3 strategy groups), Exp. 1

	<i>df</i>	<i>F</i>	η^2
Strategy group	2	3.76*	.23
Error	25	(664.21)	
Session	1	12.64**	.34
Session x Strategy group	2	0.86	.06
Error	25	(121.72)	
Length	6	87.74**	.78
Length x Strategy group	12	1.03	.08
Error	150	(233.66)	
Session x Length	6	2.00	.07
Session x Length x Strategy	12	1.44	.10
Error	150	(146.27)	

Note. Values enclosed in parentheses represent mean square errors.

* $p < .05$; ** $p < .01$

Length was included as a within-subjects variable to test the hypothesis that the parse strategy was more beneficial for long sequences. The interaction between length and strategy group was not significant. However, it is clear from Figure 5 that all three groups were essentially at ceiling for lengths 3 and 4. At length 5, the path and verbal/other groups showed a larger decline than the parse group. This difference between the parse group and the two other groups was consistent across the other, longer lengths, with a few minor bumps in the curve. Thus, the parse strategy allows solvers to persistently score about 10% higher than the other two groups across sequence lengths from 5 through 9.

Figure 5. Accuracy for the three strategy groups, Exp. 1.

The strategy reports were exploratory in that participants were only asked about their strategies at the end of the study, just prior to the debriefing. Nevertheless, the reports suggest that one source of individual differences in the spatial memory task is the way that people encoded the locations during presentation of the sequence. People who reported that they predominantly used a parse strategy formed representations of the sequences that were better recalled, thus providing some evidence for a benefit of chunking in decreasing memory load and enhancing short-term memory performance.

Serial reaction time task

Total amount of time to complete all 12 blocks of the serial reaction time task ranged from 34.2 to 43.2 minutes ($SD = 2.8$). Mean reaction times were entered into an ANOVA with 12 levels of block (repeated measure) and three training groups. Mean times to react to spatial targets did not vary for the three groups, who each interacted with one of the three layouts (Appendix A). Reaction times increased over the twelve blocks (i.e., people were slower to respond in later blocks), $F(11, 198) = 2.36$, $MSE = 7661.86$, $\eta^2 = .12$. The interaction between training group and block was significant, $F(22, 198) = 2.15$, $MSE = 23008.60$, $\eta^2 = .19$. Participants who reacted to targets in the 4-location condition slowed down over the 12 blocks, whereas those who reacted to 9 locations (same-9 or different-9) did not.

Discussion

The data provided preliminary evidence that strategy use predicts aspects of spatial short-term memory performance. Retrospective self-reports suggested that a strategy of dividing the sequence into parts, and visualizing the parts as separate shapes,

was a more effective strategy than visualizing a single object, or verbally recoding a description of the sequence. Consistent with the model proposed in Figure 1, strategic grouping was used during encoding to enhance memory performance. In Experiment 2, the role of strategic grouping in generating stable representations will be explored. Participants will perform some trials while performing an additional task, and the impact of the extra task on performance will be evaluated.

There was a large overall drop in accuracy as sequence length increased from 5 to 7 locations. This result is difficult for the perturbation model to explain. The perturbation model predicts that accuracy should decrease gradually as sequence length increases, and does not predict that sequences of length 6 should be much harder than sequences of length 4. Again, strategies may be key to explaining the effects of length on difficulty. It is likely that participants adjusted their strategies and that additional resources were recruited as length increased from 4 to 7.

The predicted effect of exposure to the same layout as used on the memory test was not obtained. Interacting with the layout for 35 minutes by rapidly pointing to random sequences of locations did not produce greater gains between pretest and posttest than interaction with a different layout or performing a nonspatial task. There was no evidence that people who interacted with the same layout developed a retrieval structure in long-term memory that they used to enhance performance on the posttest. A more effective training program would influence the way people encoded the locations during the memory test. The training used in the present study did not encourage people to use strategies. Rather, it familiarized people with the test items, which were locations on the

screen. People also practiced executing movements between the sequences, but this did not seem to facilitate responding: people who executed movements in the same-9 layout did not improve more at posttest than those who practiced movements to other layouts or did not practice movements at all.

Participants had been randomly assigned to one of the four training groups. The interaction between sequence length and training group showed that some groups were more affected by increases in length than others. The four groups performed equally well on the spatial memory task at shorter lengths (3 and 4). However, at longer lengths, the groups differed in how steeply accuracy dropped as length increased. The group that pointed to a layout of 4 locations showed the steepest decline in accuracy. This group had also shown a slowing of reaction times across the 12 blocks of the SRT task, in contrast to the same-9 and different-9 groups. Lower motivation levels in the 4-location group may have contributed both to a steep decline in accuracy as spatial task difficulty increased, and a slowing of reaction times during the SRT task. However, no independent measures of motivation were available.

In other respects, the patterns of accuracy observed were consistent with those reported in other studies that used the Corsi Blocks task. Accuracy decreased as sequence length increased (Fischer, 2001; Smyth & Scholey, 1994b). The present data add to the few studies that have demonstrated serial position effects in spatial immediate memory (Farrand et al., 2001; Jones et al., 1995; Pickering et al., 1998). Both primacy and recency advantages were observed for longer sequences (lengths 5 through 9), as measured by significant quadratic components to the position effect. Accuracy on the

last position was higher than on the penultimate position for lengths 7 through 9, consistent with a recency advantage for the last item only. The capacity of visuospatial short-term memory appears to be small when measured using a task that requires memory for both locations and their order of presentation.

In general, the serial position curves were bow-shaped, and provide some support for domain-general mechanisms that support serial memory for both verbal and spatial materials. The recency effect was further explored in the Experiment 2. When an executive-demanding task was imposed between presentation and recall, the ability to maintain a representation of the last item in short-term memory was predicted to be impaired because executive processes are needed for visual rehearsal and keeping track of serial order. Parsing activities at encoding should not be inhibited by the additional task during the retention interval, and may work to create a more stable representation in long-term memory.

Experiment 2

Rationale

The results of Experiment 1 showed that strategic grouping can enhance overall accuracy in spatial short-term memory. According to the proposed model, strategic grouping modifies the nature of the representation in the workspace by adding cues that assist retrieval. People who use strategic grouping were predicted to develop representations that are more resistant to interference. The interference imposed during the retention interval in the present study was counting backwards by sevens, a task that is assumed to be demanding of central executive resources. In this task, participants saw a two-digit

number and verbalized subtraction responses. The model predicts an interaction between strategy group and decrement caused by interference: participants who parse more should have smaller decrements from the interference task because the additional effort at encoding should translate into a representation in long-term memory that is not affected by stimuli that subsequently enter the workspace, such as digits for the counting backwards task.

The model predicts that a secondary task with executive demands will impair accuracy on the memory task because the available resources for rehearsal and keeping track of order will decrease in the interference condition. The counting backwards task imposes a heavy executive load (Vallar & Baddeley, 1982) in addition to verbal output requirements, and possibly even visuospatial demands if visuospatial representations are used to solve subtraction problems (DeStefano & LeFevre, 2004). The issue of whether multiple memory systems are tapped by the counting backwards task will be revisited in the Discussion of the present results. The data from Experiment 1 showed an advantage for recall of the last item for long sequences. To the extent that the recency advantage is based on refreshing contents of a visual buffer, it is predicted that recency will be impaired by a concurrent, executive-demanding task, because the refresh process requires central executive resources.

An additional manipulation tested the impact of increasing the retention interval. Fischer (2001) reported that accuracy on the spatial span task was higher when people had 9 seconds to rehearse as compared to a standard, 1-second retention interval. In the present model, the benefit of additional time may be related to strategic grouping or

recoding when these activities persist into the retention interval. The impact of increasing the retention interval was difficult to predict from the model because more time was allowed both for elaboration and for decay or interference in memory. In order to investigate whether the benefit of extra time offsets the costs, two intervals were selected: 5 and 15 seconds.

Method

Participants. Forty-four undergraduate students were recruited from an introductory psychology course and received extra academic credit for their participation. Sixteen males and twenty-eight females participated, reporting normal or corrected-to-normal vision. The mean age was 20.0 years ($SD = 2.3$). None of the participants had taken part in the previous study. Two participants had very low accuracy on the counting backwards task such that fewer than half of their subtraction responses were accurate. It was unclear whether these participants were performing the secondary task, so their data were excluded from all analyses. Two other participants had difficulty on the spatial memory task, and were unable to correctly reproduce sequences of four locations under single-task conditions. These two participants reported no history of head injury or neurological disorders. It is possible that they had not understood the task instructions. Due to floor effects in performance, the data for these two participants were excluded from all analyses. The attrition in this study may mean that the results are not generalizable to people who cannot remember four or more locations in order. The remaining forty participants (16 males, 24 females) had a mean age of 20.0 years ($SD = 2.4$).

Apparatus. Stimuli were presented on a 16-inch colour monitor (Dell E770s) connected to a Pentium III processor running Windows ME. Experiments were programmed in E-Prime 1.1. Responses for the spatial memory task were collected using a standard mouse. The amount of time taken to name the first digit in the counting backwards task was measured via a microphone attached to a headset. All response times were measured in milliseconds.

Materials. The spatial layout and spatial sequences were the same as those used in Experiment 1 (Appendices A-1 and B-1), with the exception of new sequences that were created for additional practice trials. None of the practice sequences were used in the experimental trials. Two-digit numbers for the counting backwards task were randomly generated by the computer program during the experiment.

Procedure. The spatial memory task was administered as described in Experiment 1 with the following exceptions. The trial did not terminate when the correct number of responses was given; participants clicked an icon labeled “Finished” to terminate the trial. The instructions were modified to indicate that participants should not touch the screen or move the mouse during presentation of the sequence.

Half of the participants had the control condition first, and the other half had the interference condition first. There were two levels of retention interval (5 vs. 15 seconds) and two orders (control condition first vs. interference condition first), resulting in four conditions. Participants were randomly assigned to one of the four conditions with the constraint that an equal number of participants were assigned to each condition.

There were three sets of practice trials: spatial memory task alone, counting backwards task alone, and both tasks together. In the first set of practice trials, participants attempted to reproduce six sequences of four locations. Immediately preceding the experimental trials for the interference condition, participants were fitted with a comfortable headset with a microphone attached. They practiced the counting backwards task (10 trials) and then the spatial memory task together with the counting backwards task (6 trials). On practice trials for the counting backwards task, a two-digit number between 69 and 99 appeared in the upper central region of the screen in blue font. Participants named the number and then counted backwards by sevens (e.g., “71, 64, 57...”) for either 5 or 15 seconds, corresponding to the interval condition to which they had been assigned. They were instructed to stop counting when the blue frame appeared at the perimeter of the computer screen.

After practicing the counting backwards task, participants practiced combining counting backwards with the spatial memory task. On these trials, participants viewed the spatial sequence, and then saw a two-digit number in blue font in the upper right corner of the screen at the beginning of the retention interval. They saw the spatial sequence and counted backwards aloud by sevens during the retention interval. After seeing the blue frame, they reproduced the spatial sequence using the mouse. Participants were asked to “get as many locations correct as possible,” and to place less emphasis on the subtraction task, but to continue performing the subtraction task throughout the retention interval. The location sequences used in the practice trials for

the interference condition were the same as the practice sequences used for the control condition.

During the experimental trials, the verbal responses produced during the counting backwards task were manually recorded and later transcribed. Reaction times for the counting backwards task were collected via a microphone for the first verbal response only. Testing and debriefing were completed within a one-hour session. At the end of the experimental trials, participants completed a questionnaire (Appendix C) on demographics, history of neurological problems or injuries, and level of computer use. Participants also rated the frequency with which they broke the sequence into “two or three groupings” on a 5-point scale (1 = never, 2 = rarely, 3 = sometimes, 4 = often, 5 = always).

Results

Questionnaire. All participants reported normal or corrected-to-normal vision. No participants reported known neurological disorders, and six out of 40 reported one or more concussions. There were no reports of memory disorders related to head injuries. Based on responses to the 7-point Likert scale questions, all participants had adequate experience with using desktop computers (mean of 5.1 on self-rated expertise), and using the mouse as an input device (mean of 6.4 on frequency of use of mouse). Thus, all participants who were not previously excluded due to floor effects in performance were retained in the final sample.

Spatial memory task.

Effects of interference task. To examine the overall effect of the load task on spatial memory performance, percentages correct were first calculated as the number of locations recalled in the correct serial position, divided by 126, which was the number of locations tested over the 21 trials in each condition. Percentages correct were entered into a 2 (condition: control vs. interference) x 2 (order: control first vs. interference first) x 2 (interval: 5 vs. 15 seconds) ANOVA with repeated measures on the first factor. ANOVA results are presented in Table 3. Participants recalled more locations correctly in the control condition than when they had to count backwards during the retention interval (72% vs. 53%). There were no effects of order, nor any interactions involving order, so order will not be included in subsequent analyses. No other main effects or interactions were significant. Participants who recalled the sequences after an interval of 5 seconds were as accurate as those who recalled after 15 seconds (62% vs. 62%). There was no additional impairment associated with the longer delay, consistent with the hypothesis that rehearsal during the retention interval offers some benefit that counteracts decay of representations. The condition by interval interaction was not significant, suggesting that participants in the 5- and 15-second interval conditions were equally impaired by the interference task.

Table 3: ANOVA for control versus interference conditions, Exp. 2

	<i>df</i>	<i>F</i>	η^2
Between subjects			
Interval	1	0.00	.00
Order	1	0.37	.01
Interval x Order	1	0.09	.00
Error	36	(209.40)	
Within subjects			
Condition	1	146.30**	.80
Condition x Interval	1	3.43	.09
Condition x Order	1	2.31	.06
Condition x Interval x Order	1	0.82	.02
Error	36	(48.27)	

Note. Values enclosed in parentheses represent mean square errors.

** $p < .01$

To test the hypothesis that the counting backwards task competed with resources for the memory task, the interaction between condition and length was examined. When two tasks use overlapping resources, we expect greater effects on primary task performance as task difficulty increases, in this case, as more locations had to be remembered. Mean percentages correct were entered into a 2 (condition) x 7 (length) x 2 (interval) ANOVA with repeated measures on the first two factors. Both the main effects of length and condition were significant. Participants recalled a lower proportion of locations correctly as the number of locations in the sequence increased, $F(6, 228) = 104.18$, $MSE = 257.33$, $\eta^2 = .73$. People were less accurate in the interference condition, $F(1, 38) = 143.04$, $MSE = 389.48$, $\eta^2 = .79$. The main effects of length and condition were

qualified by their two-way interaction, $F(6, 228) = 3.52$, $MSE = 181.36$, $\eta^2 = .09$, which is shown in Figure 6.

Figure 6. Accuracy in control and interference conditions, Exp. 2.

Within each condition, accuracy was similar at lengths 3, 4, and 5. At length 6, accuracy dropped significantly, with a steeper decline in the interference condition. Within each condition, accuracy was similar at lengths 7 and 8, with another drop in performance at length 9. The significant drop-off in performance at length 9 suggests that people were processing all of the locations, rather than selectively remembering parts of the sequence when their spans had been exceeded and when they had to combine the spatial memory task with a difficult secondary task. The overall pattern suggests that the counting backwards task caused a large overall decrement at all sequence lengths, and that the impact of the interference task was greatest at lengths 5 and 6, corresponding to

the lengths at which span is usually exceeded. As in the previous analysis of overall accuracy (Table 1), participants in the 5- and 15-second interval conditions performed equally well, $F < 1$.

Serial position effects. To further examine the effects of interference, accuracy was examined at the different serial positions. If the interference task imposed a general load that prevented rehearsal during the retention interval, we would expect impairment at all serial positions, as found by Jones et al. (1995). If the interference task were specific to a visual short-term store, we would expect additional impairment of memory for the last location in the sequence. Serial position curves for each of the sequence lengths are shown in Figure 7.

Figure 7. Serial position effects, control and interference conditions, Exp. 2.

In the control condition, both first and last positions were advantaged for longer spatial sequences, and performance was near-perfect at all serial positions for short sequences, consistent with the levels of accuracy observed in Experiment 1 (Fig. 3). As shown in the left panel of Figure 7, for short sequences (3 through 5), there was little variability in accuracy at middle positions, so there were no primacy or recency effects. There was a substantial drop in accuracy between lengths 5 and 6. Participants made more errors as sequence length increased from 5 through 9, especially on middle positions. Visual inspection of these curves suggests that the recency effect for spatial recall was confined to the last item in the sequence, consistent with the data from Exp. 1. Accuracy on the last location did not differ for the 5 and 15 second interval groups (79% vs. 82%, respectively), $t(38) = 1.45$, $p = .16$, suggesting no loss of information about the last location between 5 and 15 seconds of retention.

For lengths greater than 5, there were more errors in the middle of the sequences, but the curves were not uniformly bow-shaped. For length 6, accuracy was similar at all middle positions (81%) except the fifth (62%). For lengths 7 and 8, accuracy at the middle positions ranged from 49% to 70%, with a benefit in accuracy for the fourth position as compared to the third and fifth positions. This peaked pattern had not been observed in the data from Experiment 1 (Fig. 3), and thus the levels of accuracy at middle positions may be unstable when measured in small and medium-sized samples. For length 9, there was no peak in accuracy near the middle of the sequence.

Serial position curves for the interference task data are shown in the right panel of Figure 7. For short sequences (lengths 3 through 5), the interference task caused a large

overall drop in performance and errors in the middle of the sequences, consistent with a general load effect. For long sequences (lengths 6 through 9), the effect was to reduce the accuracy benefit of the last position over the penultimate position, consistent with a specific impairment of resources needed to maintain a visuospatial representation in short-term memory. The primacy effect, in contrast, was typically preserved.

Trend analyses were conducted to assess primacy and recency effects at each length. For the control condition, trend analyses revealed a quadratic component to the position effect for lengths 5, 7, 8, and 9. The trend analyses suggest that primacy and recency effects were obtained for the longer lengths in the control condition. In the interference condition, the quadratic effect remained significant for some lengths (5, 7, and 9), but not for length 8. In general, the trend analyses suggested that the recency effect persisted in the interference condition, although its magnitude was reduced.

Performance on the penultimate and last locations were compared in a 2 (condition) x 7 (length) x 2 (position) ANOVA with repeated measures on all factors. ANOVA results are presented in Table 4. All three main effects were significant, with better performance in the control condition, at shorter lengths, and at the last serial position. The condition by length and position by length interactions were significant, and were qualified by the significant three-way interaction⁴. To illustrate the three-way interaction, difference scores shown in Figure 8 were calculated by subtracting accuracy on the penultimate item from accuracy on the last item. As shown in Figure 8, in the control condition, accuracy on the last position was higher than on the penultimate

⁴ An identical pattern of results was obtained when interval was added as a between-groups variable, which accounted for very little variance, $F < 0.1$.

position for lengths 6 through 9. In the interference condition, the critically significant difference was exceeded for lengths 4 and 7 only. The three-way interaction occurred because recency was more impaired by interference at longer than shorter lengths.

Table 4: *ANOVA for percentages correct by serial position (penultimate vs. last), Exp. 2*

	<i>df</i>	<i>F</i>	<i>df</i>	<i>MSE</i>	η^2
Main effects					
Condition	1	147.91**	39	(1075.99)	.79
Length	6	109.87**	234	(737.60)	.74
Position	1	46.21**	39	(446.41)	.54
Interactions					
Condition x Length	6	3.47**	234	(775.50)	.08
Condition x Position	1	2.41	39	(378.81)	.06
Length x Position	6	3.89**	234	(383.77)	.09
Condition x Length x Position	6	4.67**	234	(335.02)	.11

Note. Values enclosed in parentheses represent mean square errors.

** $p < .01$

The impact of the interference task on recency was more complex than had been predicted. There was an overall decrease in accuracy when the counting backwards task was imposed during the retention interval. At longer lengths, the recency effect was reduced by interference, but for shorter lengths, there was some trend for recency to emerge because people began to make errors in the middle of shorter sequences.

To assess the relative impact of interference on the primacy and recency effects, the first and last positions were selected to represent the two effects. Mean percentages correct were analyzed in a 2 (task: control vs. interference) x 7 (length: 3 through 9) x 2 (position: first, last) ANOVA with repeated measures on the all three factors. ANOVA

results are presented in Table 5. All three main effects were significant. Participants remembered more locations in the single task condition (85%) than in the interference condition (64%). Accuracy was higher for the first position (81%) than the last position (68%).

Figure 8. Interference effect on accuracy advantage for the last location, Exp. 2.

Accuracy decreased as sequence length increased. Accuracy was highest for sequences of length 3, 4, and 5 (89%, 88%, and 87%), and somewhat worse for lengths 6 and 7 (70% and 70%). Accuracy was lowest at lengths 8 (60%) and 9 (54%). There were significant two-way interactions between condition and position, and between length and position. As indicated by the condition by position interaction, the difference in performance between the first and last item in the control condition (89% vs. 80%) was about half that in the interference condition (73% vs. 55%). This result suggests that interference has a greater impact on recency than on primacy effects. The length by

position interaction occurred because the first and last items were recalled equally well at positions 3 and 4, whereas the last items were recalled less well at lengths 5 through 9. Thus, recency decreased more with length than primacy. These two interactions were qualified by the 3-way interaction of position, length, and condition, as shown in Figure 9.

Table 5: ANOVA for percentages correct by serial position (first vs. last), Exp. 2

	<i>df</i>	<i>F</i>	<i>df</i>	<i>MSE</i>	η^2
Main effects					
Condition	1	140.69**	39	(870.63)	.78
Length	6	62.27**	234	(527.58)	.62
Position	1	82.83**	39	(584.01)	.68
Interactions					
Condition x Length	6	1.77	234	(471.31)	.04
Condition x Position	1	12.86**	39	(479.17)	.25
Length x Position	6	24.84**	234	(351.31)	.39
Condition x Length x Position	6	7.52**	234	(377.11)	.16

Note. Values enclosed in parentheses represent mean square errors.

** $p < .01$

Figure 9. Primacy and recency effects in control and interference conditions, Exp. 2.

As shown in the left panel of Figure 9, in the control condition, participants recalled the first and last locations equally well for series of lengths 3 through 7. At lengths 8 and 9, however, performance on the last item was significantly worse than on the first item. Furthermore, performance on the last item at length 9 was especially poor, dropping from 63% at length 8 to only 40% at length 9. Although accuracy on the last item at length 9 was still well above chance (11%), the recency effect was reduced when people attempted to recall sequences that were beyond their span.

As shown in the right panel of Figure 9, the impact of interference on the recency effect occurred very early, such that from length 5 to 9, participants recalled the last item less well than the first item. Furthermore, the substantial drop in performance on the last item that occurred for series of length 9 in the control condition was evident at lengths 7, 8, and 9 in the interference condition. Hence, although interference produced poorer memory for locations for both the first and the last items in this task, it had much greater impact on the last items.

These multiple ways of looking at the recency effect all suggest that recency was reduced but not eliminated in the interference condition. The executive task competed for resources that were needed to maintain a visuospatial representation of the last location in memory, resulting in a greater impairment of recency than primacy. However, there was still an accuracy advantage at some lengths for the last as compared to the penultimate location in interference condition, suggesting that the most recent item remained distinctive in memory, perhaps due to an edge effect as proposed by Brown et

al. (2000). The first and last items in a sequence suffer less interference than other items because they have only one neighbor.

Reported use of grouping strategies and relation with accuracy. To assess the impact of strategies on accuracy, participants were divided into two groups based on how frequently they estimated that they had divided the sequences into two or three groupings. The low-parse-frequency group ($n = 22$) had given ratings of 1 to 3 (never, rarely, sometimes); the high-parse-frequency group ($n = 18$) had given ratings of 4 or 5 (often, always). Overall percentages correct were entered into a 2 (condition: control vs. interference) $\times$ 7 (length) $\times$ 2 (low vs. high frequency of parsing) ANOVA with repeated measures on the first two factors. Participants who reported that they had parsed the sequences often or always were more accurate than those who reported parsing less frequently⁵ (66% vs. 59%), $F(1, 38) = 4.94$, $MSE = 1086.24$, $\eta^2 = .12$. Accuracy was lower in the interference than the control condition (58% vs. 78%), $F(1, 38) = 134.01$, $MSE = 401.00$, $\eta^2 = .78$. For participants who parsed frequently, the decrement from the control to the interference condition was 16%; for participants who parsed less frequently, the decrement was 21%. Thus, the participants who parsed more frequently showed a smaller decrement, although the interaction between strategy group and condition was not significant because the pattern was essentially the same for the two groups of participants, $F(1, 38) = 2.29$, $MSE = 401.00$, $\eta^2 = .06$. The interaction between condition and length was significant: in the interference condition, accuracy was impaired at shorter sequences than in the control condition, as previously shown in Figure 6. The interaction

⁵ Comparing high- and low-parse-frequency participants by omitting those who gave a rating of “3” on the 5-point scale yielded a similar pattern of results.

between length and strategy group was not significant: accuracy decreased similarly as length increased for the high- and low-frequency parse participants. However, the high-frequency parse group outperformed the low-frequency parse group only at lengths 6 and 7, with smaller, nonsignificant advantages at each of the other lengths. Although the interaction between strategy group and length did not reach significance, the parse group had a significant advantage at some of the longer lengths, as found in Experiment 1 (see Figure 5).

As found in Experiment 1, many participants developed a parsing strategy without any instructions to do so, and greater frequency of parsing was related to higher overall accuracy on the memory task. People who parsed more frequently were more accurate at all sequence lengths, with significantly better performance at lengths just above average span. Participants described various strategies at the end of the experiment, but there was no obvious relation between strategies, such as verbal recoding or associating locations with musical tones, and accuracy. Strategy data will be collected on a trial-by-trial basis in subsequent experiments to further examine relations between strategies and accuracy.

Subtraction performance.

Secondary task performance was measured to ensure that participants were performing the secondary task as instructed at all levels of the spatial task.

Rate of response and accuracy. The total number of subtraction responses produced during the retention interval was used as an index of secondary task performance. The first response, in which the participant named the two-digit number

that appeared on the screen, was excluded. Mean numbers of responses were entered into a 7 (length: 3 through 9) by 2 (interval: 5, 15 seconds) ANOVA with repeated measures on the first factor. There were no significant main effects or interactions. Participants produced a mean of 1.75 responses per 5 seconds. The absence of a length effect suggests that participants continued to perform the subtraction task as the difficulty of the spatial task increased. The two groups did not differ in the rate of responding: participants in the 5 and 15 second interval groups produced 1.66 and 1.84 responses per 5 seconds, respectively. Participants in the two interval conditions performed the subtraction task at an equal speed and presumably with an equal amount of effort.

The analyses of subtraction accuracy also showed that participants maintained their performance as the difficulty of the spatial task increased. Percent correct was calculated as the number of correct responses divided by the number of subtraction responses over the 21 trials in the interference condition. Mean accuracy was 88% ($SD = 13\%$). Mean percentages correct were entered into a 7 (length: 3 through 9) by 2 (interval: 5, 15 seconds) ANOVA with repeated measures on the first factor. There was no effect of length on subtraction accuracy, $F < 1$. However, participants who performed the subtraction task for 15 seconds were more accurate at subtracting (92%) than those who subtracted for 5 seconds (84%), $F(1, 38) = 9.49$, $MSE = 1362.89$, $\eta^2 = .20$. Participants in the 15 second group may have had higher arithmetic skill than those in the 5 second group, or the subtraction task may have been slightly easier in the longer interval condition. This hypothetical advantage in arithmetic skill did not mitigate the load imposed by the counting backwards task: the decrement in accuracy on the spatial

task was of similar magnitude for the two interval groups, and in fact the decrement was slightly greater for the 15 second interval group.

The absence of length effects on subtraction response rate or accuracy suggests that the amount of effort allocated to the interference task was constant as length increased. The effects reported above involving length therefore do not need to be qualified with respect to tradeoffs between the two tasks. To ensure that the high parse frequency participants did not sacrifice performance on the counting backwards task to meet the demands of the primary task, secondary task performance was assessed for the two strategy groups by entering mean subtraction accuracies and latencies into separate 7 (length) x 2 (strategy group: high-frequency parse vs. low-frequency parse) ANOVAs with repeated measures on the first factor. There were no differences between the two groups on subtraction accuracy or speed. The two groups did not appear to differentially allocate their mental resources to the two tasks. Thus, it seems reasonable to attribute performance differences between the two groups to the activities performed by participants during the encoding phase of the spatial memory task.

Naming times. Naming times were compared for the two interval groups to determine whether they were equally fast at switching from the spatial task to the counting backwards task. For 86 of the 840 trials, reaction times of zero were recorded due either to no verbal response by the participant (5 trials) or equipment failure (81 trials). Naming times between 15 and 300 ms were considered likely to reflect accidental triggering of the microphone (e.g., from loud breathing) and were excluded (8 trials). Naming times greater than 4000 ms were considered likely to reflect failure of the

microphone to register the naming response, and were excluded (35 trials). Of the 840 trials, 85% were retained. Based on the remaining trials ($n = 711$), mean naming times were calculated for each participant. There was no difference in naming times for the two groups, $t(38) = -.096$, $p = .92$. Participants in the 5-second interval condition had mean naming times of 1394 ms as compared to 1408 ms for the 15-second interval condition. At the start of the retention interval, participants in both groups rapidly shifted their attention from the last location that was presented to the upper right corner of the screen, where the two-digit number was presented.

Correlations among measures.

Correlations among the performance measures reported above are presented in Table 6. Accuracy on the spatial task, in both control and interference conditions, was positively correlated with subtraction response speed and subtraction accuracy. People who performed well on the spatial task also tended to perform well on the counting backwards task. Subtraction response speed and subtraction accuracy were positively correlated, suggesting that participants did not trade off between speed and accuracy on the subtraction task. Digit naming speed showed a moderate negative correlation with subtraction response speed: participants who were faster to name the first digit produced more responses during the counting backwards task. Together with the ANOVA results, the correlational data suggest positive relations between primary and secondary task performance, and no tradeoffs between the two tasks.

Table 6: *Intercorrelations for Spatial Memory and Subtraction Task Measures, Exp. 2 (N = 40)*

Measure	1	2	3	4	5
1. Percent locations correct: control	--				
2. Percent locations correct: interference	.61**	--			
3. Subtraction response speed	.33*	.36*	--		
4. Subtraction accuracy	.37*	.33*	.43**	--	
5. Digit naming speed	.16	-.11	-.37*	-.23	--

* $p < .05$; ** $p < .01$

Discussion

The results are largely consistent with those reported in the extant literature, with some new findings that add to the existing data. As found in previous studies using a serial spatial memory task, a secondary task designed to consume executive resources impaired accuracy on the spatial task. The results are consistent with those implicating the central executive in the processing of visuospatial information (Klauer & Stegmaier, 1997; Miyake et al., 2001). Accuracy was impaired in the interference condition even for short sequences of lengths 3 and 4, for which performance had been near ceiling in the control condition. These data are consistent with other studies showing interference effects for short sequences (Smyth & Pelky, 1992; Smyth & Scholey, 1994b, Experiment 5). For verbal items, short sequences below a person's span can be maintained while performing a secondary task. In contrast, there was no evidence for a component of spatial working memory that is resistant to interference. As suggested by the model in Figure 1, rehearsal of representations in the workspace requires executive processing.

The present results support the emerging perspective that spatial short-term memory relies heavily on executive involvement.

Participants who used strategic grouping did better both in the control and the interference condition. There was some evidence that the people who used a parsing strategy formed representations that were more resistant to interference than people who infrequently parsed: the high parse frequency group showed a smaller decrease in overall accuracy when interference was imposed than the low parse frequency group. The strategies used during encoding did not interact with the processes that cause decay of the representation during the retention interval.

The interaction between task condition and length supported a role for executive processes in the spatial span task. As the number of locations that participants had to remember increased, the impact of the interference task increased. In particular, the differential changes in slope at length 6 for the control versus interference conditions suggest that as span is exceeded, different procedures are recruited to accomplish the spatial memory task. This hypothesis will be further explored in subsequent experiments.

It seems likely that participants tended to select different strategies at different lengths. Smyth and Scholey (1992, Experiment 2) had reported an interaction of length with condition (control vs. articulatory suppression) in a dual-task study. Spatial recall was impaired by articulatory suppression, and this effect was due to a large impairment at length 6. The decrement observed at length 6 was triple that found at each of the other lengths tested (3 through 8). In the present research, performance at length 6 also showed exaggerated sensitivity to interference, as shown in Figure 6. As seen in the left panel of

Figure 7, performance decreased at all serial positions when length increased from 5 to 6, with a reduction of the primacy effect at length 6. The sensitivity of 6-item sequences to impairment may be related to shifts in strategy selection as length increases. This hypothesis will be revisited using the data from Experiments 3 and 4. Limited strategy data were available based on questions posed at the end of the experiment. Strategy reports will be valuable in assessing whether increased executive load at longer lengths is related to the use of effortful strategies.

When people counted backwards during the retention interval, there was an overall decrement in performance for lengths 3 and 4, but accuracy did not vary across serial positions. There were no primacy or recency effects at these short lengths, and thus no primacy or recency effects to be impaired. When people had to count backwards while retaining sequences around their span length (5 and 6) or above span (7 through 9), the primacy effect was relatively spared but the recency effect was reduced. This result suggests that the counting backwards task uses resources that are also required to maintain the most recent spatial item, either through rehearsal or through a control process that maintains the serial position of the last item (i.e., the “keeping track” process in Fig. 1). Recency for the last visual-spatial item was impaired by a central executive task, so a spatial-specific task is not required to impair recency.

The present results contradict those reported by Fisk and Sharp (2003), who found that random letter generation did not impair the recency effect in spatial short-term memory. Random letter generation and counting backwards are similar in that they involve executive processes and a series of verbal responses. In the present study,

percentage correct averaged across lengths decreased from 72% in the control condition to 53% in the interference condition. Fisk and Sharp (2003; Experiment 1) reported a comparable decrease in accuracy from 71% in the control condition to 57% in the random letter generation condition. The reason that they did not find a specific effect of interference on recency was probably related to the nature of the spatial memory task that they used. In their spatial task, participants reproduced the last four locations, whether 4, 6, 8, or 10 locations had been presented. The purpose of this task modification was to require participants to update their representations in working memory, and to experimentally manipulate the number of times the representation had to be updated. Fisk and Sharp hypothesized that more updating would require central executive resources, as one of the functions of the central executive is to update memory representations. The recency effect that they obtained was enhanced by lower response interference than in the present study, which required participants to produce all locations in the correct order. As suggested by Cowan et al. (2002), recall of recent items is impaired when output interference is increased. The task used by Fisk and Sharp may also have caused a shift in the amount of attention people gave to the parts of the sequence. When recall of all items is required, as in the present study, people may be encouraged to pay attention to early parts of the sequence. When the number of locations is unknown, and only the last four locations must be recalled, participants may be biased to pay more attention to later-presented items, as these have a greater probability of being tested for recall. Thus, two sources are proposed for the spared recency effect obtained

by Fisk and Sharp: 1) decreased output interference and 2) increased attention given to items presented late in the sequence.

Also inconsistent with Fisk and Sharp, the data show an interaction between condition (control vs. interference) and length. Fisk and Sharp (2003) had predicted such an interaction between condition (random letter generation vs. spatial tapping) and length (short vs. longer sequences). They argued that the central executive task, random letter generation, would cause more impairment for longer sequences because more updating was required. Updating in their task referred to adding locations to the memory representation and dropping early-presented items that would not need to be recalled. Contrary to their prediction, they found that random letter generation was equally disruptive at all sequence lengths. The nature of the primary task may have created greater executive demands than expected even for the shortest sequences, and longer sequence lengths may not have required greater executive resources to process. The present data indicate that the interaction predicted by Fisk and Sharp can be obtained with certain combinations of spatial and executive-requiring tasks.

With respect to the recency effect, these data provided further evidence that recency for locations presented sequentially is confined to the last location. These data were not consistent with those reported by Jones et al. (1995), who reported an accuracy advantage that extended over the last two spatial locations. However, their task differed from the one used in the present study in that participants did not have to remember which locations had been presented, but only their order. In the present study, the requirement to remember location as well as order information reduced the extent of the

recency effect. Jones et al. only tested sequences of seven locations, and reported that the recency effect was unaffected by interference tasks that included tapping in a pattern and reciting alphabetic sequences. In contrast, when an executive-demanding task was interpolated between presentation and recall in the present study, the recency effect was reduced. It should be noted that Jones et al. imposed secondary tasks both during encoding and the retention interval, so their participants did not have to start a new task just after the end of sequence presentation. The reduction of the recency effect in the interference condition of the present study may be partly attributable to an interruption effect, but this possibility cannot be evaluated given the available data. It would be interesting to examine the effects of different types of interruptions on accuracy, such as visually presented digits that participants did not have to respond to, which would engage spatial attention but impose no executive load.

Contrary to Fischer's (2001) report of a rehearsal benefit in spatial memory, there was no effect of increasing the retention interval. The attentional resources required for rehearsal may cancel out the benefit afforded by the extra time available to consolidate items to long-term memory. With a 1-second interval between presentation and recall, the demand to begin recall right away may work as an interruption of processing the sequence. Fischer may have found a benefit for the 9-second interval over the 1-second interval because in the 9-second condition, participants were able to continue some strategic grouping or recoding. The benefit of extra rehearsal time may only extend to a few seconds. Beyond a certain interval, extra time does not seem to help as attentional resources are required for rehearsal, and longer intervals produce greater decay and

increase the probability of confusions in memory. Extending the retention interval from 5 to 15 seconds had no impact on the amount of forgetting, on the effects of increasing sequence length, on the decrement caused by the interference task, or on the size of the recency effect. Thus, it seems safe to conclude that between 5 and 15 seconds of retention, the benefits of an active rehearsal process are balanced against loss of information that occurs through decay or interference.

As in other studies of spatial serial memory (Smyth & Scholey, 1994a; Farrand et al., 2001), predictions made from models of verbal memory were not supported when locations were used as stimuli. A well-established formula in the study of verbal serial memory is that the size of the recency effect can be predicted from the ratio between the inter-item presentation interval (IPI) and the retention interval (RI). Two IPI:RI ratios were compared in the present study: 0.2 (1 second : 5 seconds) and 0.07 (1 second : 15 seconds). In verbal serial memory, this difference in the ratio produced a smaller recency effect, as found by Nairne et al., (1997) who included two ratios similar to those used in the present research: 0.25 and 0.08. They tested participants on free recall of letters, and found that the recency effect decreased as the ratio decreased. No such difference was found in the present study of memory for spatial locations when the IPI:RI ratio was manipulated over a similar range of values.

The data have been interpreted to support the hypothesis that executive processes are used to refresh the visuospatial representation of the last location in the sequence. However, an alternative hypothesis suggested by the literature on verbal serial memory should be considered. The suffix effect refers to the finding that presenting an irrelevant

cue, such as the word “Recall,” at the end of a to-be-remembered list, decreases the recency effect (Roediger & Crowder, 1976). For speech stimuli, the irrelevant cue has automatic access to the auditory trace, and is hypothesized to be automatically added to the memory representation, thus weakening the advantage for recent items. In the present study, the number to be used in the distractor task was presented in the upper right corner of the screen. This cued location could potentially work as a suffix to the presented sequence of locations, and thus the recency effect could have been impaired in the interference condition because the location of the number was added to the memory representation. However, the extant literature suggests that encoding of spatial locations is not automatic (Naveh-Benjamin, 1987, 1988; Zimmer, 1996), and in particular that encoding locations as sequences requires executive resources (Smyth & Pelky, 1992). There is no evidence to suggest that the location of the presented two-digit number would be automatically grouped with the sequence of locations being maintained in memory. An appropriate control condition could reduce the spatial salience of the number cue by presenting digits auditorily from a centrally located speaker. However, the spatial salience of the number cue was low in the present study because the number always appeared in the same location, and the location of the number was not relevant to either task. The explanation that the diminished recency effect in the interference condition is due to a suffix effect is less plausible than the explanation that the interference task consumes resources needed to maintain the last location in memory.

Another possibility that must be addressed is that the counting backwards task interfered with spatial memory by consuming visuo-spatial working memory resources

rather than executive processes. People may visualize digits when they solve arithmetic problems (Hayes, 1973). One dual-task study reported that subtraction problems in particular may engage visuospatial processing (Lee & Kang, 2002). The relative contributions of spatial and executive interference cannot be isolated given the available data. However, there was no evidence that spatial interference alone caused the observed decrements in the present study. The amount of impairment associated with counting backwards in the present study was of a similar magnitude to that caused by a central executive task in other research (e.g., Fisk & Sharp, 2003), and nearly double the decrement associated with visuospatial tapping tasks, such as tapping in a square pattern with one finger (e.g., Smyth & Pendleton, 1989, Experiment 2). The task requirements also made it unlikely that people would use visualization for solving subtraction problems. Participants were asked to try to “get as many locations correct as possible,” and to place less emphasis on subtracting accurately. Thus, they were likely to devote their visuospatial resources to the demanding primary task. If people had used visuospatial resources for subtraction, there would have been some relation between subtraction performance and increasing the difficulty of the primary task. However, no such relation was observed, so there was no evidence that people used visuospatial resources for subtraction.

The data suggested that one reason that parsers are more accurate is that the representations they generated during encoding were more resistant to interference from the counting backwards task. It is proposed that additional effort at encoding translates to better performance on the spatial span task. To further explore this possibility,

participants in the next two experiments were presented with different types of sequences, with some that were designed to bias people to use grouping more than others. In Experiment 3, half the sequences were easier to parse based on spatial separation of locations. In Experiment 4, grouping was encouraged by inserting a pause during encoding for half of the sequences.

The serial position effects obtained in Experiments 1 and 2 were somewhat inconsistent, especially for the middle positions of longer lengths. In Experiment 2, there were peaks in accuracy for two of the longer lengths, possibly related to grouping effects: if people remembered the sequence in two chunks, there may have been primacy and recency effects for each chunk. This was an intriguing possibility that was followed up by comparing primacy and recency effects for different groups of participants (high vs. low frequency of parsing) in Experiment 3. The serial position effects obtained thus far were somewhat unstable due to the small number of trials at each sequence length, producing patterns that were not identical to those found in Experiment 1. To obtain more reliable estimates of serial position effects, it was necessary to test a greater number of sequences on a smaller range of sequence lengths. Lengths 5 through 8 were selected for testing in subsequent experiments.

With respect to the model proposed in Figure 1, keeping track of serial order was a mandatory process in performing the spatial memory task, and was impaired by a concurrent, executive-demanding task. Strategic grouping was an optional process that, although presumably requiring executive resources, conferred an overall benefit to performance. The role of a rehearsal process in the spatial span task remained unclear.

Extra time for rehearsal neither conferred an advantage, as proposed by Fischer (2001), nor impaired accuracy, as would be predicted by models of serial memory (Estes, 1997). Preventing rehearsal by imposing a secondary task impaired accuracy, but whether rehearsal involved visualization or covert movements was not directly investigated. In subsequent experiments, participants will be asked to describe the processes used for rehearsal.

Chapter 4

One of the main findings from the first two experiments was that people who reported parsing the location sequences into groups scored higher on the spatial memory task than those who parsed the sequences less frequently. Parsers also formed representations that were resistant to interference from a demanding task interpolated between stimulus presentation and recall. If parsing aids recall due to the extra information that has been encoded, then recall should be higher for trials on which people use parsing, independent of whether the people were classified as high- or low-frequency parsers. Trial-by-trial self-reports will be used to test this hypothesis in Experiments 3 and 4.

People reported using multiple strategies over the course of the experiment, but additional data are needed to assess the determinants of strategy use. Item characteristics are known to affect strategy selection when there are multiple ways of performing a task. For example, strategy selection in mental arithmetic is related to problem characteristics, such as size of the operands (LeFevre, Greenham, & Waheed, 1993). According to models of strategy selection such as the Adaptive Strategy Choice Model (Siegler & Lemaire, 1997), strategies are chosen based on a competition process, whereby the problem is compared to previously solved problems and the success rate of different strategies on previous trials is factored in. People keep track of the success rate of different strategies. The distribution of strategy choice will shift over time because people prefer strategies with higher success rates (Schunn, Lovett, & Reder, 2001). When the problems are manipulated so that one strategy is more effective, people will

shift over trials to use that strategy more (Schunn et al., 2001). It is assumed that people can use information about the success rate of alternative strategies without awareness of these selection processes (Reder & Schunn, 1996; Siegler, 1996).

It is important to examine strategy use in complex tasks because aggregating across people may mask the activity of subgroups who are performing the task differently and thus relying on different combinations of mental processes (Lohman & Kyllonen, 1983; Siegler, 1987). Strategy reports can be used to determine which strategies are effective on a specific task, and then these can be used in training (e.g., Thorndyke & Stasz, 1980). Kyllonen, Lohman, and Woltz (1984) used the componential approach advocated by Sternberg (1977) to model individual differences in performance on a mental synthesis task. In this task, participants viewed two abstract shapes in succession, and had to judge whether a third shape could be composed of the first two shapes. Kyllonen et al. hypothesized that participants could adopt different strategies for encoding the first two shapes. One strategy was to analyze each figure into a set of basic features, such as angles. Another was to decompose each figure into units such as triangles and rectangles. A third was to apply verbal labels to describe the figure. They found that a single model did not provide a good fit to the data from most participants. Multiple models were needed to fit the data from individual participants, and some participants' data were fit equally well by more than one model, suggesting that participants used different strategies over the course of the experiment. A procedure for switching strategies in response to item characteristics was added to some of the models, resulting in better fits to the data for some participants. The results from Kyllonen et al.

suggest that some participants adapted their strategies to task demands on a trial-by-trial basis.

The available data on strategies used on the spatial span task are quite limited. Miyake et al. (2001) used the Corsi Blocks task as one of two visuospatial short-term memory (VS STM) tasks in a large-scale correlational study. They found a strong relation between executive functioning and VS STM and suggested this might be due to strategic processing, and thus executive involvement, in VS STM tasks. They noted:

Although we tried to discourage the use of idiosyncratic strategies...many participants nonetheless spontaneously reported using strategies to cope with the visuospatial demand by, for example, mentally creating a path.... These strategies are not particularly well-practiced for most participants, and implementing such effortful strategies likely makes the STM span tasks more than just simple storage tasks. (pp. 632-633).

Thus, Miyake et al. provided anecdotal evidence that effortful, executive-requiring strategies were used on the Corsi task, but specific strategies were neither identified nor connected to performance.

In an unpublished dissertation, Schwartz (1996) tested performance on the Corsi task. At the end of the experiment, she asked participants whether they had used any of nine strategies listed on a questionnaire. The frequencies of the reported strategies were not reported. Schwartz noted that the two most common strategies were “simply remembering the location of the blocks and a connect-the-dots strategy” (p. 45). She also

noted that almost all participants circled more than one strategy on the questionnaire, suggesting that they changed strategies on a trial-by-trial basis.

Given that participants' strategy reports will provide critical data, it is worthwhile to address the major issues related to using verbal reports as data. The issue of greatest concern is whether participants can provide veridical reports of the procedures they use in completing a task. Ericsson and Simon (1984) suggested that verbal reports are most useful when the task is deliberate, and when its execution is relatively slow. Thus, tasks that involve categorization are poor candidates, whereas tasks that require strategy selection, such as problem solving, are good candidates. The spatial span task meets the criteria established by Ericsson and Simon (1984), as information processing is both deliberate and relatively slow. Another issue related to self-reports is reactivity: people may change what they are doing when they know they will be asked to describe their processing. The reactivity issue can be directly addressed by comparing performance in self-report and no-report conditions, but was not addressed in the present research. It was likely that one effect of requiring self-reports on each trial was to discourage people from simply guessing, because they did not want to report that they had guessed.

The data from the Experiments 1 and 2 suggested that parsing the sequence into two groupings was an effective strategy. I hypothesized that for people who used parsing, accuracy could be further enhanced when sequences were amenable to parsing. New sequences (Appendix B-2) were designed such that some could be visualized as two, nonoverlapping shapes. Kemps (2001) used a related manipulation, comparing performance on two types of sequences, which she called "structured" and "complex."

Structured sequences had at least one of the following three characteristics: symmetry, continuation, or repetition. Structured sequences were more likely to have good continuation, meaning that the path did not cross itself. Kemps found that structured sequences were more accurately recalled, but the contribution of the continuation variable was not separated out from the other two characteristics.

Based on the work of Kemps (2001), it seemed likely that path continuation would be one predictor of problem difficulty: Continuous paths should be better recalled. I predicted an interaction between strategy use and the accuracy advantage for paths with good continuation: people who parsed the sequences should be better able to take advantage of the spatial separability of sequences. Berch, Krikorian, and Huha (1998), in their review of studies that used the Corsi Blocks task, argued that path configurations affect the complexity of spatial sequences, and that path configurations might “constitute the critical item information” (p. 331) in this task. They also noted that varying the placement of the blocks could affect the complexity of path configurations. This hypothesis was supported by the data from Kemps (1999), who found that recall was better when locations were arranged in a 5 x 5 grid than in an asymmetric layout. Smirni, Villardita, and Zappalà (1983) showed that the difficulty of a spatial sequence was not adequately predicted by the number of locations that had to be remembered: when tested on sequences ranging in length from 3 to 9, they found that 58% of their participants could correctly reproduce longer sequences after failing on some shorter ones. Thus, the limited available data suggest that both sequence length and path complexity affect task difficulty.

Experiment 3

Rationale

This study further explored the benefit noted in Experiment 2 for the people who parsed the sequence. Self-reported strategies were collected on each trial to provide additional data on the relationship between strategies and accuracy. Ten spatial sequences were tested at each of 4 lengths (5 through 8). Length increased every ten trials. Half of the sequences were designed so that they could be visualized as two distinct groupings; the other half could not. I hypothesized that the sequences that formed two groupings would be easier overall, and that people who used a parsing strategy would do especially well on these sequences.

Method

Participants. Eight males and twelve females reporting normal or corrected-to-normal vision participated for extra academic credit. None had participated in the previous experiments. Mean age was 19.6 years ($SD = 2.3$).

Apparatus. Same as Experiment 2 except that the microphone was not used.

Materials. Forty sequences (ten for each length from 5 through 8) were selected from a pool of forty-eight sequences created by the author. Half of the sequences could be visualized as two spatially separate groupings (“spatially separable”); the other half could not (“spatially nonseparable”). A research assistant who was not aware of the hypotheses of the study visualized the original set of forty-eight sequences and judged whether each sequence could be visualized as two groupings. For three of the sequences, the two raters provided opposite judgments. These three sequences and five others were

discarded to produce a set of forty sequences so the testing could be completed within a one-hour session. The spatial layout was the same as in previous experiments (Appendix A-1). Sequences of locations are presented in Appendix B-2.

Procedure. The procedure was very similar to that used in previous experiments. Participants were familiarized with the apparatus and instructions using two practice trials at each of five sequence lengths (4 through 8). A retention interval of 5 seconds was used on all trials. Following the practice trials, experimental trials of each length were presented in blocks (i.e., ten trials at length 5, followed by ten trials at length 6, etc.). Four lists of sequences were created such that spatially separable and nonseparable sequences were interleaved, with no more than three consecutive sequences of the same type. At the end of each trial, participants saw a text message in the screen indicating their score on that trial, and on the next line, the following message: “How did you try to remember the sequence?” They were asked to verbally report their strategies in as much detail as possible, and to focus on what they had tried to do, rather than explaining their errors. Participants were asked to keep in mind that there was no “correct” way to remember the sequences. The experimenter recorded any overt behaviors, such as patterned hand movements, that were observed. Testing and debriefing were completed within a one-hour session.

Results

Questionnaire. All participants reported normal or corrected-to-normal vision. None of the participants reported neurological disorders. Seven of the 20 participants reported having had at least one concussion. In addition, one participant reported that she

had been diagnosed with a learning disability. Based on responses to the 7-point Likert scale questions, all participants had adequate experience with using desktop computers (mean of 5.5 on self-rated expertise), and using the mouse as an input device (mean of 6.5 on frequency of use of mouse). All participants were retained in the final sample.

Strategy reports. Twenty participants reported their strategies on 40 trials, resulting in 800 strategy reports. On 37 trials (4.6%), no strategy was coded. On these trials, participants reported that they were unsure what strategy they had used, or that they had been distracted during the trial and had used guessing. On the remaining 763 trials, there were four strategies that were commonly reported. Two of these had been anticipated based on interviews with participants from previous studies: rehearsing during the retention interval (RI) and parsing (i.e., “strategic grouping”). Two new strategies that were used during encoding emerged from the detailed self-reports in the present study: 1) counting, and 2) rehearsing while encoding the sequence. Other strategies were reported with frequencies too low to conduct analyses of their distributions. For example, recoding parts of sequences with names such as “backwards N” or cues such as “clockwise” occurred on only 4% of trials.

Participants reported that rehearsal during the retention interval was accomplished using various procedures, such as tracing over a mental image or moving one’s eyes to the locations in the order they had appeared. They reported tracing the pattern between one and three times during the 5 second retention interval, with fewer repetitions possible as length increased. Rehearsing using patterned movements of body parts such as fingers or head were included in this category.

Parsing involved dividing the sequence into parts. The parts usually corresponded to images that were being visualized. Some examples of specific parsing strategies were dividing the sequence into (a) a triangle and a line (length 5), (b) two triangles (length 6), or (c) two other shapes (e.g., 4-sided plus 3-sided, two 4-sided shapes, a semicircle and a line, and two arrows). Of the trials on which parsing was reported, participants divided the sequence into two groupings 55% of the time, and into three or four groupings 45% of the time. In some cases, participants claimed to group the items without maintaining images, for example, by counting “1, 2, 3, 1, 2, 3” while encoding a sequence of six locations, and this was interpreted as use of parsing.

Counting during encoding involved associating the locations with a verbal code corresponding to the serial position, for example, “one” for the first location. Participants who reported rehearsing during encoding said that they rehearsed the early items in the sequence while later items were presented on the screen. One form of rehearsal was to continually trace over an imagined path that got longer as each item was presented. Some participants also described adding on to the sequence while counting, “1...1, 2...1, 2, 3...1, 2, 3, 4....”.

The frequencies with which these four strategies were reported are illustrated in Figure 10. A single trial could satisfy the criteria for multiple strategies, for example, parsing the sequence and rehearsing during the retention interval could be reported on the same trial. Percent use was calculated as the number of times the strategy was reported out of the number of trials at each length (i.e., 200). On 34% of trials, people reported using one of the three encoding strategies (rehearsal during encoding, counting, or

parsing). On 33% of the trials, people reported using two of the three encoding strategies. On the remaining third of the trials, participants used none of the three (26%) or all of the three (7%). Thus, as in other research where strategy reports were collected, the use of multiple strategies by individuals was common (Lemaire & Siegler, 1995; Reder, 1987; Smith-Chant & LeFevre, 2003).

As shown in Figure 10, people shifted their strategy use as length increased, supporting the hypothesis that sequence length is a determinant of strategy selection. The frequency of reported parsing increased as length increased, whereas participants tended to report the other three strategies less frequently as the experiment progressed. Rehearsal, both during encoding and during the retention interval (RI), decreased in frequency for the longer lengths. Counting was less frequent at length 8 than at lengths 6 and 7. The increased use of the parse strategy may have been related to decreasing use of the other strategies.

Figure 10. Frequency of four most commonly reported strategies, Exp. 3.

Participants reported parsing somewhat more frequently on spatially separable sequences (39%) than on nonseparable sequences (34%), $t(19) = 1.78$, $p = .09$, $\eta^2 = .14$. This result provides some support for the hypothesis that spatial separability was a determinant of strategy selection. The other three strategies were used equally frequently for the spatially separable and nonseparable sequences, $ps > .14$.

Accuracy. Results will be presented in four parts. First, the simple correlations between participants' strategy use and overall accuracy will be described. Second, the participants will be separated into high- and low-parse frequency groups, as in Experiment 2, and the effects of sequence type and strategy group will be tested. Third, trials will be separated into parse and nonparse, and the effects of sequence type and trial

strategy will be tested. Fourth, serial position effects will be examined for the two strategy groups.

Relation between frequency of reported strategies and accuracy. The frequency of use for each of the four strategies was calculated for each participant. These frequencies were correlated with the overall accuracy, based on 40 trials for each participant. Intercorrelations are shown in Table 7.

Table 7: *Intercorrelations for Spatial Memory and Strategy Frequency, Exp. 3 (N = 20)*

Measure	1	2	3	4	5
1. Percent locations correct	--				
2. Parsing	.53*	--			
3. Rehearsal during encoding	-.06	-.16	--		
4. Counting during encoding	.06	.46*	.24	--	
5. Rehearsal during retention interval	.16	-.07	-.60**	-.30	--

* $p < .05$; ** $p < .01$

Parsing was the only strategy that predicted accuracy: people who used parsing were more accurate overall. This result is consistent with the results from Experiments 1 and 2 suggesting that people who parsed more frequently were more accurate on the spatial span task. The frequency of parsing was correlated with the frequency of counting during encoding, but counting was unrelated to accuracy. Participants who rehearsed during encoding also tended to rehearse during the retention interval, but neither type of rehearsal significantly predicted accuracy. It was surprising that frequency of reported rehearsal during the retention interval showed only a small relation to accuracy. Based on the current proposal that encoding activities strengthen the

representation of the sequence in memory, it was also surprising that rehearsal during encoding was unrelated to accuracy. Participants may have been unable to both rehearse early locations and encode locations presented later in the sequence. To address this possibility, participants in Experiment 4 were given a pause in which to rehearse the first three locations before viewing the rest of the sequence. Under modified task conditions, there may be a positive relation between rehearsal during encoding and accuracy.

High- vs. low-frequency parse participants. I had hypothesized that spatially separable sequences would be better recalled, and that people who used a parsing strategy during encoding would benefit more from spatial separability. Sequences comprised of two nonoverlapping shapes were hypothesized to be easier to parse, and thus the parse strategy should be especially effective on those sequences. To test this hypothesis, participants were classified into two groups based on how frequently they reported parsing. Parsing was reflected in descriptions of dividing the sequence into parts, such as visualizing a sequence of six locations as two arrow shapes. Participants in the high-frequency parse group ($n = 12$) reported using the parse strategy on more than one quarter of the trials (mean of 54%). Participants in the low-frequency parse group ($n = 8$) reported parsing on fewer than one quarter of trials (mean of 11%). All eight of these low-frequency parse participants visualized a path (i.e., tried to represent the sequence as one object) on at least half of the trials.

Mean percentages correct were entered into a 2 (sequence type) x 4 (length) x 2 (strategy group: high vs. low frequency of parsing) ANOVA with repeated measures on the first two factors. ANOVA results are reported in Table 8.

Table 8: ANOVA for percentages correct (2 strategy groups), Exp. 3

	<i>df</i>	<i>F</i>	η^2
Strategy	1	6.74*	.27
Error	18	(810.40)	
Spatial separability (SEP)	1	4.99*	.22
SEP x Strategy	1	0.30	.02
Error	18	(72.28)	
Length	3	62.45**	.78
Length x Strategy	3	3.68*	.17
Error	54	(97.37)	
SEP x Length	3	7.95**	.31
SEP x Length x Strategy	3	0.88	.05
Error	54	(94.91)	

Note. Values enclosed in parentheses represent mean square errors.

* $p < .05$; ** $p < .01$

The main effect of strategy group was significant, with high-frequency parsers performing better than those in the low-frequency parse group (85% vs. 73%). As found in Experiments 1 and 2, participants who reported a parsing strategy were more accurate on the spatial memory task than those who reported using other strategies. The interaction between length and strategy group was significant. As shown in Figure 11, high-frequency parsers maintained their performance as sequence length increased from 5 to 6, whereas those in the low-frequency parse group showed a significant decrease in accuracy. The advantage of parsing was seen at lengths greater than 5.

Figure 11. Accuracy for high- vs. low-frequency parse groups, Exp. 3.

The main effects of length and spatial separability were significant, as was their interaction. Accuracy on spatially separable sequences was higher (80%) than on nonseparable sequences (77%). As shown in Figure 12, spatially separable sequences were better recalled for the two longest lengths (7 and 8), but less well recalled at length 6. Accuracy on separable sequences was preserved across the three longer lengths whereas accuracy on nonseparable sequences decreased steadily as length increased. Thus, there was an advantage for sequences that could be visualized as two, nonoverlapping shapes that was independent of how frequently participants applied a parsing strategy. That is, there was no interaction between strategy group and spatial separability, $F < 1$ (Table 8). The source of the advantage for the nonseparable sequences at length 6 was unclear. The sequences designed by the experimenter may

have varied on some dimension other than spatial separability that was not controlled across sequence type, and the nonseparable sequences at length 6 may have been less difficult than expected.

Figure 12. Accuracy for the two sequence types, Exp. 3.

The predicted interaction between strategy group and spatial separability was not obtained, $F < 1$. People who parsed the sequences did not show a greater advantage on the spatially separable sequences than people who typically visualized a single, path-type object. This result suggests that spatial separability affects grouping at a perceptual level, before the effects of strategic grouping arise.

Parse versus nonparse trials. To assess whether the parsing advantage was related not just to some characteristic of people who parsed more, but to better performance on trials where parsing was used, mean percentages correct were entered

into a 4 (length) x 2 (trial strategy: parse or nonparse) ANOVA. Data were missing for 12.5% of the means because some participants did not use each strategy at each of the lengths tested.⁶ Missing data were replaced with means. People were more accurate on trials where parsing was used than where it was not: 87% vs. 75%, $F(1,19) = 45.33$, $MSE = 119.04$, $\eta^2 = .71$. Accuracy decreased as sequence length increased, $F(3, 57) = 48.54$, $\eta^2 = .72$. As found in the previous analysis using strategy as a between-groups variable, there was an interaction between length and the parse strategy such that parsing was only advantageous at the longer lengths, $F(3, 57) = 4.12$, $MSE = 167.60$, $\eta^2 = .18$. The interaction is shown in Figure 13.

Figure 13. Accuracy on trials where parsing was used versus not used, Exp. 3.

⁶ Means were collapsed across sequence type in order to reduce the number of cells that had missing data from 20.9% to 12.5%.

The effect of parsing on accuracy was more evident when the data were grouped by trials on which participants parsed rather than by participants who parsed more versus less frequently. In the former case, parsing accounted for 71% of the variance in accuracy, whereas the between-groups variable (high- vs. low-frequency parse participants) accounted for 27% of the variance in accuracy. Thus, it will be useful to collect strategy reports on a trial-by-trial basis in subsequent investigations.

Serial position effects. Serial position curves are shown in Figure 14. As found in Experiments 1 and 2, trend analyses showed a significant quadratic component of the main effect of position for each of the sequence lengths (5 through 8), suggesting that both primacy and recency were observed.

Figure 14. Serial position effects, Exp. 3.

Additional ANOVAs tested the hypothesis that the effect of serial position would differ for the two strategy groups. For example, those who parsed the sequence might show two serial position curves, one for the first chunk and one for the second chunk. Mean percentages correct were entered into four separate ANOVAs with 2 groups (high- vs. low- frequency parse) and the number of levels of position equal to the sequence length. ANOVA results are presented in Table 9. For all four lengths, the main effect of position was significant because accuracy was lower for middle positions in the sequence. For lengths 6 and 7, the high-frequency parse group was more accurate overall, and the interactions with position were significant, suggesting that the serial position curves took different shapes for the two strategy groups. At lengths 5 and 8, the advantage of the parse group was not significant, although the differences were in the expected direction.

The interactions between strategy group and position reported in Table 9 are shown in Figure 15. Participants who parsed frequently did not show bow-shaped curves except at the longest length, whereas low-frequency parsers showed bow shaped curves at lengths 6, 7, and 8. The high-frequency parse group did not show peaks in accuracy at middle positions, which would have suggested chunk boundaries in their mental representations. Rather, they were better able to represent the whole sequence, consistent with a decrease in memory load related to strategic grouping.

Table 9: ANOVA for serial position effects for the two strategy groups, Exp. 3

	<i>df</i>	<i>F</i>	<i>df</i>	<i>MSE</i>	η^2
Length 5					
Strategy group	1	1.62	18	(190.60)	.08
Position	4	6.11**	72	(27.52)	.25
Strategy group x Position	4	1.49	72	(27.52)	.08
Length 6					
Strategy group	1	9.71**	18	(817.17)	.35
Position	5	2.53*	90	(69.85)	.12
Strategy group x Position	5	2.51*	90	(69.85)	.12
Length 7					
Strategy group	1	6.10*	18	(1401.92)	.25
Position	6	7.55**	108	(129.16)	.30
Strategy group x Position	6	2.22*	108	(129.16)	.11
Length 8					
Strategy group	1	3.75	18	(1431.63)	.17
Position	7	7.92**	126	(182.22)	.31
Strategy group x Position	7	0.63	126	(182.22)	.03

Note. Values enclosed in parentheses represent mean square errors.

* $p < .05$; ** $p < .01$

Figure 15. Serial position effects for the two strategy groups, Exp. 3.

Discussion

The trial-by-trial self-reports were useful in identifying three distinct strategies at encoding. Counting was a commonly reported strategy, and its frequent use was surprising given that the task was designed to measure nonverbal short-term memory. According to some models (e.g., Estes, 1997), serial memory requires forming associations between items and their temporal positions. Counting could be helpful in forming such associations by helping people to connect the locations with a well-learned sequence. However, when many different trials occur close together in time, the serial positions (e.g., “one”) must be associated with different locations on different trials, and people may be unable to learn new associations due to interference from previously learned associations. The buildup of proactive interference over trials likely rendered counting ineffective. Whether counting would benefit memory performance under conditions where proactive interference were reduced remains an open question. Participants in the present study may have become aware that counting was ineffective: they used counting less at length 8, at the end of the experiment, than at the two intermediate sequence lengths that were tested earlier.

The strategy of rehearsing early items while the sequence was being presented was also not effective, and was used less frequently at length 8 than it was earlier in the experiment. People adapted to the task by shifting their resources from ineffective strategies, such as counting and rehearsing while encoding, to the effective parsing strategy. The frequency of reported parsing increased as length increased, and was a significant predictor of accuracy. Parsing was especially beneficial at longer sequence

lengths, corroborating the interaction between length and strategy group observed in Experiment 1. The trial-by-trial data showed that participants shifted strategies as the experiment progressed, but there was no dramatic change in the distribution of strategies as sequence length increased from 5 to 6. The drop in performance between lengths 5 and 6 that has been noted in all three experiments thus does not seem to depend on strategy selection.

One goal of this experiment was to assess whether path configuration contributed to problem difficulty. As predicted, participants remembered sequences that had high separability better than those that did not. Consistent with the findings of Kemps (2001), a structural characteristic related to path configuration predicted problem difficulty. The advantage for separable sequences, in which each group had three or four items⁷, is consistent with the memory advantage demonstrated for verbal list recall when lists were grouped at presentation into subsets of three or four items as compared to ungrouped lists, or other groupings (see Cowan et al., 2002, for a review; Severin & Rigby, 1963; Wickelgren, 1967). There was some tendency for participants to report parsing more frequently on spatially separable sequences. However, the benefit for these sequences was of similar magnitude for people who were classified as high-frequency parsers as those who were not, suggesting that spatially separable sequences were easier to recall even when a parse strategy was not used.

The present results help decompose the accuracy advantage that Kemps (2001) reported for structured vs. complex sequences. Her structured sequences had one or more

⁷ Sequences of length 5 were comprised of one pair and one group of three locations.

of the following characteristics: 1) good continuation (the path did not cross itself); 2) symmetry (the path configuration was symmetrical about the horizontal, vertical, or 45 degree axis of the display); and 3) repetition (one part of the sequence was repeated in a translated position, for example, by rotating the first shape formed by the first four locations by 90 degrees). The spatially separable sequences in the present study had higher continuation than the nonseparable sequences. Paths that represented spatially separable sequences crossed themselves an average of 0.7 times, compared to nonseparable sequences, which crossed themselves an average of 2.5 times. In the present study, none of the sequences were symmetrical or contained repeated parts.

The accuracy advantage found for separable sequences in this study was small (3%) compared to the advantage reported by Kemps for the structured over complex sequences. Kemps (2001) tested accuracy on sequences of lengths 3 through 8, with three structured and three complex sequences at each length. One third of a span point was awarded for each sequence that was correctly reproduced, and this number was added to 2, the sequence length below starting level for the test. Kemps reported that accuracy was 5.95 span points for structured versus 4.73 span points for complex sequences. The maximum number of points that a person could earn was 6.00 (minimum score was 2.00; maximum was 8.00). Thus, the mean difference of +1.22 points corresponded to a 20% change (1.22 out of 6.00). Given the large effect when all three variables (continuation, symmetry, repetition) were involved, the number of times the path crosses itself was probably the least important contributor to the structure of the sequences used by Kemps. Symmetry and repetition of parts were likely to have been the

main contributors to the accuracy advantage for structured sequences, consistent with the hypothesis that grouping of stimuli supports spatial short-term memory performance. The structured sequences used by Kemps (2001) supported both perceptual grouping, because the paths did not cross themselves, and strategic grouping, because groups of locations could be recoded as two symmetrical or repeated parts within the same sequence.

Examination of performance across serial positions showed that the recall advantage of the high-frequency parse group was related to greater accuracy at middle positions, rather than an overall, upwards displacement of the curve, or peaks in accuracy corresponding to chunk boundaries at the third or fourth serial positions. In contrast to the multiply-bowed curves obtained when verbal items were presented with intermittent pauses (Cowan et al., 2002; Hitch et al., 1996), there was no evidence that strategic grouping of the locations produced multiply-bowed curves. These results point to different processes in verbal and spatial serial memory.

Experiment 4

Rationale

The results from Experiments 1, 2, and 3 suggest that strategically grouping sequences leads to moderate increases in accuracy, and that sequences that are easier to group based on spatial separability are easier to maintain in short-term memory. The opportunity to group the locations was increased in the present experiment by allowing participants to control the length of the pause after the first three items. On half of the trials (“variable

pause” condition), participants were allowed to pause for up to ten seconds before the fourth item appeared. They pressed a mouse button when they were ready to continue viewing the sequence. On the other half of the trials, the inter-item pause was fixed at one second for all intervals, as in the previous three experiments. I hypothesized that the variable pause would increase participants’ ability to effectively group locations. The additional time was predicted to allow participants to consolidate the items as a group and to leverage long-term memory. During the pause, participants could visualize a shape, such as an arrow, and rehearse the three-item group without interference from new stimuli appearing on the screen. Thus, accuracy was predicted to be higher for variable than for fixed pause trials.

Strategy reports were collected to test whether participants were more likely to use strategic grouping and recoding when the length of the pause was under their control. Serial position effects will be examined with a focus on the first three serial positions. If extra rehearsal of the first three items leads to consolidation of the memory trace, or enhances the transfer of items to a long-term store, then there should be an accuracy advantage for the first three items in the variable pause condition.

Method

Participants. The final sample included 28 participants, 11 males and 17 females. The mean age was 19.6 years ($SD = 1.5$). None of the participants had been in any of the previous studies. An additional three participants were recruited but excluded. One participant reported difficulty and frustration during the practice trials and was excused before completion of the experiment, one participant did not follow the instructions

during the experimental trials, and one participant viewed an incorrect list of sequences due to a programming error.

Apparatus. The apparatus was identical to that used in Experiment 3 except that the 16-inch colour monitor (Dell E770s) was connected to a Pentium 4 processor (CPU 1.80 GHz) running Windows 2000. Response times for termination of the pause in the variable-pause trials were measured in milliseconds using a standard mouse.

Materials. The spatial layout was the same as that used in previous experiments (Appendix A-1). Of the forty sequences tested in Experiment 3, thirty-two were selected as indicated in Appendix B-2. Some of the easier sequences were dropped to reduce ceiling effects in performance. Two sets of 16 sequences (four at each of the lengths 5 through 8) were selected. The two sets were estimated to have equal difficulty based on accuracy for these sequences in Experiment 3. Four lists of sequences were created. Trial type (variable vs. fixed pause) for each item was counterbalanced across lists so that each item was presented with a variable pause in two lists and a fixed pause in the other two lists. Within each length (5 through 8), there were 4 variable pause trials and 4 fixed pause trials. Trial type was mixed within length. In each of the four lists, which used different item orders, there were no more than three consecutive trials of the same type. Participants were assigned randomly to the four list conditions such that seven were assigned to each of the four lists.

Procedure. Participants were tested as described in Experiment 3 with the following changes. The total number of practice trials was increased from 10 to 22. Participants first practiced the standard version of the task, which had no instructions

about pause length, for six trials at length 4. In the remaining 16 practice trials (four practice trials at each of the four lengths, 5 through 8), participants were familiarized with the instructions for the two trial types. Each trial was preceded by a text message indicating either “Please *click to continue* after the third location appears” or “Please *watch* after the third location appears.” The italicized text was presented in blue font to contrast with the surrounding text, which was presented in black font. Throughout the practice session, the experimenter gave instructions and feedback to ensure that participants could perform both kinds of trials and switch between trial types. Practice sequences were the eight sequences of lengths 5 through 8 used for practice in Experiment 3 (2 at each length) and the eight sequences from the pool of 40 that were used in Experiment 3 but subsequently dropped. None of the practice sequences were used in the spatial memory test.

Results

Questionnaire. All participants reported normal or corrected-to-normal vision. In response to the question on history of neurological disorders, one participant reported dyslexia and another reported history of diabetic seizures. Eleven participants out of 28 reported at least one head injury. One of these 11 participants reported that she fell and hit her head after losing consciousness, but did not report the cause of loss of consciousness. Based on responses to the 7-point Likert scale questions, all participants had adequate experience with using desktop computers (mean of 4.9 on self-rated

expertise), and using the mouse as an input device (mean of 6.6 on frequency of use of mouse). All participants were retained in the final sample.

Strategy reports. Twenty-eight participants reported their strategies on 32 trials, resulting in 896 strategy reports. On 2.6% of trials ($n = 23$), no strategy was coded because the participants were either unsure of what they did, or reported being distracted and unable to implement any strategy. For the four strategies examined in Experiment 3 (i.e., rehearse during encoding, parse, count, and rehearse during the retention interval), percent use of the strategy at each combination of trial type and sequence length was calculated. As in Experiment 3, a single trial could satisfy the criteria for multiple strategies. Frequency of reported use for each of the four strategies is shown in Figure 16 for the two trial types. For each strategy, mean percentages of use were entered into a 2 (trial type: variable vs. fixed pause) x 4 (length) repeated measures ANOVA. ANOVA results are presented in Table 10. To preview the results, participants used rehearsal during encoding and parsing more frequently on the variable than the fixed pause trials.

Table 10: ANOVA for percent use of four reported strategies, Exp. 4

Strategy	<i>df</i>	<i>F</i>	<i>df</i>	<i>MSE</i>	η^2
Rehearse during encoding					
Trial type	1	18.64**	27	(227.66)	.41
Length	3	2.25	81	(664.99)	.08
Trial type x length	3	2.42	81	(268.17)	.08
Parse					
Trial type	1	9.63**	27	(844.49)	.26
Length	3	7.66**	81	(925.79)	.22
Trial type x length	3	3.34*	81	(326.14)	.11
Counting					
Trial type	1	1.75	27	(192.94)	.06
Length	3	1.46	81	(494.96)	.05
Trial type x length	3	1.74	81	(91.53)	.06
Rehearse during RI					
Trial type	1	0.03	27	(404.68)	.00
Length	3	1.37	81	(664.55)	.05
Trial type x length	3	0.69	81	(221.97)	.03

Note. Values enclosed in parentheses represent mean square errors.

* $p < .05$; ** $p < .01$

Participants reported rehearsal during encoding more frequently on variable pause trials (27%) than on fixed pause trials (17%). This pattern is consistent with the hypothesis that people attempted to use the pause to strengthen the memory trace of the early-presented items. As expected, participants reported parsing more frequently on the variable pause trials (47%) than on the fixed pause trials (35%), suggesting that the temporal grouping manipulation encouraged the use of parsing. Both the main effect of length and the interaction between trial type and length were significant. However, as

seen in Figure 17, the increase in reported parsing with length was similar for variable and fixed pause trials. Reported frequency of parsing increased from length 5 to 6, and remained stable over the three longer lengths. Comparisons at each length, however, indicated that participants reported parsing more frequently in the variable pause condition only on lengths 7 and 8 (Figure 17). Thus, changes in strategy reports occurred only on the hardest sequences.

The analyses of percent use of counting and rehearsal during the retention interval yielded no significant effects, as shown in Table 10. Overall, participants reported counting on 29% of trials and rehearsal during the retention interval on 68% of trials. Frequency of these two strategies did not vary with sequence length nor with whether participants controlled the pause length. These results suggest that when participants controlled the pause length, they used parsing and rehearsal during encoding more frequently: they changed the way that they grouped the items at encoding. In this sense, the temporal grouping manipulation had its intended effect. For the other two strategies, which did not involve grouping of items, frequency of reported use did not differ between the variable and fixed pause conditions.

Figure 16. Frequency of four most commonly reported strategies, Exp. 4

Figure 17. Reported frequency of parsing for the two trial types, Exp. 4.

Cross-experiment analyses were conducted to assess whether the task modifications in Experiment 4 affected overall strategy distributions. Participants may have been influenced to use different strategies due to exposure to the temporal grouping manipulation, even on those trials where the pause length was fixed. The analyses reported in Table 11 compared percent use of each strategy on the fixed pause trials of Experiment 4 to all trials of Experiment 3, in which a fixed pause was standard. For each of the four strategies, mean percentages of use were entered into a 4 (length) x 2 (experiment) ANOVA with repeated measures on the first factor. Reported frequency was somewhat higher in Experiment 3 than in Experiment 4 for two of the four strategies: rehearsal during encoding and counting. People rehearsed during encoding almost twice as frequently in Experiment 3 (33%) as in Experiment 4 (17%), and this difference

approached significance, $p = .08$. In Experiment 4, the less frequent use of rehearsal during encoding may have contributed to lower overall performance on items in the first three serial positions, as will be discussed in the section on serial position effects below.

Table 11: *ANOVA for percent use of strategies for fixed pause trials only, Exps. 3 and 4*

	<i>df</i>	<i>F</i>	<i>df</i>	<i>MSE</i>	η^2
Rehearse during encoding					
Experiment	1	3.25	46	(3693.43)	.07
Length	3	0.49	138	(412.58)	.01
Experiment x length	3	2.61	138	(412.58)	.05
Parse					
Experiment	1	0.04	46	(3413.40)	.00
Length	3	8.54**	138	(440.02)	.16
Experiment x length	1	3.60*	138	(440.02)	.07
Counting					
Experiment	1	3.88	46	(6121.91)	.08
Length	3	2.65	138	(331.83)	.05
Experiment x length	1	0.94	138	(331.83)	.02
Rehearse during RI					
Experiment	1	0.36	46	(4605.53)	.01
Length	3	2.35	138	(319.51)	.05
Experiment x length	1	0.65	138	(319.51)	.01

Note. Values enclosed in parentheses represent mean square errors.

* $p < .05$; ** $p < .01$

Participants in Experiment 3 (51%) reported that they counted the items more frequently than those in Experiment 4 (29%), and this difference approached significance, $p = .06$. The main effect of length was marginally significant, $p = .05$. Counting was

reported less frequently at length 8 (34%) than at the three shorter lengths (42%, 40%, and 43%, for lengths 5, 6, and 7, respectively). For the other two strategies, the frequency of reported use did not differ between experiments. Parsing was reported as frequently in Experiment 3 (37%) as on the fixed pause trials of Experiment 4 (35%). As expected from previous analyses, the main effect of length on parse frequency was significant. Parsing was less frequent at length 5 (23%) than at the three longer lengths (36%, 42%, and 41% at lengths 6, 7, and 8, respectively). The interaction between length and experiment was significant. As shown in Figure 18, the frequency of parsing increased monotonically with length in Experiment 3, whereas parsing was adopted earlier in Experiment 4 and its use remained stable at the three longer lengths. Thus, reports of parsing were similar across lengths for the two experiments, except for length 8 where participants in Experiment 4 reported parsing less frequently than participants in Experiment 3.

The higher frequency of two of the encoding strategies reported by the participants in Experiment 3 suggested that they used a greater variety of strategies during encoding than participants in Experiment 4. To explore this hypothesis, the strategy reports were analyzed in terms of how often a participant added a new strategy to her repertoire. The transcribed data were scored by a research assistant who was unaware of the hypotheses of the two studies. The number of times that a participant reported a strategy that she had not reported previously was divided by the number of trials in the

study to provide a rate-of-switching measure.⁸ Rate of trying new strategies was higher in Experiment 3 (25%) than Experiment 4 (16%), $t(46) = 3.14, p < .01$. Note that, in Experiment 4, participants were forced to change their behaviour every few trials because variable and fixed pause trials were mixed within blocks. This additional switching requirement may have consumed some of the resources that people typically used to generate and execute new strategies.

Figure 18. Reported frequency of parsing for fixed pause trials, Exps. 3 and 4.

The participants in Experiment 4 were also more likely than those in Experiment 3 to use a single strategy during the encoding phase, rather than two strategies in combination. In Experiment 4, participants used a single strategy at encoding (out of the three that were analyzed above) on 46% of trials. In contrast, participants in Experiment

⁸ In addition to the four strategies that have been discussed, participants generated strategies such as verbal recoding and moving fingers/hands/head to mimic the spatial sequence. Guessing was not considered a strategy.

3 used a single strategy at encoding on 34% of trials. The distributions are further compared in Figure 19. In Experiment 4, participants were more likely to use a single strategy, and generated new strategies less often. They used the parse strategy more than participants in Experiment 3, and used other strategies less frequently. Note also that with the exception of increased use of parsing from length 5 to length 6, participants in Experiment 4 did not adjust the use of strategies as length increased: there was no main effect of length on reported frequency of rehearsal during encoding, counting, or rehearsal during the retention interval (Table 10).

Figure 19. Number of encoding strategies reported on the same trial.

One concern was that participants in the present study were biased to report parsing because they were exposed to the temporal grouping manipulation, and in some sense believed that parsing was the strategy they were supposed to use (i.e., their self-

reports were not veridical). One way to address this possibility is to examine performance measures that were independent of the self-reports. For the variable-pause trials, the amount of time that participants paused was measured. The pattern of these response times matched the frequency of reported parsing on the variable pause trials that was shown in Figure 17 (striped bars): the pause was shorter at length 5 than at the other three lengths. Mean pause times were entered into a repeated-measures ANOVA with 4 levels of length. The main effect of length was significant, $F(3, 81) = 5.83$, $MSE = 898270.77$. Pairwise comparisons showed that the mean response time for length 5 (2313 ms) was significantly different from those for lengths 6 (2986 ms), 7 (3149 ms), and 8 (3289 ms), but that none of the other means differed significantly from each other. This parallel between the response times and the reported frequency of parsing suggests that when people parsed, they also paused longer during encoding. It does not seem that participants were simply reporting more parsing in this study than in Experiment 3; they were taking additional time for processing during encoding.

Accuracy. Results will be presented in four parts. First, the simple correlations between participants' strategy use and overall accuracy will be described. Second, the participants will be separated into high- and low-parse frequency groups, as in Experiments 2 and 3, and the effects of trial type and strategy group will be tested. Third, trials will be separated into parse and nonparse, and the effects of trial type and trial strategy will be tested. Fourth, serial position effects for the first three locations will be examined in cross-experiment analyses.

Relation between frequency of reported strategies and accuracy. The frequency of use for each of the four strategies analyzed in Experiment 3 was calculated for each participant. These frequencies were correlated with the overall accuracy for each participant. Intercorrelations are shown in Table 12. Frequency of strategy use showed small positive correlations with accuracy for all four strategies, but none of the four correlations were significant. This pattern differs from that found in Experiment 3, in which parsing was positively related to accuracy. Another difference was that the relation between rehearsal at encoding and accuracy was stronger in the present study than in Experiment 3, in which the two variables were unrelated ($r = -.06$). The temporal grouping manipulation did affect how people encoded the sequences, and the correlations between encoding strategies and performance show a quite different pattern than that obtained in Experiment 3. The relation between accuracy and rehearsal during the retention interval was unaffected: as found in Experiment 3, rehearsal during the retention interval was common and did not enhance accuracy.

On the fixed pause trials, participants who counted more frequently used the parse strategy less often ($r = -.34$), whereas in Experiment 3, parsing and counting during encoding were positively correlated ($r = .46, p < .05$). As suggested by the distributions shown in Figure 19, participants in Experiment 4 were less likely to use multiple strategies on a single trial. The temporal grouping manipulation influenced the frequency with which strategies were chosen and, potentially, participants' effectiveness at executing strategies, thus producing quite different correlations between strategy use and performance than those observed in Experiment 3.

Table 12: *Intercorrelations for Spatial Memory and Strategy Frequency, Exp. 4 (N = 28)*

Measure	1	2	3	4	5
1. Percent locations correct	--	.28	.11	.13	.07
2. Parsing	.11	--	-.23	-.11	-.37
3. Rehearsal during encoding	.18	-.20	--	.21	.19
4. Counting during encoding	.20	-.34	.14	--	.46*
5. Rehearsal during retention interval	-.03	-.44*	.13	.48*	--

Note. Values for variable pause trials are presented above the diagonal; values for fixed pause trials are presented below the diagonal. * $p < .05$.

Participants reported parsing more frequently on spatially separable sequences (44%) than on nonseparable sequences (38%), $t(27) = 3.22$, $p < .01$, $\eta^2 = .28$. The difference in frequency of reported parsing suggests that spatial separability was a determinant of strategy choice. The other three strategies were used equally frequently for the spatially separable and nonseparable sequences, $ps > .20$.

High- vs. low-frequency parse participants. Using the criterion developed in Experiment 3, participants were classified into two groups based on how frequently they reported using parsing on the trials for which the pause length was fixed. Participants who reported parsing on more than one quarter of the trials (mean of 59%) were assigned to the parse group ($n = 15$). Participants who reported parsing on one quarter of the trials or fewer (mean of 7%) were assigned to the nonparse group ($n = 13$). Mean percentages correct were entered into a 4 (length) x 2 (trial type: variable vs. fixed pause) x 2 (strategy group) ANOVA with repeated measures on the first two factors.

The main effect of length was significant, $F(3, 78) = 53.45$, $MSE = 174.98$, $\eta^2 = .67$. No other main effects or interactions were significant. The predicted effect of temporal grouping was not obtained: participants recalled 78% of locations when they controlled the duration of the pause vs. 77% of the locations when the pause was fixed at one second. Participants who parsed less frequently were as accurate as those who reported parsing more frequently (77% vs. 78%, respectively). This finding was inconsistent with that obtained in Experiment 3, in which people who parsed frequently were more accurate overall.

Figure 20. Accuracy for the two sequence types, Exp. 4.

The effect of spatial separability obtained in Experiment 3 was replicated in the present study. Mean percentages correct were entered a 4 (length) x 2 (sequence type: spatially separable vs. nonseparable) x 2 (strategy group) ANOVA with repeated

measures on the first two factors. ANOVA results are presented in Table 13. Spatially separable sequences were more accurately recalled than nonseparable sequences (80% vs. 75%). Accuracy decreased across sequence length. The interaction between sequence type (separable vs. nonseparable) and length was significant (Figure 15): the advantage for spatially separable sequences was observed only for the two longer lengths (7 and 8), as found in Experiment 3 (Figure 11). Spatial separability did not interact with strategy use, $F < 1$. The accuracy advantage for spatially separable sequences was of similar magnitude for participants in the high- and low-frequency parse groups (6% vs. 4%, respectively).

Table 13: ANOVA for percentages correct (2 strategy groups), Exp. 4

	<i>df</i>	<i>F</i>	η^2
Strategy	1	.06	.00
Error	26	(954.78)	
Spatial separability (SEP)	1	11.93**	.32
SEP x Strategy	1	1.73	.06
Error	78	(105.10)	
Length	3	53.45**	.67
Length x Strategy	3	0.06	.00
Error	54	(174.98)	
SEP x Length	3	10.11**	.28
SEP x Length x Strategy	3	0.70	.03
Error	78	(123.68)	

Note. Values enclosed in parentheses represent mean square errors.

* $p < .05$; ** $p < .01$

Parse versus nonparse trials. Trials were split into those on which people reported versus did not report parsing. Mean percentages correct were entered into a 4 (length) x 2 (trial strategy: parse or nonparse) ANOVA. Data were missing for 21% of the means because some participants did not use each strategy at each of the lengths tested. Missing data were replaced with means. The pattern of results was identical to that obtained in Experiment 3. People were more accurate on trials where parsing was used than where it was not: 87% vs. 75%, $F(1, 27) = 25.55$, $MSE = 227.21$, $\eta^2 = .49$. Accuracy decreased as sequence length increased, $F(3, 81) = 61.89$, $MSE = 155.66$, $\eta^2 = .70$. The interaction between trial strategy and length was significant, $F(3, 81) = 3.75$, $MSE = 145.04$, $\eta^2 = .12$, as shown in Figure 22. Consistent with previous analyses, the benefit of the parse strategy was restricted to longer lengths.

Figure 21. Accuracy on trials where parsing was used versus not used, Exp. 4.

Accuracy was higher on trials where participants used parsing, suggesting that parsing did confer some advantage to performance. The data must be interpreted cautiously due to the large number of missing data points. To obtain better estimates of performance on trials where the parse strategy was used versus not used, a choice/no-choice methodology is recommended, in which participants are instructed to use a specific strategy on all trials in a given block (Siegler & Lemaire, 1997).

Figure 22. Serial position effects, Exp. 4

Serial position effects. Serial position effects for the two trial types are presented in Figure 22. Patterns were similar for the two trial types. The analyses in this section will focus on performance at the first three serial positions, for which accuracy was predicted to be enhanced by extra time allowed for consolidation of locations into a group. Analyses to contrast the two strategy groups are not reported, as there were no differences in accuracy between the two strategy groups. To test the hypothesis that the temporal grouping manipulation affected recall of the first three items, mean percentages correct were entered into a 2 (trial type) x 4 (length) x 3 (position) repeated measures ANOVA. Consistent with the above analyses of overall accuracy, there was no main effect of trial type, $F < 1$, and thus no evidence that the variable pause enabled participants to group and more accurately recall the first three items. The main effect of length was significant, $F(3, 81) = 27.40$, $MSE = 715.20$, $\eta^2 = .50$, with accuracy decreasing as length increased. The main effect of position was significant, $F(2, 54) = 5.29$, $MSE = 191.14$, $\eta^2 = .16$. When the position effect was analyzed into its two components, with one degree of freedom each, only the quadratic component was significant, accounting for a large amount of variance, $F(1, 27) = 8.91$, $MSE = 181.65$, $\eta^2 = .25$. Thus, when the data were averaged across the two trial types, the serial position curve for the first three items was bow-shaped, or V-shaped in this case. There was no evidence that the shape of the curves differed for the two trial types, given the nonsignificant interaction between position and trial type. However, additional analyses revealed that accuracy at the first three positions was sensitive to the temporal grouping manipulation, in that different curves were obtained in Experiments 3 versus 4.

Two cross-experiment analyses were conducted compare accuracy on the first three serial positions. The first analysis compared accuracy in Experiment 3 with the fixed pause trials of Experiment 4, and the second analysis compared accuracy in Experiment 3 with the variable pause trials of Experiment 4. Mean accuracies were entered into 4 (length) x 3 (position) x 2 (experiment) ANOVAs with repeated measures on the first two factors. For the analysis of the fixed pause trials in each experiment (Table 14, middle columns), the position effect had a strong linear component, and accuracy decreased monotonically across the three positions (85%, 79%, 78%), consistent with a primacy effect. The quadratic component of the position effect was not significant.

When the variable pause trials of Experiment 4 were compared to Experiment 3 (Table 14, rightmost two columns), the proportion of variance accounted for by the linear component of the position effect decreased, and the proportion accounted for by the quadratic component increased. The position curve had a slight upturn (85%, 80%, 81%). The position by experiment interaction, as shown in Figure 23, was significant overall, with a significant linear component and a nonsignificant quadratic component. This interaction suggests that the slopes of the best-fitting line for the three means were different in Experiments 3 and 4. As shown in Figure 23, accuracy decreased across the three serial positions in Experiment 3, but accuracy was similar across the three serial positions in the variable pause trials of Experiment 4. Thus, participants were affected by the temporal grouping manipulation in that there was a reduction of the primacy effect. When participants controlled the length of the pause, they were not more accurate on the

first three serial positions. Rather, the variable pause introduced an additional task requirement that may have disrupted processing of the first three items. The primacy effect was impaired for variable pause trials.

Table 14: *ANOVA for percentages correct, first three serial positions, Exp. 3 vs. Exp. 4.*

	<i>df</i>	<i>Exp. 3 vs. fixed pause of Exp. 4</i>		<i>Exp. 3 vs. variable pause of Exp. 4</i>	
		<i>F</i>	η^2	<i>F</i>	η^2
Experiment	1	2.31	.05	0.89	.02
Error	46	(1783.24)		(1749.27)	
Length	3	21.65**	.32	26.43**	.37
Length x Experiment	3	2.37	.05	1.83	.04
Error	138	(532.23)		(508.30)	
Position: Linear	1	17.26**	.27	8.47**	.16
Position: Quadratic	1	2.59	.05	6.89*	.13
Position x Experiment: Linear	1	2.43	.05	7.56**	.14
Position x Experiment: Quad	1	0.17	.00	1.98	.04
Error: Linear	46	(177.15)		(180.73)	
Error: Quadratic	46	(151.19)		(144.95)	
Length x Position	6	2.09	.04	1.04	.02
Length x Position x Experiment	6	0.60	.01	0.39	.01
Error	276	143.96		147.80	

Note. Values enclosed in parentheses represent mean square errors.

* $p < .05$; ** $p < .01$

Figure 23. Accuracy on first three serial positions (Exp. 3 vs. variable pause trials of Exp. 4).

Summary. The main effect of experiment was not significant in any of the above analyses, so there was no evidence that participants in Experiment 4 were able to use the pause to consolidate spatial items into groups or to use rehearsal effectively. Visual inspection of the serial position curves suggested that the performance on early positions was impaired in Experiment 4 as compared to Experiment 3, and cross-experiment analyses supported this conclusion.

Discussion

The temporal grouping manipulation encouraged people to adopt a parsing strategy. People reported parsing more frequently when they controlled the length of a pause between the presentation of the third location and the presentation of the remainder of the spatial sequence. However, the increased use of parsing on the variable pause trials did not lead to an accuracy advantage on those trials. For verbal items, presenting lists in temporally spaced groups of three or four items enhances recall, but no such advantage was found for temporally grouped locations in the present study. In the present study, participants reported more effort devoted to parsing the sequences and rehearsing the locations that were presented early in the sequence than participants in Experiment 3. However, their increased effort yielded no benefits to accuracy. Unlike the processing of verbal materials, encoding spatial locations is effortful, and the processes of parsing and rehearsing may only outweigh their costs some of the time (i.e., on some sequences or trials).

It remains possible that there was some benefit to having additional time for rehearsing the first three items, but that this benefit was completely negated by the processing required to switch tasks on the two trial types and to decide when to terminate the pause. Both task switching and decision making have been identified as executive functions (Miyake et al., 2000; Rabbitt, 1997), so it was not surprising that the demands in Experiment 4 interfered with spatial span performance, given that the spatial span task requires executive resources. To determine whether increased task requirements in Experiment 4 masked a benefit of extra time, two fixed interval conditions could be

tested in blocks: 1 second between each item versus a longer, fixed pause (2.5 seconds) between the third and fourth items. Given the lack of evidence thus far that rehearsal during encoding can be accomplished without some cost to performance, it seems unlikely that the pause will benefit accuracy even when task demands are reduced by removal of the decision making and task switching requirements. Nevertheless, such an experiment would be useful for indicating whether these requirements masked a benefit of temporal grouping.

In essence, the temporal grouping manipulation had some unintended consequences. In addition to overall increased task difficulty, it biased participants to rely on a single strategy rather than adapting their strategies as the experiment progressed. Using more than one of the encoding strategies on a trial was more common in Experiment 3 than Experiment 4, and participants generated new strategies more often in Experiment 3. The tendency to rely on a single strategy during encoding may have made parsing less effective for the participants in Experiment 4. Indiscriminate use of a strategy may have decreased its effectiveness. Under conditions of increased task difficulty, participants who used parsing more frequently no longer outperformed those who parsed less frequently. Nevertheless, accuracy was higher on trials on which parsing was reported, in support of the results of Experiments 1 through 3. Additional data are needed to obtain better estimates of the accuracy benefit conferred by the parse strategy.

Chapter 5

In this thesis, I examined participants' performance on a commonly used spatial memory span test. Variables known to influence verbal span measures were manipulated. An important goal of this research was to test the hypothesis that spatial memory span is not entirely supported by the same processes and structures as similar verbal measures. In this chapter, I will first provide an overview of the experimental results. Second, I will comment on the implications of the results for models of working memory, and finally, on the nature of processes and representations used in spatial memory.

Overview of results

In general, performance on the spatial span task suggested that people process location sequences differently from verbal sequences. Although word familiarity enhances span performance (Hulme et al., 1991), familiarity with the layout of locations did not enhance span in Experiment 1, and thus long-term memory does not appear to play the same role in spatial span as in word span. Long-term memory would be more likely to augment spatial span when the locations were not only familiar in terms of their relative positions, but also meaningful to the participants. Another contrast with verbal serial memory was that decreasing the ratio between inter-item presentation time and retention interval had no effect on the recency portion of the sequence, whether recency was measured as accuracy on the last location, or the slope of percent correct over the last two locations (Experiment 2). Also, there was essentially no effect of increasing the retention interval from 5 to 15 seconds, suggesting rapid loss of spatial serial information between 0 and 5 seconds, and relatively little loss of information between 5 and 15

seconds. In contrast, representations of verbal sequences are better preserved between 0 and 5 seconds, and loss of information continues over longer intervals, such as between 5 and 15 seconds. This finding relates to the longer duration of the phonological trace (Watkins & Watkins, 1980) as compared to the representation of a visuospatial sequence in a visual cache or buffer (e.g., Logie, 1995).

One of the most important findings across all experiments was that participants reported a variety of strategies on the spatial span task. These results add to the literature on strategy use showing that cognitive tasks are performed in a variety of ways (Reder, 1982, 1987; Siegler, 1987). This research identified three distinct strategies used during encoding: rehearsal of early items while the sequence was being presented, counting the items as they were presented, and parsing the sequence into groups of locations. Participants reported relying primarily on visual images, but verbal codes were often generated, especially numbers that corresponded to the serial position of the location. People activated verbal codes for counting quite often (40%, Exps. 3 and 4, averaged), suggesting that they attempted to use verbal codes to supplement spatial short-term memory. In contrast, other types of verbal recoding, such as describing the parts of sequences with names of familiar objects, were rare (3%) and idiosyncratic. For example, participants sometimes reported referring to directions (“up”), to patterns in the location sequences (“backwards N”), or to information about the sequences (“clockwise”). Although these verbal codes were used too infrequently in Experiments 3 and 4 to permit analysis, it seems likely that verbal codes for information about the sequence, such as “symmetrical,” can significantly enhance the ability to recall sequences of locations

(Kemps, 2001). When spatial sequences contain repeated patterns, people may be able to form hierarchical representations, with higher-order information such as “symmetrical” or “clockwise” at a level above the representation of groups of individual locations. The use of hierarchical representations in spatial memory appears to benefit recall (De Lillo, *in press*), as for verbal representations, but the benefits to performance are much smaller, enabling people to remember long sequences (e.g., nine locations as tested by De Lillo) more accurately, but not to vastly increase the number of locations they can remember in order.

Parsing the spatial sequence during encoding was a strategy that participants spontaneously generated to enhance their performance. Two types of benefits of parsing were discovered. First, parsing appeared to facilitate memory for the middle positions, on which participants typically make the most errors (Experiment 3). Rather than introducing chunk boundaries into the representation, which would have produced multiply-bowed curves, parsing helped participants to successfully encode the entire spatial sequence. This result suggests that parsing conferred an overall benefit in terms of decreasing memory load. Second, the representations formed by parsers were more resistant to interference than those of nonparsers: participants who reported parsing more frequently showed smaller decrements from the interference task than those who reported parsing less frequently (Experiment 2). Thus, the parsing activities performed at encoding may have helped to create a more stable representation by connecting to long-term memory, for example, by relying on a schema for “two arrows” to represent a sequence of six locations. By connecting to information in long-term memory, the

limited capacity of the workspace was augmented, as suggested by the long-term working memory model (Ericsson & Kintsch, 1995).

Studies of expert memory have previously shown that elaborative cues generated at encoding are key to the ability to augment short-term memory span (Chase & Ericsson, 1982; Staszewski, 1990). The fact that effortful, elaborative encoding is required introduces a confound when participants are allowed to select strategies on each trial. Participants who recode the sequences into groups are probably also the participants who make more effort overall. This issue was partially addressed by showing an accuracy advantage for trials on which parsing was reported, rather than simply for people who reported parsing (Experiments 3 and 4). However, participants who chose parsing more frequently contributed more to the mean accuracies for the parse trials, and thus the confound was not totally removed. The benefits of the parse strategy will be better estimated by requiring participants to apply that strategy to specific problems on specific trials (Siegler & Lemaire, 1997), and contrasting performance with trials on which participants are instructed to visualize a single, continuous path.

Another limitation of the benefit of the parse strategy was demonstrated by the differences between Experiments 3 and 4. The trial-by-trial strategy reports collected in Experiment 3 showed that when participants simply watched as the locations were presented, they used the parsing strategy adaptively such that they selected it more as length increased. Under these task conditions, frequency of using the parse strategy was a good predictor of accuracy on the spatial task. When task demands were increased in Experiment 4 by task-switching and decision-making requirements, participants no

longer applied the parse strategy selectively, and frequency of parsing did not predict accuracy. Thus, although the parse strategy was generally considered a good strategy, using it more frequently was not as beneficial as using it adaptively.

Although people were able to provide useful self-reports regarding encoding processes, strategy reports did not illuminate the construct of spatial rehearsal. The data yielded somewhat contradictory results in the sense that preventing rehearsal by imposing a secondary task severely impaired accuracy, but rehearsal, as reported by participants, did not enhance accuracy (Experiments 3 and 4). It seems that the rehearsal techniques used by participants, such as moving their eyes to the locations in the order presented or tracing over an image, did not effectively enhance visualization of the sequence, and thus that the representation in the workspace shown in Figure 1 depends more on executive processes for maintenance than on continuous spatial inputs. Participants reported rehearsing during the retention interval on approximately 70% of trials. One reason that the reported use of rehearsal during the retention interval was unrelated to accuracy may be that strategies must be used selectively to enhance performance on this task. Based on the present findings, there was no evidence that rehearsal during the retention interval was worth the effort, perhaps because it occurs too late to assist consolidation of the sequence in memory. Eye movement data would serve to identify the trials on which participants used eye movements, and to determine whether eye movement rehearsal supports spatial short-term memory.

The results supported the involvement in spatial short-term memory of two of the executive processes that were shown in Figure 1: strategic grouping and keeping track of

serial order. Changing the task requirements by increasing executive load impaired performance in various ways. When participants had to perform the difficult task of counting backwards by sevens during the retention interval, accuracy decreased overall by 19%. The counting backwards task did not interfere with strategic grouping, but did impair the keeping track of serial order. As the difficulty of the spatial task increased, with more locations that had to be remembered, the amount of decrement observed in the interference condition increased, suggesting that the two tasks competed for common resources. In contrast to the general decrements imposed by the counting backwards task in Experiment 2, the executive load (i.e., task switching and decision making requirements) imposed in Experiment 4 compromised performance in more subtle ways. Rather than a load imposed during the retention interval, the load was diffused across the stages in which the participants prepared for the trial and encoded the items. At the start of each trial, participants were informed about whether they would be required to make a decision (i.e., terminate the pause) during encoding, and were required to keep this information active while viewing the first three locations in the sequence. This diffused executive load resulted in some loss of the primacy effect in Experiment 4. It was suggested that the task-switching demands in Experiment 4 reduced participants' ability to select strategies adaptively.

In summary, strategy reports were useful for identifying alternative processes that participants used during encoding, but not for differentiating processes used for spatial rehearsal. Accuracy on the spatial span task was impaired when additional tasks were imposed that had executive demands, such as mental arithmetic, decision making, and

task switching. Accuracy was unaffected by increasing the retention interval from 5 to 15 seconds, suggesting rapid loss of serial spatial information between 0 and 5 seconds of retention. The cognitive processes that participants use on the spatial span task were diverse, and in particular the use of concurrent, executive-demanding processes on the same trial (e.g., strategy selection, strategic grouping, visualization) makes the spatial span task more complex than would be suggested by the simple instructions to “watch the sequence and click on the locations in the order that they appeared.” The complex requirements of the spatial span task will be considered in the following section.

Implications of present research for models of working memory

As noted in Chapter 1, short-term memory (STM) tasks have been designated as those that have a memory requirement, such as remembering a string of digits, but no explicit concurrent processing requirement (Daneman & Merikle, 1996). These tasks are thought to estimate temporary storage capacity. In contrast, working memory (WM) span tasks require participants to retain items in short-term memory while performing an additional processing task, such as sentence comprehension or mental arithmetic. In the domain of verbal tasks, the distinction between short-term and working memory tasks has been supported using large-scale correlational studies. A meta-analysis of correlational studies showed that verbal WM tasks predicted reading comprehension performance better than simpler, STM tasks (Daneman & Merikle, 1996). According to Engle et al. (1999), WM tasks involve more controlled attention. As noted by Miyake et al. (2001), the construct of controlled attention has similar functions to those described in other models as executive processes. Two executive processes recruited more for WM than

STM tasks are dual-tasking (i.e., coordinating storage and processing), and resisting interference from irrelevant information (i.e., the processing task contains information that must be excluded from storage).

The spatial span task has typically been classified as a short-term memory rather than a working memory task (e.g., Miyake et al., 2001) because it lacks an explicit concurrent processing requirement, such as transforming mental images. The detailed examination of performance on the spatial span task in the present research suggests that the distinction between short-term and working memory does not transfer straightforwardly from verbal to spatial tasks. Whereas a string of digits in a verbal STM task can be rehearsed with relatively little supervision, in effect, recruiting a specialized memory subsystem in relative isolation, the nature of visual rehearsal is that it engages executive processes (Baddeley, Cocchini, Della Sala, Logie, & Spinnler, 1999). The present data clearly showed that when people attempted to remember sequences of locations, many concurrent processes were recruited, including visual image generation, verbal coding, and strategy selection. Thus, spatial memory tests, such as the Corsi Blocks test, that do not have an explicit concurrent processing requirement, such as mental rotation of images, may tap concurrent storage and processing in the sense that spatial encoding (processing) competes with storage for shared resources. It may be necessary to define spatial memory tasks in terms of processing requirements, such as maintaining serial order and selecting strategies, and to specify how people supplement visuospatial representations with other types of information, such as verbal codes and hierarchical schemas.

In addition to supporting a role for strategic grouping, related to person characteristics, the present research also supported a role for perceptual grouping, related to item characteristics. Consistent with Kemps (2001) and Smirni, Villardita, and Zappalà (1983), the results from Experiments 3 and 4 showed that path complexity is an important predictor of sequence difficulty. Sequences that could be visualized as two, non-overlapping shapes were better remembered than those with path configurations that crossed themselves more. As suggested by Kemps (2001), the structure of the paths helped to predict how many locations people can remember in the correct order. When using variants of the Corsi Blocks task to assess spatial memory, it will be critical to use sequences that have been carefully designed with respect to their path configurations.

Processes and representations in spatial memory

The present research showed that verbal and spatial short-term memory processes have certain similarities. First, the presence of bow-shaped serial position curves were consistent with those obtained in verbal memory tasks. Second, the reduction of the recency effect with nonspatial interference supported the operation of domain-general mechanisms in visuospatial serial memory. Third, strategically grouping the items during encoding enhanced recall. However, the data also pointed to a variety of differences in the cognitive processing of verbal versus spatial sequences. First, recall that the primacy effect for verbal sequences is related to additional rehearsals of words that are presented early (Fischler, Rundus, & Atkinson, 1970; Tan & Ward, 2000). For spatial sequences in the current research, however, additional rehearsals of locations did not enhance the primacy effect, and in fact, when rehearsal of the first three items was

encouraged by a variable pause inserted between the third and fourth locations, the primacy effect was reduced. This finding is in stark contrast to the studies of sequence memory that have shown that temporal grouping during sequence presentation enhances memory performance for items that can be encoded verbally, such as digits (Cowan et al., 2002) or letters (Hitch et al., 1996).

In general, the failure in the present research to reproduce certain effects that are robust in verbal serial memory supports the hypothesis that multiple codes are used in short-term and working memory. Representations of speech items retain temporal properties of the stimuli (i.e., words that take longer to pronounce are represented with a larger number of phonemes), and phonological representations in short-term memory are affected by the grouping within the stimuli. In contrast, a location sequence can be represented in multiple ways. Some researchers have suggested that the primary mode of representing the spatial sequence is to generate a visualized path. To the extent that people use a visual path representation that can be “read off” in either direction, performance should be similar for forward and backward report, whereas accuracy is much poorer when digits or words must be recalled in reverse order. Isaacs and Vargha-Khadem (1989), in a study of children ages 7 to 15, found that spatial span was performed backwards with no loss of accuracy, but verbal span was poorer for backwards recall. Farrand and Jones (1996) also compared forward and backward recall of verbal and spatial sequences, and found an accuracy advantage for the forward report condition when both item and order information were required. Thus, the results from the few studies available were inconsistent. The present examination of strategy reports shows

that it cannot be assumed that people will rely on a path-type representation. Rather, they can be expected to strategically split their resources between verbal and visual strategies, depending on item characteristics and their own preferences for visualizing, verbalizing, or adding other kinds of cues to form patterns, such as musical tones. One reason that verbal and spatial serial memory are differentially affected by task variables such as temporal grouping is that the underlying representations for spatial sequences are more diverse than those for verbal sequences.

Due to the diversity of cognitive processes and underlying representations used in spatial short-term memory, models of verbal serial memory cannot be straightforwardly applied to spatial memory. The perturbation model that was discussed in Chapter 2 is too simple to account for the range of data presented here. For example, the perturbation model would not predict large performance differences between memory for four-location versus six-location sequences. The model would predict lower accuracy at middle positions for both sequence lengths, with slightly worse performance for six-location sequences. Instead, we see near-ceiling performance for four-location sequences, and lower performance at all serial positions for six-location sequences. The perturbation model also predicts perfectly symmetrical serial position curves, as the underlying mechanisms for primacy and recency are assumed to be the same. The present data do not reflect symmetrical curves, but greater primacy than recency.

The assumption of the perturbation model that primacy and recency have the same sources is not supported at all in the present research. I found that the primacy and recency portions of location sequences were differentially affected by task manipulations.

The recency effect was more impaired by a nonspatial interference task than the primacy effect, when interference was imposed during the retention interval. The primacy effect was impaired when participants performed an additional task during encoding (i.e., controlling the duration of the interval between the third and fourth locations). In a similar manner, studies of verbal serial memory had previously shown that different variables affect the primacy and recency parts of the curves. For example, word familiarity affects primacy and the ratio of inter-item presentation to retention intervals affects recency. However, variables relevant to verbal sequences either do not apply to spatial sequences (i.e., word familiarity), or do not affect spatial serial memory in the same way. For example, a longer retention interval had been associated with a smaller recency effect for letter span when inter-item interval was held constant, but this effect was not found in the present data. With verbal data, rehearsals of early items contribute to enhanced accuracy on items that are presented early in a sequence. With spatial data, the primacy effect did not appear to be related to rehearsal of early items: when people were given additional time to rehearse the first three items, the primacy effect was muted, not enhanced.

Thus, current models of serial memory that have been developed based on data from verbal tasks may not be very useful in understanding spatial serial memory. Instead, a model of spatial serial memory will need to include the different processes that people use during the task, and the characteristics of items that predict problem difficulty. Based on the present data, encoding processes that should be included in the model are (a) grouping of locations into visualized shapes, and (b) activating verbal codes

corresponding to serial positions and descriptions of shapes. Parsing appears to be an encoding strategy that affects the mental representation of the sequence and enhances recall. All three of the encoding strategies are resource demanding, so executing any of them detracts from the total resources available for processing the sequence during presentation. Of the three strategies, only the parse strategy showed that the benefits of additional encoding outweighed the costs.

A complete model will predict which strategies are more accurate than others, and how much time the strategies take to execute based on the steps involved and problem characteristics. The model will also incorporate mechanisms for strategy choice, as it is clear that multiple strategies are used on the spatial span task, and that strategy adaptivity is relevant to short-term memory performance. In other research on strategy use, researchers have found that when people have multiple strategies to choose from, they choose based on characteristics of the particular problem, and the previous success rate of different strategies (Schunn et al., 2001). Strategy selection is finely attuned to task demands. In Experiment 4, participants were biased to use a parsing strategy, and had two additional demands: remembering whether they would give a response while viewing the sequence, and deciding when to terminate the pause. Under these task conditions, strategy use was rendered less adaptive.

The executive processes in the model in Figure 1 of strategic grouping and keeping track of serial order were involved in task performance. Additional mechanisms must be added to the model for strategy selection: although people may not be aware of how they choose strategies, and of the base rates of success of the strategies, the process

of adapting to the task did require executive resources, as suggested by the loss of strategy adaptivity when additional task-switching requirements were imposed in Experiment 4.

Other research on working memory use in spatial tasks has suggested that people use both verbal and spatial codes, especially when the spatial tasks are difficult (Barshi & Healy, 2002; Garden, Cornoldi, & Logie, 2002). Garden et al. (2002) asked participants to learn a route by either studying maps, or by walking around a small city. When participants used maps, they relied primarily on visuospatial working memory, and a spatial tapping task interfered with learning, whereas a verbal task did not. In contrast, when participants navigated in the city, learning was impaired by both spatial and verbal tasks. In more complex situations, such as navigating in the real world, participants will recruit verbal codes to supplement visuospatial working memory. The results of the present research are consistent with those found by Garden et al. when working memory was investigated using more complex cognitive tasks, such as navigation, in that people relied on combinations of verbal and spatial information.

Garden et al. also reported that participants who scored lower on tests of spatial ability were more affected by the concurrent verbal task. Participants with low spatial ability may have relied more on verbal representations, and thus were more impaired by a concurrent verbal task. Consistent with models of strategy choice (e.g., Siegler & Lemaire, 1997), individual differences in strategy efficiency affect strategy selection when people perform spatial tasks. In the context of the present research, the parsing strategy may have been helpful only for some participants. Further research is needed to

determine the conditions under which strategic grouping is beneficial to spatial short-term memory performance.

In conclusion, the present research supported to emerging consensus that spatial memory taps multiple cognitive systems, and connected individual differences in performance to participants' strategies for encoding spatial information. Spatial memory span tasks, even the relatively simple one used here, recruit diverse processes and representations as compared to verbal memory tasks, for which representations and rehearsal processes are more homogeneous across participants, trials, and task conditions. More complex tasks requiring spatial memory, such as navigating in the world, will also recruit verbal codes and executive processes to supplement the limited resources of the specialized visuospatial memory system.

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Appendix A-1: Layout of locations for spatial span task

Appendix A-2: Layout of locations for serial reaction time task, Exp. 1

Appendix B-1: Location sequences, Exps. 1 and 2

Trial	Location Sequence
1	L4-L7-L9
2	L3-L1-L9
3	L4-L2-L5
4	L3-L4-L1-L7
5	L6-L1-L5-L8
6	L5-L8-L3-L2
7	L5-L2-L1-L8-L6
8	L4-L2-L7-L3-L1
9	L9-L7-L5-L8-L3
10	L3-L9-L2-L4-L8-L7
11	L3-L7-L8-L2-L9-L4
12	L9-L2-L7-L6-L1-L9
13	L5-L9-L1-L7-L4-L2-L8
14	L5-L7-L9-L2-L8-L4-L6
15	L1-L9-L6-L2-L7-L9-L1
16	L5-L8-L1-L9-L2-L6-L4-L7
17	L5-L9-L3-L6-L7-L2-L4-L3
18	L2-L9-L7-L6-L3-L1-L5-L4
19	L5-L3-L8-L7-L1-L2-L4-L6-L9
20	L4-L3-L6-L8-L1-L7-L9-L3-L5
21	L2-L7-L5-L8-L6-L2-L5-L8-L4

Note: From Schellig and Hättig (1993).

Appendix B-2: Location sequences, Exps. 3 and 4

Stimulus	Location Sequence	Percent correct	
Number		<i>M</i>	<i>SD</i>
Spatially separable			
5116	L6-L3-L5-L2-L9	82	27
5118	L8-L5-L6-L3-L2	90	22
5111	L5-L2-L7-L3-L6	96	10
5114	L2-L1-L5-L8-L6	96	14
5102*	L4-L2-L7-L3-L1	98	9
6120	L7-L8-L2-L9-L3-L6	72	34
6114	L3-L9-L1-L7-L2-L8	77	29
6111	L4-L3-L2-L6-L5-L8	82	24
6116	L8-L4-L7-L6-L2-L3	84	23
6118*	L6-L9-L7-L4-L1-L5	98	7
7114	L4-L8-L7-L9-L1-L3-L5	76	23
7121	L7-L2-L4-L8-L1-L6-L9	79	24
7118	L8-L3-L6-L5-L1-L2-L4	83	25
7112*	L1-L5-L3-L6-L7-L8-L2	84	25
7119	L3-L5-L9-L6-L1-L7-L2	88	23
8119	L6-L3-L9-L1-L2-L8-L7-L4	54	29
8121	L9-L5-L3-L6-L2-L8-L4-L7	64	30
8115	L8-L5-L9-L6-L4-L7-L2-L1	71	24
8117	L7-L1-L5-L4-L3-L6-L8-L9	76	25
8113*	L4-L7-L8-L9-L1-L6-L5-L3	91	16
Nonseparable			
5212	L4-L3-L6-L1-L8	93	19
5213	L9-L3-L2-L5-L7	93	20
5219	L8-L3-L9-L6-L4	93	16
5215	L2-L5-L7-L4-L3	97	11
5217*	L6-L4-L8-L9-L3	98	6
6212	L4-L6-L8-L3-L1-L9	81	26
6213	L3-L8-L1-L9-L2-L7	82	27
6217	L6-L5-L7-L9-L2-L8	83	30
6219	L7-L6-L4-L8-L1-L9	89	21
6215*	L8-L1-L9-L3-L2-L6	98	8

7220	L3-L7-L9-L2-L8-L5-L6	58	25
7217	L8-L3-L4-L1-L9-L6-L5	69	30
7211	L1-L9-L6-L2-L7-L3-L8	74	32
7215	L2-L3-L8-L5-L6-L7-L4	74	28
7213*	L4-L3-L5-L1-L6-L2-L7	80	32
8212	L2-L5-L8-L4-L7-L3-L9-L1	52	29
8222	L9-L4-L6-L3-L5-L1-L7-L8	54	28
8214	L4-L9-L3-L1-L6-L7-L2-L8	58	30
8220	L6-L1-L4-L8-L3-L9-L2-L7	60	28
8216*	L8-L3-L2-L6-L1-L5-L4-L9	73	23

Note: $N = 48$ except for those sequences marked with an asterisk (*), $N = 20$ (Exp. 3 only).

Appendix C: Questionnaire

1. What is your age in years? _____ 2. Please circle your gender: M F

3. Do you wear / have you ever worn corrective lenses (i.e., glasses or contacts)?

If **yes**, for what purpose do / did you wear them (e.g., driving, reading):

4. Have you ever had a head injury (e.g., concussion)? YES NO

If **yes**, please describe the location(s) of injury:

If **yes**, how severe was the head injury? (Please circle one.)

1	2	3	4	5	6	7
mild		moderate			severe	

5. Do you have any known neurological disorders (e.g., epilepsy)? YES NO

If **yes**, please describe briefly:

6. Please rate your level of expertise with using desktop computers: (Circle one.)

1	2	3	4	5	6	7
novice		intermediate			expert	

7. How often do you use a computer with a mouse as an input device? (Circle one.)

1	2	3	4	5	6	7
less than once per month		2-5 times per week			every day	

8. Language(s) spoken:

Appendix D: Span-equivalent measures, Exps. 1 through 4

	Condition	Span	<i>SD</i>
Experiment 1 (N = 28)	pretest	5.61	0.74
	posttest	6.07	1.03
	both tests	5.87	0.79
Experiment 2 (N = 40)	control	5.78	0.75
	interference	4.04	0.98
Experiment 3 (N = 20)	all trials	6.30	0.70
Experiment 4 (N = 28)	all trials	6.15	0.87

Span-equivalent scores were calculated as recommended by Smyth and Scholey (1992). Participants received a fraction of a point for each sequence reproduced perfectly at that sequence length. For example, a participant who reproduced two of the three sequences at length 4 on the pretest would receive 0.67 points. These fractions of points were summed and added to the number below which testing began, which was either 2 (Exps. 1 and 2) or 4 (Exps. 3 and 4). Maximum span was 9.0 in Exps. 1 and 2, and 8.0 in Experiments 3 and 4.