THE BREADTH OF SERIAL ORDER STM

CHARACTERIZING SERIAL ORDER PROCESSING IN WORKING MEMORY AND IN THE LANGUAGE DOMAIN

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Lay Abstract

An extensive body of literature indicates functional similarities between verbal and visuo-spatial domains of short-term memory (STM) with respect to serial order processing (i.e., the mind's ability to remember sequential information), highlighting the possibility of a domain-general ordering mechanism. Moreover, a growing body of work has elucidated strong relations between serial order STM capacity and word-learning ability (see Baddeley, Gathercole & Papagno, 1998, for a review), suggesting that a similar domain-general ordering mechanism may be at play within the language acquisition system. The present project aimed to directly address these two related themes by first studying a) whether serial order processing is domain-general and then b) whether serial order STM underlies vocabulary learning. In a series of experiments, we provide direct evidence that common ordering mechanisms are employed by the verbal and visuo-spatial STM domains and, furthermore, that these mechanisms also support vocabulary acquisition.

Abstract

The present project aimed to characterize the role of serial order within the working memory and language domains by first addressing a) whether serial order processing is domain-general and then b) whether serial order processing underlies vocabulary acquisition. Experiment 1 revealed that order memory in the visuo-spatial domain is qualitatively similar to order memory for verbal memoranda by reporting visuo-spatial equivalents of two well-known effects in verbal STM for serial order, *repetition inhibition* (e.g., Crowder, 1968) and r*epetition facilitation* (Crowder, 1968). The effects were, however, accompanied by critical differences that may be due to modality-specific processes. Experiment 2 directly investigated whether verbal and visuo-spatial STM rely on common ordering mechanisms using a delayed recall dual-task design that contrasted two types of visuo-spatial interference tasks during a concurrent verbal serial order memory task (digit sequence memory). The visuo-spatial tasks probed either serial order STM or non-serial order (item) STM. Serial-order specific interference effects with the concurrent verbal serial order STM task were found. In experiment 3, we replicated the investigations of Experiment 2 using a word-learning paradigm as a concurrent task in place of the verbal serial order STM task that was previously used. Again interference by a visuo-spatial STM task was found only when it required memory for serial order.

In sum, the results suggest that verbal and visuo-spatial STM subsystems rely on common mechanisms for serial order processing. These in turn appear to

communicate with domain-specific processing substrates involved in item-level memory representations. Furthermore, the results indicate that such domain-general serial ordering mechanisms are also involved in novel word-learning. Taken together, the present findings provide crucial constraints for modeling of order representations. They also offer insight into mechanisms shared by vocabulary acquisition and STM tasks.

This dissertation is dedicated to *Appa* and *Amma*,
who started my adventure at McMaster University.

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Table of Contents

List of Figures and Tables

List of all Abbreviations and Symbols

CBT: Corsi Blocks Task

STM: Short-term memory

LTM: Long-term memory

R1: First occurrence of repeated item

R2: Second occurrence of repeated item

S1: Item subsequent to first occurrence of repeated item

S2: Item subsequent to second occurrence of repeated item

R-0: No repetition of digit sequences/word-forms

R-1: First repetition of digit sequences/word-forms

R-2: Second repetition of digit sequences/word-forms

ANOVA: Analysis of Variance

MSE: Mean squared error

η_p^2: Partial eta-squared

d: Cohen's d effect size

p: p-value in statistical tests

F: f-value in ANOVA

t: t-value in t-tests

ms: millisecond

Declaration of Academic Achievement

Chapter 2:

Dr. Elisabet Service, my supervisor, provided insight on the theoretical development of this project, including the experimental design. I was responsible for programming the experiment as well as the data collection and analysis, interpretation, and write-up of the findings. Dr. Elisabet Service provided invaluable guidance on statistical techniques and the composition of the chapter.

Chapters 3 and 4:

Under the supervision of Dr. Elisabet Service, I was responsible for the theoretical development of this project, design and programming of the experiments, as well as data collection and analysis, interpretation, and write-up of the findings. Dr. Elisabet Service advised on stimuli and measures, statistical techniques and the composition of the chapter. Dr. Elisabet Service and my supervisory committee members, Dr. John Connolly, Dr. Suzanna Becker, and Dr. Bruce Milliken provided insight on the interpretation of the data. Neetika Dhaddha, a member of the Language and Memory Lab, assisted with data collection.

Introductory Chapter

Summary of Research Objectives

The ability to remember information in the short-term is thought to be an integral part of several higher level cognitive processes ranging from vocabulary acquisition (Baddeley, Gathercole, & Papagno, 1998) to mental imagery (Kosslyn, 1980) and motor skill development (Damasio & Benton, 1979; Lashley, 1951). It was most influentially conceptualized in the working memory model by Baddeley and Hitch (Baddeley, 1986; Baddeley & Hitch, 1974), in which the "phonological loop" processed and stored a sequence of verbal and the "visuo-spatial sketchpad" visuo-spatial items. The two-subsystems are completed by an "episodic buffer" that integrates information from the two sub-systems as well as long-term memory (LTM) and a "central executive" that functions as an attentional control system (Baddeley, 2000). Despite decades of research since Baddeley and Hitch's (1974) conceptualization of working memory, the exact mechanisms by which serial order is represented remains unclear. Explicit mechanisms for the coding of serial order in the phonological loop were later introduced by Burgess and Hitch (1992) and followed by others (e.g., Page & Norris, 1998; Farrell & Lewandowsky, 2002).

Addressing explicit mechanisms for serial order first requires knowledge of whether the verbal and visuo-spatial STM subsystems rely on common, order mechanisms or whether distinct mechanisms apply to different domains. A growing body of evidence suggests some level of functional equivalence between verbal and visuo-spatial domains of short-term memory (STM) with respect to serial order processing (see Hurlstone, Hitch, & Baddeley, 2014, for a review). Particularly, a recent review (Hurlstone et al., 2014) highlighted that a number of verbal serial memory phenomena have also been observed in the visuo-spatial domain: *error patterns, serial position curves,* the *sequence length effect*, the *temporal grouping effect*, the *suffix effect*, and the *Hebb repetition effect.* Such functional similarities across verbal and visuo-spatial domains are hypothesized to reflect a common, domain-general ordering mechanism. However, so far, not all relevant effects have been investigated in the visuo-spatial domain (Hurlstone et al., 2014). It, therefore, remains unclear to what extent common ordering principles apply to visuo-spatial and verbal STM. Furthermore, there is a need to move beyond finding functional similarities and directly address whether the two domains share a common ordering mechanism.

The domain-generality of serial order processing is also of critical interest in the language domain as several studies have indicated an association between serial order verbal STM capacity and vocabulary acquisition (see Baddeley et al., 1998, for a review). It has been proposed that the link between vocabulary acquisition and serial order STM may arise from reliance on a common "order processing" mechanism required in both tasks (Page & Norris, 2009a). For instance, serial recall tasks often consist of learning a sequence of items such as letters (e.g., recalling the letters R T C). Similarly, learning a novel word-form (e.g., artecey) may consist of learning the sub-lexical units of the word in the correct order (e.g., the syllables, ar, te, cey -> artecey; Szmalec, Brysbaert, & Duyck, 2012). However, presently, there is no direct evidence indicating that serial order STM underlies vocabulary acquisition.

The overall objective of my research was two-fold: a) to address whether serial order processing is domain-general and b) to study whether serial order STM underlies vocabulary learning. In what follows, I review the literature pertinent to these two related aims.

Serial Order in Working Memory

Modular approach to serial order STM

Several researchers have revealed evidence supporting a modality-specific approach to immediate serial memory; that is a dissociation between verbal and visuo-spatial memory representations in STM. This has been most influentially put forth in the working memory (WM) model by Baddeley and Hitch (Baddeley, 1986; Baddeley & Hitch, 1974). Early evidence stemmed from empirical studies that crossed verbal and visuo-spatial primary tasks with verbal and visuo-spatial secondary tasks to highlight modality-specific interference effects (e.g., Baddeley, Grant, Wight, & Thomson, 1975; Farmer, Berman, & Fletcher, 1986; Logie, Zucco, & Baddeley, 1990; Morris, 1987). For instance, Smyth, Pearson, and Pendleton (1988) reported impairments on a spatial span task when participants were required to simultaneously tap around a set of four metal plates arranged in a square but not when participants performed a concurrent articulatory suppression task by vocally repeating verbal material.

Neuropsychological data also suggest that serial verbal and visuo-spatial information are functionally distinct in STM. For instance, the brain damaged STM patient PV exhibited a severe deficit on a digit span task but normal performance on a spatial span task (Vallar & Baddeley, 1984). The opposite dissociation has also been reported, i.e., preserved verbal span in combination with impaired visuo-spatial STM (Hanley, Young, & Pearson, 1991). Furthermore, a wealth of neuroimaging data show neural activations in distinct parts of the brain for verbal and spatial stimuli (e.g., Awh, Jonides, & Reuter-Lorenz, 1998; Smith, Jonides, & Koeppe, 1996). In contrast, other experiments have produced fMRI evidence against stimulus-based neural activations in working memory tasks (Nystrom et al., 2000; Postle, Stern, Rosen, & Corkin, 2000).

While the above reported double dissociations may support the argument for distinct spatial and verbal STM stores, it is unclear whether the two sub-systems also employ separate ordering mechanisms. Many recent STM models suggest that performance in STM tasks is mediated by two distinct processes, the ability to store the phonological/visuo-spatial characteristics of the items of the memory list (item information) and the ability to store the sequential order in which the items are presented (serial order information; e.g. Burgess & Hitch, 1999; Gupta, 2003). Several of the above mentioned studies have used span tasks to measure STM performance. In a serial span task, participants are typically presented with a sequence of items (e.g., digits, words, spatial locations) and required to immediately recall the items in the order of presentation. Although the reported findings may appear to support modality-specific aspects of serial order memory it is important to highlight that many of these studies (e.g., Hanley et al., 1991; Smyth et al., 1988) used spatial tasks that have been criticized for not being valid measures of the sequential aspects of spatial serial memory. Several studies used slight variations of the Corsi Blocks task (CBT; Corsi, 1972). In this task, participants are presented with a fixed set of locations (visible throughout encoding, maintenance, and recall) and required to encode and recall the order of presentation of spatial locations indicated by pointing to or highlighting on a screen in a sequence. Although it has been the most commonly used spatial serial memory task in clinical (e.g., Kaplan, Fein, Morris, & Dellis, 1991; Milner, 1971) as well as experimental (e.g., Smyth & Scholey, 1994a, 1994b) settings, there are conceptual limitations inherent in the task. One concern is that although the task is assumed to employ processes that encode sequential information, participants may use alternative mechanisms to perform the task. Particularly, since all the locations are fixed and visible throughout the duration of the task, participants may use a possibly verbal recoding or encoding of the marked sequence as a whole configural path representation as opposed to a sequential ordering of items (Berch, Krikorian, & Huha, 1998). Although the CBT was developed as a spatial alternative to procedures assessing memory for verbal sequences, its validity in assessing memory for visuo-spatial order remains unclear.

Recently, visuo-spatial serial memory has been studied using a new Corsi-type task (The Dots Task; Jones, Farrand, Stuart, & Morris, 1995) in which dots are sequentially displayed in different locations on a screen one at a time. At recall, the whole configuration is presented simultaneously on a response screen. Participants are required to indicate the original order of presentation by using a mouse to point and click on the dots. Since the dots are presented sequentially, it is less likely that the sequence will be remembered as a whole configural representation as opposed to a sequential ordering of items. Moreover, the Dots Task is particularly useful for assessing memory for serial order information because all the dot locations are provided as cues at the time of serial recall, therefore reducing the demand for item memory while maximizing the demand for order memory. This task is also regarded as a more appropriate counterpart of the digit span (Jones et al., 1995; Parmentier & Andrés, 2006; Parmentier, Elford, & Maybery, 2005). Overall, such a task would prove useful in studies specifically addressing whether serial order mechanisms are shared across verbal and visuo-spatial STM.

In a modular model, tasks relying on different modalities should not interfere with each other. However, some studies have reported interference effects between verbal and visuo-spatial tasks in dual-task designs. For example, the requirement to perform an articulatory suppression task that consisted of counting backwards resulted in impaired performance on a spatial span task (Smyth et al., 1988; Smyth & Pelky, 1992). Likewise, visuo-spatial location tracking appeared to interfere with a verbal span task involving the recall of consonants presented out loud (Morris, 1987). Jones et al. (1995) also found that a changing-state articulatory suppression task, had the same detrimental effect on the serial recall of consonants and on performance in the Dots Task. Similarly, a changing-state sequential tapping task had the same detrimental effect on the serial recall of consonants and on performance in the Dots Task. While these results were later replicated by others (Meiser & Klauer, 1999; Guérard & Tremblay, 2008; Guitard & Saint-Aubin, 2015), asymmetries emerged where additional modality-specific interference was also observed. Although such interfering task pairs may both employ the central executive component along with the respective verbal and visuo-spatial WM components; these findings, nevertheless, present some level of challenge to the purely modular view of STM underpinning order processing. Furthermore, little research has addressed the question whether the original data from brain-damaged patients indicate a dissociation between verbal and visuo-spatial binding in STM or deficits in other fundamental processes specific to the nature of the tasks (e.g., sequential vs. configural) employed in these studies. Similarly, it is unclear whether the neuroimaging data indicating modality-specific activation support a dissociation between verbal and visuo-spatial serial order STM systems or more generally between sensory networks specialized in processing modality specific item information (e.g., verbal vs. visuo-spatial stimuli).

Serial order: Functional similarities across verbal and visuo-spatial STM

Several other findings suggest some level of functional equivalence between verbal and visuo-spatial domains of STM with respect to serial order processing. Particularly, a recent review (Hurlstone et al., 2014) highlighted a number of verbal serial memory phenomena that have also been observed in the visuo-spatial domain: the *sequence length effect*, *temporal grouping effect*, the *suffix effect*, and the *Hebb repetition effect*. The *sequence length effect* was first reported with verbal sequences, in which serial recall accuracy declined as the sequence length increased. This effect has since been replicated with many types of visual and spatial stimuli. Another phenomenon found with both verbal and nonverbal stimuli is what has been characterized as the *temporal grouping effect*. This consists of a marked improvement in the immediate memory for a sequence of items when temporal pauses are inserted during list presentation. The *suffix effect* is a phenomenon first observed in the verbal domain, as an impairment in recalling the terminal items of a list when one extra to-be-ignored spoken item (the suffix; e.g. "Recall") is added at the end of the list. This phenomenon has since the original reports been observed in several other modalities. Similarly, the *Hebb Repetition Effect* (Hebb, 1961) was first reported with verbal stimuli, as increased performance on the immediate serial recall of a list of items that are repeatedly presented on every third trial in an immediate serial recall experiment. This phenomenon was initially regarded as distinctive to verbal stimuli, resulting from the transfer of information from verbal STM to LTM. However, recent evidence casts light on the modality-free nature of this effect, with many studies reporting similar findings with visuo-spatial locations, pictures, and auditory spatial locations (see Hurlstone et al., 2014, for a review).

Another widely reported phenomenon concerns recall accuracy as a function of serial position. When task requirements are equated, both verbal and visuo-spatial stimuli exhibit similar *serial position curves* with marked primacy and recency effects in recall tasks. This holds true for a variety of visuo-spatial stimuli including visuo– spatial locations (e.g., Avons, 2007; Farrand, Parmentier, & Jones, 2001; Guérard & Tremblay, 2008; Jones et al., 1995; Tremblay, Parmentier, Guérard, Nicholls, & Jones, 2006), visuo–spatial movements (e.g., Agam, Galperin, Gold, & Sekuler, 2007), auditory–spatial locations (e.g., Groeger, Banks, & Simpson, 2008; Parmentier & Jones, 2000; Tremblay et al., 2006), visual matrix patterns (e.g., Avons, 1998; Avons & Mason, 1999), and unfamiliar faces (e.g., Smyth, Hay, Hitch, & Horton, 2005; Ward, Avons, & Melling, 2005).

Finally, the pattern of errors in visuo-spatial serial recall (e.g., Avons, 1998; Guérard & Tremblay, 2008; Parmentier, Andrés, Elford, & Jones, 2006; Parmentier & Jones, 2000) is similar to that found in verbal serial recall (e.g., Bjork & Whitten, 1974; Conrad, 1965; Henson, Norris, Page, & Baddeley, 1996) when sequences contain novel or dissimilar items. A commonly reported type of error in serial recall is an adjacent transposition. In these errors, items encountered in close succession at the time of presentation exchange positions at the time of recall. Furthermore, a distinctive feature of transposition errors is that when an item *i* is incorrectly recalled too early in the list, the skipped item *i*-1 is more likely to be recalled next (*fill-in error*) relative to the item *i*+1 (*infill error*; e.g., Farrell, Hurlstone, & Lewandowsky, 2013). Likewise, migration gradients are observed such that items recalled in incorrect positions would be recalled in positions close to their correct serial position (locality constraint; Henson et al., 1996). Verbal and visuo-spatial serial memory tasks also show increased error rates when sequences contain similar items, such as phonologically similar sounding items (Baddeley, 1966, 1968; Conrad, 1964; Wickelgren, 1965a,1965b) and visually/spatially similar items (Avons & Mason, 1999; Jalbert, Saint-Aubin, & Tremblay , 2008).

Hurlstone and Hitch (2014) also analyzed recall error patterns in a spatial serial recall task in order to determine whether the response times during transposition errors matched those found with verbal stimuli. But more interestingly, the results allowed the examination of which of five alternative mechanisms of serial order best predicted the dynamics of the transposition latencies. The empirical results were in line with findings in the verbal domain (Farrell & Lewandowsky, 2004; Lewandowsky & Farrell, 2008b) and matched the predictions of a competitive queuing serial order mechanism based on principles of a primacy gradient, position marking, and response suppression. This was the first study to show that verbal and visuo-spatial STM rely on common principles for serial order representations.

Given previous distinctions between item and order STM processes, Majerus et al. (2010) investigated the commonality of neural networks underlying verbal and visuo-spatial STM with respect to item vs. order processing using fMRI. They contrasted two types of STM recognition tasks, one which presented sequences of non-words (verbal) and the other which presented sequences of unfamiliar faces (visual) for later recognition. Following a short delay, memory for either order or item information was probed. Results indicated domain-specific effects for verbal and visual STM, in sensory networks specialized in processing modality-specific item information (i.e., language and face processing areas respectively). The modality differences were strongest for item STM conditions relative to order STM conditions. However, results also revealed that identical neural networks (parieto-fronto-cerebellar) were activated during serial order processing in both the verbal and visual STM conditions, supporting recent behavioural data showing identical serial position curves for the recall of face and word sequences (Smyth et al., 2005). In light of these results, it was argued that overlap of neural networks for verbal and visual STM therefore depends on the type of information, item vs. order, to be remembered, with modality-specific networks supporting item information and common neural networks coding order information (Majerus et al., 2010).

Based on such neuro-imaging and behavioural data showing extensive functional similarities between verbal and visuo-spatial STM, it may appear parsimonious to assume the operation of a common, ordering mechanism during verbal and visuo-spatial STM tasks. However, functional equivalence between verbal and visuo-spatial serial order phenomena cannot be taken as direct evidence for a shared ordering mechanism. The two domains may use distinct, domain-specific ordering mechanisms that merely rely on functionally similar principles. Currently, direct evidence is needed to address the question of whether the two domains share a general ordering mechanism or whether distinct, modality-specific mechanisms are applied.

Serial Order in Vocabulary Acquisition

The link between serial order STM and word-form learning

Vocabulary learning is a corner stone in all language acquisition. Whether it is children learning a native language or adults learning a second language, novel word forms are acquired with high speed and efficiency. While research demonstrates that such rapid learning of language exists through repeated exposures (e.g., Dobel et al., 2010) the mechanism underlying this phenomenon is far less understood. A long line of research reflects the importance of verbal STM capacity for forming novel phonological word-form representations. Particularly, phonological processing/storage capacities (i.e., the ability to store and immediately recall phonological information) is closely associated with lexical development (e.g., Avons, Wragg, Cupples, & Lovegrove, 1998; Baddeley, Gathercole, & Papagno, 1998; Gathercole & Baddeley, 1989; Gathercole, Hitch, Service, & Martin, 1997; Gathercole, Service, Hitch, Adams, & Martin, 1999;

Gathercole, Willis, Baddeley, & Emslie, 1994; Gathercole, Willis, Emslie, & Baddeley, 1992; Service, 1992; Service & Craik, 1993; Service & Kohonen, 1995). More recently, a growing body of evidence also suggests that the processing of serial order in verbal STM is related to vocabulary acquisition (see Baddeley et al., 1998, for a review), however, the mechanisms driving this association are unclear.

Verbal/phonological short-term memory performance is classically probed using non-word repetition tasks or span tasks. In a non-word repetition task, participants must immediately recall out loud the last heard non-word. Several studies indicate that non-word repetition ability is associated to vocabulary measures, suggesting that memory for phonological information is involved in novel word-learning (Service & Craik, 1993; Service & Kohonen, 1995). In a span task, a sequence of items (e.g., digits, words) are presented for immediate serial recall (Conway et al., 2005). Recent work suggests that performance in verbal STM span tasks is mediated by two distinct processes, the ability to store the phonological and semantic characteristics of the items of the memory list (item information) and the ability to store the sequential order in which the items are presented (serial order information; e.g. Perez, Majerus, Mahot, & Poncelet, 2012). Thus, the question arises whether the well established link between verbal STM capacity and vocabulary acquisition may be driven specifically by underlying serial order STM processes.

There are three lines of evidence supporting the association between serial order STM capacity and vocabulary level stemming from developmental and neuropsychological research as well as research with individuals who are either gifted or have specific language learning difficulties (see Baddeley et al., 1998, for a review). Developmental research indicates that vocabulary size is predicted by immediate serial recall ability at early stages of word learning (Gathercole et al., 1992). Also, neuropsychological work with patients suffering from short-term memory deficits (e.g., Basso, Spinnler, Vallar, & Zanobio, 1982; De Renzi & Nichelli, 1975; Trojano & Grossi, 1995; Warrington & Shallice, 1969) shows that such patients exhibit impairments in serial order STM tasks (e.g., recalling auditorily presented lists) as well as specific deficits in learning novel phonological word-forms even when their general language function is largely preserved (Baddeley, Papagno & Vallar, 1988). Furthermore, research with gifted adults and individuals with learning disabilities shows strong associations between immediate serial recall ability and language learning skill, independent of IQ (see Baddeley et al., 1998, for a review).

The above mentioned studies have mainly used verbal serial recall tasks (e.g., the digit span) and therefore the reported links between serial order STM and word learning may also reflect a common dependence on verbal STM processes. To address this, recent studies are investigating the association between lexical development and verbal STM by distinguishing between item and order memory (Majerus, Heiligenstein, Gautherot, Poncelet, & Van der

Linden, 2009; Majerus, Poncelet, Elsen & Van der Linden, 2006; Majerus, Poncelet, Greffe, & Van der Linden, 2006; Majerus, Poncelet, Van der Linden, & Weekes, 2008; Leclercq & Majerus, 2010; Majerus & Boukebza, 2013). One approach is to selectively probe item versus order information in classic immediate serial recall tasks. For instance, Majerus et al. (2009) analyzed the proportion of item versus order errors when recalling word lists and found that vocabulary knowledge in 6-7-year-old children correlated with the proportion of order errors made. Using a similar methodology, this correlation was also evident in adults (Majerus et al., 2006).

In another approach, Leclercq and Majerus (2010) employed verbal STM tasks that either maximized the requirement for maintaining serial order information while minimizing the requirement for maintaining item information (e.g., immediate serial recall of word lists consisting of highly familiar words), or maximized item processing requirements while minimizing the requirement for maintaing order information (e.g., delayed recall of novel, unfamiliar items). The results of this longitudinal study with 4-year-old children indicated that performance in item and order STM tasks independently predicted their vocabulary level after one year. More notably, order STM was found to be a stronger predictor. In a similar approach by Majerus et al. (2006), order STM was more strongly associated to vocabulary development in 4 and 6-year-old children. Likewise, a similar pattern of findings extended to research with bilingual adults, which showed that serial order STM relative to item STM was a stronger predictor of novel word-learning (Majerus et al., 2008). Finally, Majerus & Boukebza (2013), using a similar design to Leclercq and Majerus (2010), provided evidence that serial order coding ability in 6-7-year old children predicted the rate of phoneme migration errors during the learning of novel word-forms.

An alternative approach to tease apart the roles of serial order STM versus general verbal STM processes in vocabulary development is to study order memory in nonverbal tasks. One possibility is to use a visuo-spatial serial order reconstruction task such as the Dots Task (Jones et al., 1995). Indeed, it has been shown that both visuo-spatial sequence learning (in the Dots task) and verbal sequence learning correlated to the same extent with novel word-learning ability (Mosse & Jarrold, 2008).

A rationale explaining the link between serial order STM and word learning

Page and Norris (2009) proposed that the link between vocabulary acquisition and serial order STM may arise from a reliance on a common "order processing" mechanism required in both tasks. For instance, serial recall tasks often consist of learning a sequence of items such as letters (e.g., recalling the letters R T C in a serial order STM task). Similarly, learning a novel phonological word-form (e.g., artecey) may consist of learning the phonological units of the word in the correct order (i.e., the syllables, ar, te, cey -> artecey). This process involves repeated order processing of the phonological units within a word-form until a stable lexical representation of the whole word-form is established.

Page and Norris (2009a) argued that this proposed word-form learning process is analogous to the Hebb repetition effect in the working memory literature (Hebb, 1961). The Hebb repetition effect refers to the phenomenon that occurs in an immediate serial recall task when a particular sequence is repeated across trials. Typical results indicate that memory for the repeated sequence progressively improves across repetitions relative to unrepeated sequences. The Hebb repetition effect is considered a serial-order learning effect, in which sequence information in STM gradually transforms into a LTM representation with repeated exposure. The learning of novel word-forms is argued to mimic this process (Szmalec, Duyck, Vandierendonck, Mata, & Page, 2009; Szmalec, Page, & Duyck, 2012). Page and Norris (2009a) compiled indirect support for this claim by reviewing data that showed that the attributes of the Hebb repetition effect also extend to the word-learning phenomenon. Namely, the Hebb repetition effect persists over long-term recall delays and even when repetitions occur far apart, secondly, multiple lists can be learned at once, and, thirdly, learning occurs relatively fast. Furthermore, the Hebb learning effect is evident in young children, also partial lists can be learned, and, finally, recall is not necessary for the effect to occur, but facilitates recall. Such properties can also be applied to novel word-form learning, which suggests that the mechanisms underlying both functions are similar (see Page & Norris, 2009a, for a review).

Empirical support for this claim stemmed from a two-part study in which participants first learned sequences of nonsense syllables [consonant-vowel (CV) structures] through a standard Hebb learning paradigm. In the second part, they performed a lexical decision task- often used in psycholinguistics to study lexical access. They critically manipulated the syllables from which the nonwords were constructed. Nonwords were either constructed from the syllables in the repeated Hebb sequences or from the nonrepeated (filler) sequences. They predicted that if Hebb materials enter the mental lexicon just as novel lexical representations do, then participants will take longer to reject Hebb-based nonwords as nonwords. Results confirmed their prediction with slower lexical decision times for Hebb-based nonwords compared to nonwords constructed from nonrepeated sequences (Szmalec et al., 2009). In another study, Szmalec et al. (2012) presented Dutch speaking participants with a Hebb learning paradigm consisting of visually presented syllables. Critically, the repeated Hebb sequences were constructed with syllables forming three orthographic nonword neighbours of existing Dutch base-words. When given a lexical decision task the following day, participants exhibited slower lexical decision times for these Dutch-base words compared to matched control words. This was argued to reflect lexical competition between the newly learned Hebb-based words and the existing Dutch-base words, supporting the assumption that Hebb-based words enter the mental lexicon just as novel word-forms do. Both studies are in line with views that natural vocabulary acquisition comprises of repeated, order processing of a sequence of sub-lexical units (e.g., phonemes or syllables) leading to the consolidation of that sequential representation in long-term memory (Page & Norris, 2009a).

A related proposal suggested that if sub-lexical units such as syllables making up a novel word are represented as a sequence analogous to the items within Hebb repetition paradigms and STM serial recall tasks, then the sub-lexical items within a word should exhibit the same hallmark features observed in those tasks (e.g., serial position effects). As predicted, a study revealed classic effects of syllable serial position during repetition of polysyllabic nonwords (analogous to novel word-forms; Gupta, 2003). Along these lines, paired associate learning of novel word-forms is also affected by factors well known to affect immediate serial recall in similar ways: concurrent articulation (Papagno, Valentine, & Baddeley, 1991), phonological similarity and word length (Papagno & Vallar, 1992).

In sum, while there is a growing body of data suggesting functional similarities between serial order STM processes and phonological word-form learning (Majerus et al, 2009; Leclercq & Majerus, 2010; Majerus & Boukebza, 2013; Szmalec et al., 2009, Szmalec et al., 2012), it still remains unclear whether common ordering mechanisms underlie both functions.

Outline of Experiments

The following chapters each in turn describe the findings from a series of experiments that aimed to study, first, whether serial order STM is domain-general and second, whether serial order STM contributes to vocabulary acquisition. It is proposed that the different domains (e.g., visuo-spatial and verbal STM, lexico-semantic LTM) share at least partially a general ordering mechanism which in turn interacts with domain-specific item-level memory representations. For instance, domain-specific representations of item information (e.g., sub-lexical phonological units, visual abstract shapes) are thought to interact with a domain-general, common ordering mechanism during immediate serial recall. Verbal item STM representations (sub-lexical phonological units) in conjunction with serial ordering mechanism are hypothesized to interact with lexico-semantic representations in LTM during word-learning. Specifically, repeated processing of sub-lexical phonological units in their correct serial order may lead to LTM representations of whole word-forms.

Experiment 1 set out to explore whether order memory in the visuo-spatial domain is qualitatively similar to order memory for verbal memoranda by trying to find visuo-spatial equivalents of two well-known effects in verbal STM for serial order, *repetition inhibition* (the Ranschburg effect; e.g., Crowder, 1968; Duncan & Lewandowsky, 2003) and r*epetition facilitation* (Crowder, 1968). Experiment 2 attempted to move beyond finding functional similarities between verbal and visuo-spatial serial order phenomena, and directly investigated whether verbal and visuo-spatial STM rely on common ordering mechanisms using a delayed recall dual-task design that contrasted two types of visuo-spatial interference tasks during a concurrent verbal serial order memory task (digit sequence memory). First two types of visuo-spatial interference tasks were developed that probed either serial order STM or item (non-serial order STM). These were implemented as concurrent tasks to study serial-order specific interference effects on a primary verbal serial order STM task. Finally, Experiment 3 aimed to directly address whether common ordering mechanisms underlie vocabulary acquisition and immediate visuo-spatial serial recall by replicating the investigations of Experiment 2 using a word-learning paradigm as the primary task in place of the verbal serial order STM task used previously. In the concluding chapter, a conceptual framework characterizing the commonality of serial order in working memory and in the language domain more generally is discussed.

Chapter 2

Order Coding in Visuo-spatial STM: The Nature of Facilitative and Inhibitory Repetition Effects

Introduction

As mentioned above, a recent review (Hurlstone et al., 2014) highlighted several functional similarities between verbal and visuo-spatial serial order phenomena. Correspondence between serial order phenomena in the verbal and visuo-spatial domains provides valuable information for modeling serial order in STM. In particular, it aids in addressing which principles of serial order in verbal STM also translate to the visuo-spatial domain. An early model of serial order is the associative chaining account which postulates that order information is maintained through pairwise chaining associations between successive items. At retrieval, serial order is constructed through a process of associative cuing whereby each item becomes the cue for the subsequent item (e.g., Ebbinghaus, 1964; Lewandowsky & Murdock, 1989). This model has since been rejected by most current researchers as it has failed to account for various empirical findings relating to recall error patterns. Most contemporary models of serial order STM employ one or more of the following principles: position marking, activation gradients, and response suppression (see Hurlstone et al., 2014, for a review). For instance, positional models argue that order representations are encoded and retrieved by a set of position cues. At encoding, each item in a sequence is linked to a specific position cue. At retrieval, these position cues are reinstated bringing forth the recall of their respective items (e.g., Lee & Estes, 1977; Burgess & Hitch, 1999). Position cues can take the form of temporal, absolute, or relative codes (Henson, 1999).

Models using activation gradients assume that activation level decreases as a function of the position of the item in the list. A retrieval pattern based on activation strength is initiated such that items are recalled as a function of the strength of the item and suppressed once recalled, allowing for the recall of the next strongest item (e.g., Page & Norris, 1998). Response suppression refers to the assumption that items are inhibited following recall to allow for competitive cueing between successive items. Although fundamental to several models of serial order, response suppression tends to be more important for approaches relying on activation gradients relative to position marking (see Hurlstone et al., 2014, for a review).

Functionally equivalent serial order phenomena in verbal and non-verbal domains highlight crucial limitations in existing models of serial order in STM. For instance, while associative models can account for primacy and recency effects in verbal and non-verbal domains (Lewandowsky & Murdock, 1989) they fail to reproduce other core serial order phenomena, including patterns of recall errors in sequences with dissimilar items, similar items, and repeated items. Associative models have difficulty characterizing adjacent transposition errors when an item is recalled too early: this should cue the following item and not the skipped item. Thus, they predict more in-fill errors relative to fill-in errors based on the assumption that an item recalled too early will cue the item that it was associatively linked to during encoding relative to any other item in the sequence. However, both verbal and visuo-spatial data indicate a ratio of 2:1 for fill-in errors versus in-fill errors (Farrell et al., 2013; Henson et al., 1996; Page & Norris, 1998; Surprenant, Kelley, Farley, & Neath, 2005). Associative models also cannot account for the locality constraint characterizing migration errors in verbal and visuo-spatial recall tasks with dissimilar items (i.e., items recalled in incorrect positions tend to be recalled in positions close to their correct serial position). Furthermore, they have difficulty accommodating item similarity effects in verbal serial recall tasks. In particular, associative models predict that sequences of alternating similar and dissimilar items will result in impaired recall of dissimilar items because the similar items are ambiguous retrieval cues. However, this prediction is not in line with existing data which indicate that recall of dissimilar items in alternating lists is equivalent to recall of items in corresponding positions in dissimilar (control) sequences (e.g., Farrell, 2006; Farrell & Lewandowsky, 2003; Lewandowsky & Farrell, 2008a).

Relevant to the present study, chaining models are also unable to accommodate the pattern of recall errors in the context of *repetition facilitation* and *repetition inhibition*. In serial order STM, verbal sequences containing adjacent repeated items are recalled better than ones with unique items (*repetition facilitation*; Crowder, 1968) and verbal sequences containing distant repeated items are recalled less well than ones with unique items (*repetition inhibition*; the

Ranschburg effect; Crowder, 1968; Duncan & Lewandowsky, 2003; Henson, 1998; Jahnke, 1969; Kahana & Jacobs, 2000; Vousden & Brown, 1998). Associative models predict impaired memory for items following repeated items because repeated items are ambiguous retrieval cues for subsequent items. This prediction is not consistent with existing data in verbal serial order STM. These show that recall of adjacent repeated items is facilitated and recall of one or both occurrences of a repeated item is impaired in distant repetition sequences (Crowder, 1968; Duncan & Lewandowsky, 2003; Henson, 1998; Jahnke, 1969; Kahana & Jacobs, 2000; Vousden & Brown, 1998). It has also been occasionally reported that recall of the items immediately following the repeated items (subsequent items; Wickelgren, 1966) is impaired. The latter error type has been attributed to increased adjacent item transposition errors (fill-in errors) resulting from impaired memory for the repeated item (Henson, 1998; Crowder, 1968). However, errors on subsequent items (items in positions directly following the repeated items) were analyzed in these experiments without controlling for accuracy on the repeated items. It, therefore, remains unclear whether errors on subsequent items are in fact due to fill-in errors. Better recall of adjacently repeated items has been attributed to such items having increased distinctiveness (Lee, 1976a), benefitting from chunking (Wickelgren, 1965c) and/or tagging strategies (Lee, 1976b).

Contemporary models of serial order are able to explain a host of serial order phenomena in verbal and visuo-spatial STM, most critically the locality constraint affecting migration errors, and greater number of adjacent transposition errors (see Hurlstone et al., 2014, for a review). Adjacent transposition errors are explained as resulting from increased confusion between neighboring position cues (Burgess & Hitch, 1999) or activation strengths (Page & Norris, 1998) relative to distant position cues and activation strengths. In contrast to associative chaining models, contemporary models based on response suppression (e.g., Duncan & Lewandowsky, 2003; Lewandowsky & Farrell, 2008a) can also account for the pattern of recall errors in verbal sequences with distant repeated items and verbal sequences with alternating similar and dissimilar items. Repeated items are thought to have ambiguous position cues. The second occurrence of an item may also be associated with suppression during recall contributing to impaired memory for such items. Similar items have overlapping representations making them more vulnerable to forgetting of discriminating information.

Finally, the recent C-SOB (serial order in a box; Lewandowsky & Farrell, 2008b) model is particularly effective at accounting for patterns of recall errors in sequences with similar items and repeated items. Unlike temporal models of serial order with temporal primacy or recency gradients (e.g., Page & Norris, 1998) C-SOB consists of an associative network in which memory items are connected to an event-driven context signal. That is, progression through the sequence occurs because successive items are added (event-driven) and not due to the passage of time. The defining feature of this model is based on the principle of novelty encoding, that is the encoding strength of each item depends on its novelty or dissimilarity relative to other items within a list (Lewandowsky & Farrell, 2008b). Sequences with dissimilar items will therefore be encoded better than ones with similar items. Likewise, given that the second occurrence of the repeated item presents the most extreme case of similarity, the model predicts impaired memory for this item. Verbal STM tasks exhibiting repetition inhibition effects are in line with this prediction. The modality-generality of C-SOB model's predictions have not yet been confirmed in the visuo-spatial domain, as no studies to date have investigated error patterns in sequences with repeated items (*repetition inhibition* and *repetition facilitation*) and sequences with alternating similar and dissimilar items (Hurlstone et al., 2014).

Given previously reported functional similarities between verbal and visuo-spatial domains of STM with respect to serial order representations, it appears parsimonious to assume a domain-general ordering mechanism. Particularly, a mechanism that relies on some form of position marking, activation gradients, response suppression, and/or novelty encoding can be hypothesized. However, not all relevant effects have been investigated in the visuo-spatial domain (Hurlstone et al., 2014). Therefore, it remains unclear to what extent common or equivalent ordering principles apply to visuo-spatial and verbal STM.

The present project studied the effects of *repetition inhibition* and *repetition facilitation* using a visuo-spatial serial order reconstruction task, the Dots Task (Jones et al., 1995). Given previously reported functional similarities between verbal and visuo-spatial serial memory phenomena, a shared ordering memory mechanism for the two modalities was hypothesized. Based on this hypothesis, we expected to generalize earlier findings in the verbal domain by showing repetition facilitation: improved recall for visuo-spatial sequences containing adjacent repeated items relative to sequences with no repetition. We also expected to see repetition inhibition: impaired recall for visuo-spatial sequences containing distant repeated items relative to sequences with no repetition. Errors were expected to arise from difficulties in remembering the serial positions of the first and/or second occurrence of a repeated item and the items subsequent to the repeated item (due to adjacent transpositions). However, on trials when the repeated items were correctly recalled, we did not expect errors on subsequent items (Crowder, 1968).

Experiment 1

Method

Participants

Thirty undergraduate and graduate students aged 18–29 from McMaster University took part in this study. They were recruited through advertisements placed on bulletin boards around the campus. All participants were native English speakers and had normal or corrected-to-normal vision. All participants gave informed written consent prior to the beginning of the study. Participants were paid $10 per hour for their participation. The protocol was cleared by the McMaster University Research Ethics Board.

Stimuli

The Dots Task was programmed in Super Lab 4.0 and run on an iMac computer with a 21.5 inch screen with a resolution of 1920 x 1080 pixels. In each trial, seven black dots (radius of 12 pixels) were displayed on a blank white matrix (1200 x 900 pixels). The locations of the dots (coordinates) were semi- randomly constructed to meet the requirements for each condition within a 15 x 11 matrix using Adobe Illustrator. There was a restriction that the central points of two successive dots must be separated by at least 150 pixels in Euclidian space (note exception: adjacent repeating items). Given the detrimental effect of three and six path crossings on serial memory performance in the Dots Task (Parmentier et al., 2005), sequences were constructed containing 0 or 1 path crossings, equally distributed in all conditions of the task**.** One path crossing was included in the sequences to assert some task difficulty as a condition with no path crossings in a previous study (Parmentier et al., 2005) led to near ceiling performance in the Dots Task. The sequence path connecting successive spatial locations was drawn to ensure that sequences contained no symmetry or obvious prototypical shapes.

Procedure

Participants were required to perform a visuo-spatial order reconstruction task (the Dots Task). Responses were collected using a computer mouse. In each trial, seven black dots were presented in succession and in quasi-random locations within a blank white matrix (see Figure 1). The presentation rate of the dots was one per two seconds (1 s on, 1 s off). Following presentation of the whole sequence, all the dots were simultaneously re-presented in their original spatial coordinates, and participants were required to recall the correct order of presentation by clicking on the dots with the computer mouse. Feedback regarding accuracy was not provided. A “next trial” icon appeared after the seventh response, prompting participants to click when ready to initiate the next trial. Once clicked, a blank screen appeared for one second, followed by the presentation of the next trial.

Participants were presented with three different types of trials: no repetition, repetition, and adjacent repetition (see Figure 1). Each no-repetition trial consisted of all dots displayed in unique spatial locations. In a repetition trial, the spatial coordinates of one dot were repeated in a sequence, but never for successive dots. In an adjacent repetition trial, the spatial coordinates of one dot were repeated in a sequence, but only for successive dots.

A total of 45 test trials were presented in random order, with 15 in each condition. The test trials were preceded by 6 practice trials (2 per condition) presented in random order. After every 15 trials, a “break” icon appeared prompting participants to take a break if necessary.

In each trial, participants were encouraged to recall the order of the items as accurately and quickly as possible. Participants were explicitly told that on some trials the spatial location of one dot would be repeated within a sequence. Participants were tested individually and data was collected and saved via computer responses. This part of the experiment lasted 20–30 minutes. The dependent measure was accuracy of recall. An accurate response consisted of a dot recalled in the correct serial position.

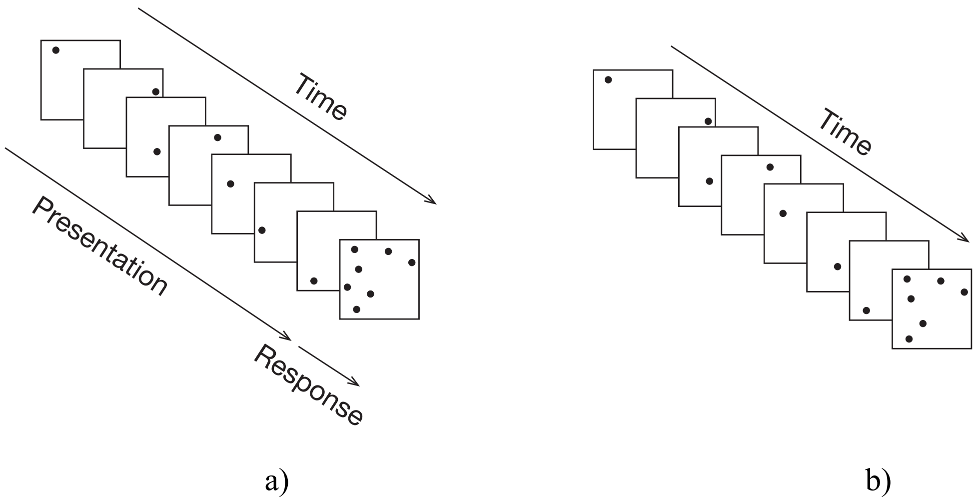

Figure 1. Illustration of the a) no repetition and b) repetition conditions of the Dots Task.

Results

Overall, serial recall performance in the Dots Task was best in the adjacent repetition condition (*M* = 80.29 %, *SD* = 13.98), and poorest in the repetition condition (*M* = 66.79 %, *SD* = 16.98), with the no-repetition condition falling in between (*M* = 71.43 %, *SD* = 17.85). Primacy and recency effects were visible in all conditions (see Figure 2). A 3 (repetition condition) x 7 (serial position) repeated measures analysis of variance (ANOVA) was conducted on the percentage of correct responses. Analyses showed significant main effects of repetition, $F(2, 58) = 34.25$, $MSE = 10229.91$, $p < 0.0001$, $\eta_p^2 = 0.54$, serial position, $F(6, 174) = 30.87$, $MSE = 3547.47$, $p < 0.0001$, $\eta_p^2 = 0.52$, as well as an interaction between the two variables $F(12, 348) = 4.12$, $MSE = 298.23$, $p < 0.0001$, $\eta_p^2 = 0.12$. Planned contrasts revealed that performance was better in the adjacent repetition condition than in both the no-repetition and repetition conditions; $F(1, 29) = 28.40$, $MSE = 1176.74$, $p < 0.0001$, $d = 0.96$ and $F(1, 29) = 65.89$, $MSE = 2730.54$, $p < 0.0001$, $d = 1.60$, respectively. Furthermore, performance in the no-repetition condition was better than in the repetition condition, $F(1, 29) = 7.776$, $MSE = 322.24$, $p = 0.012$, $d = 0.48$. The Bonferroni-corrected alpha-level for the pairwise contrasts was 0.0167.

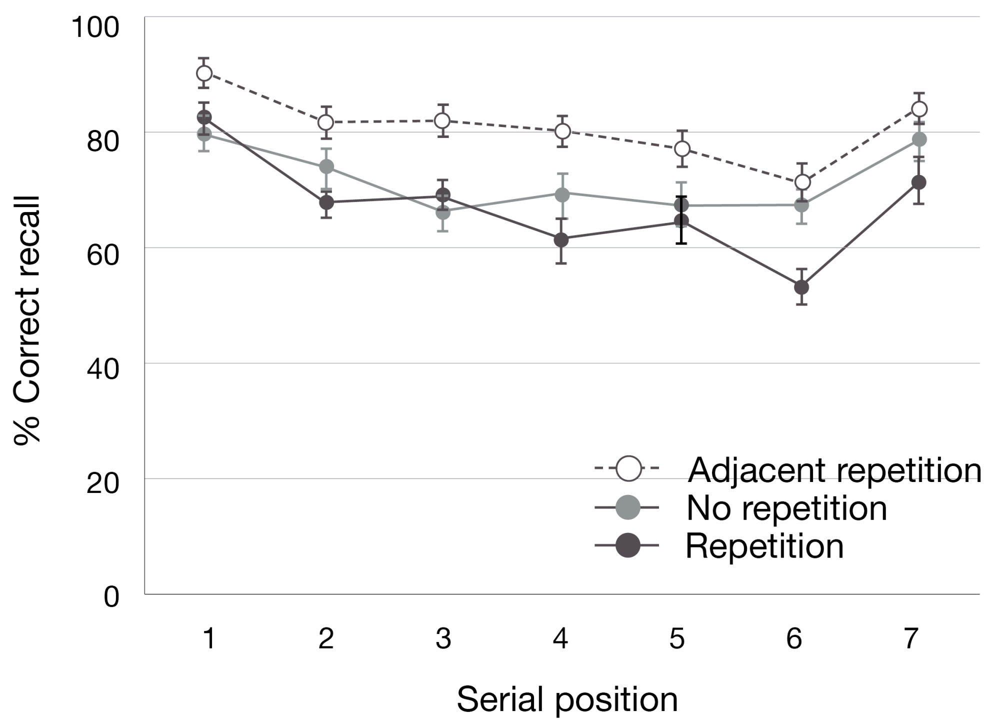

Figure 2. Serial recall accuracy as a function of serial position and repetition condition (error bars represent standard errors).

In a second set of analyses, serial recall accuracy of distantly repeated items (first and second occurrence; R1 and R2) and items following repeated items (subsequent items; S1 and S2) when preceding items had been correctly recalled versus items in corresponding positions in sequences with no repetition was analyzed. First, a 2 (repetition condition: repetition vs. no repetition) x 2 (order of occurrence: first vs. second) repeated measures ANOVA was conducted on the percentage of correct responses for the repeated items and their counterparts. The main effect of repetition condition was significant, $F(1, 29) = 5.59$, $MSE = 2591.18$, $p < 0.05$, $\eta_p^2 = 0.16$, whereas the order of occurrence and interaction between both variables were not, $F(1, 29) = 3.32$, $MSE = 2155.37$, $p = 0.08$ and $F < 1$, respectively. Paired t-tests revealed significantly poorer recall of the second occurrence of the repeated item compared to its counterpart [t (29) = -2.43, p = 0.021, d = 0.444], but the difference between the first occurrence of the repeated item and its counterpart was not significant [t (29) = -1.52, p = 0.14]. The Bonferroni-corrected alpha-level for the pairwise contrasts was 0.025 (see Figure 3).

A 2 (repetition condition: repetition vs. no repetition) x 2 (order of occurrence: first vs. second) repeated measures ANOVA was also conducted on the percentage of correct responses for the subsequent items and their counterparts. Analyses did not show significant main effects of repetition condition, $F < 1$, or order of occurrence, $F < 1$ but the interaction between repetition condition and order of occurrence was significant, $F(1, 29) = 43.28$, $MSE = 10167.44$, $p < 0.0001$, $\eta_p^2 = 0.60$. Paired t-tests revealed significantly better recall of the item subsequent to the first occurrence of the repeated item compared to its counterpart [t (29) = 5.83, $p < 0.0001$, $d = 1.06$], and poorer recall of the item subsequent to the second occurrence of the repeated item compared to its counterpart [t (29) = 3.36, $p < 0.01$, $d = 0.61$;. The Bonferroni-corrected alpha-level for the pairwise contrasts was 0.025 (see Figure 3).

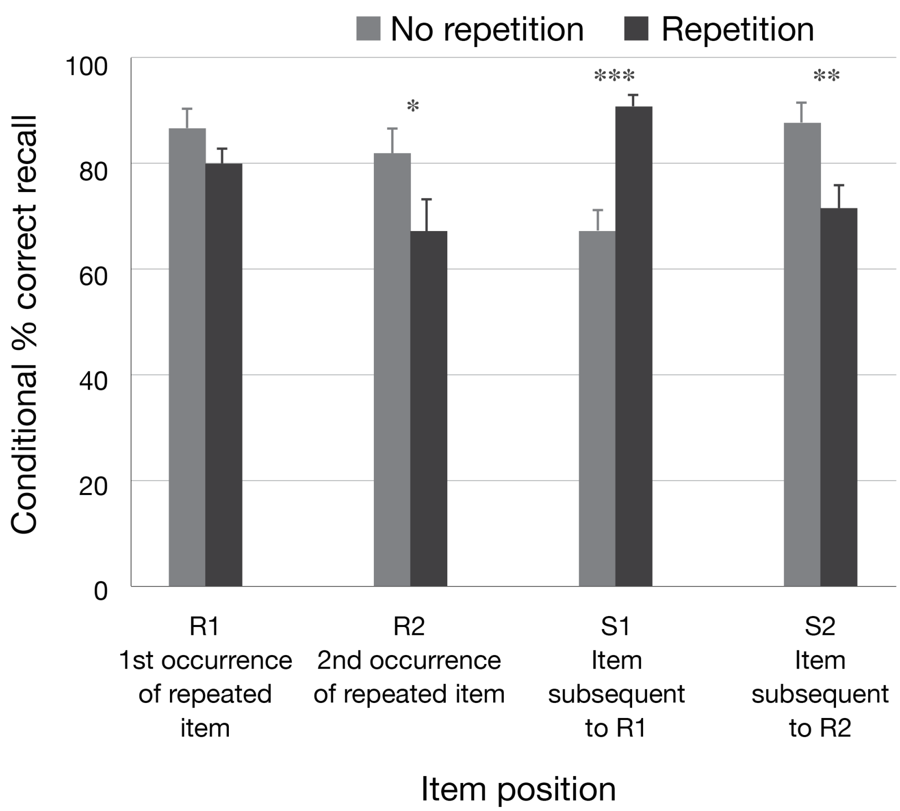

Figure 3. Serial recall accuracy of distantly repeated items and items subsequent to repeated items when preceding items had been correctly recalled vs. items in corresponding positions in sequences with no repetition (error bars represent standard errors).

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.0001$

A more traditional analysis, examining serial recall accuracy of repeated items (first and second occurrence; R1 and R2) and items following repeated items (subsequent items; S1 and S2) versus items in corresponding positions in sequences with no repetition was also conducted without controlling for accuracy on preceding items. All of the same effects reported above still remained. However, in addition, paired t-tests revealed significantly poorer recall of the first occurrence of a repeated item compared to a non-repeated counterpart [t (29) = 2.81, $p < 0.01$, $d = 0.51$].

In a third set of analyses, the proportion of different error types were analyzed for the S2 serial positions (positions of items subsequent to the second occurrence of repeated items) versus corresponding positions in sequences with no repetition. Specifically, a paired t-test was conducted to compare the proportion of times S1 was selected in the serial position of S2 among errors versus items in corresponding positions in the no repetition condition. Analyses revealed that the S1 error type occurred significantly more in the repetition condition versus the no repetition condition, [t (29) = 3.92, $p < 0.001$, $d = 0.73$]. Paired t-tests were also conducted to compare the proportion of times adjacent items to S2 (previous and subsequent) were selected in the serial position of S2 among errors versus items in corresponding positions in the no repetition condition. However, no significant differences were found [t (29) = 1.21, $p = 0.24$; t (29) = 1.26, $p = 0.22$; see Figure 4].

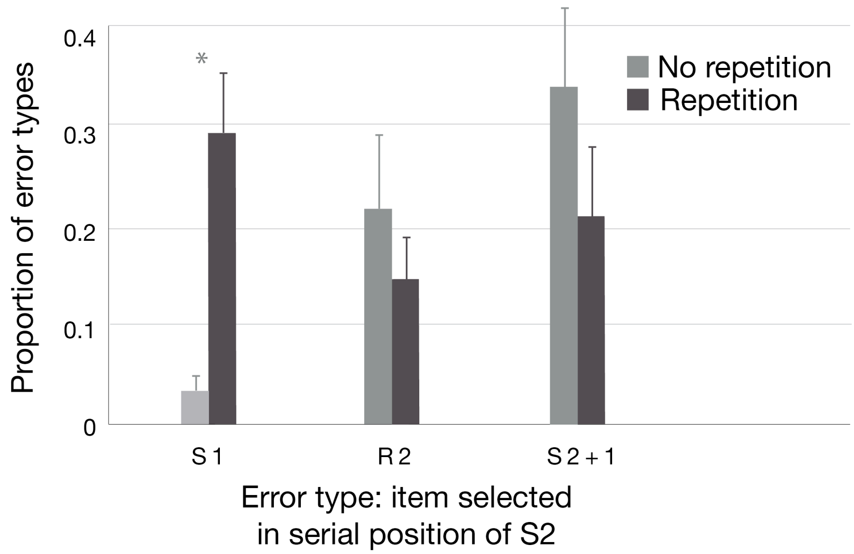

Figure 4. Proportion of different error types for S2 (item subsequent to second occurrence of repeated item) serial positions vs. corresponding positions in sequences with no repetition (error bars represent standard errors). S1, item subsequent to first occurrence of repeated item; R2, second occurrence of repeated item; S2 + 1, item subsequent to S2.
* $p < 0.001$

Discussion

The present study set out to explore whether order memory in the visuo-spatial domain is qualitatively similar to order memory for verbal memoranda. Spatial order reconstruction was studied in the Dots Task. Visuo-spatial equivalents of two well-known effects in verbal serial order STM were found: *repetition facilitation* (Crowder, 1968) and *repetition inhibition* (the Ranschburg effect; e.g., Crowder, 1968; Duncan & Lewandowsky, 2003). Repetition facilitated memory for a sequence of visuo-spatial locations when the repeated items appeared close together in a sequence (adjacent repeated items) and impaired memory when the repeated items were separated by a number of intervening items, just as in the verbal domain. We were thus, able to demonstrate another functional similarity between serial memory for verbal and visuo-spatial sequences.

However, our results also highlight a critical difference between verbal and visuo-spatial serial order representations for sequences with repetition. As predicted if memory for order in STM is modality-general, serial recall of both the first and second occurrences of the repeated item was impaired. Furthermore, recall of the item following the second occurrence of a repeated item was impaired relative to items in corresponding positions in sequences with no repetition. This recall impairment for the item following the second occurrence of a repeated item still remained when the repeated items themselves were correctly recalled in their second position of occurrence. This rules out fill-in explanations describing situations where the repeated item might have first been replaced by the subsequent item but then filled in into the subsequent item's slot; or in-fill explanations where the repeated item would have been omitted altogether and the sequence continued without it. Finally, recall of the item following the first occurrence of a repeated item was robustly facilitated compared to items in equivalent positions in sequences with no repetition. This novel pattern of results has not been reported in the verbal domain (Wickelgren, 1966) and thus appears to reveal a key difference between visuo-spatial and verbal serial order representations when sequences contain repeated items.

Visuo-spatial equivalents of repetition facilitation and repetition inhibition effects

Replicating classic verbal repetition facilitation and inhibition effects in the visuo-spatial domain suggests that serial order in the two domains is processed in functionally equivalent ways (Hurlstone et al., 2014). As with verbal stimuli, repetition facilitation when recalling visuo-spatial sequences can be attributed to adjacent repeated items having increased distinctiveness (Lee, 1976a), benefitting from chunking (Wickelgren, 1965c) and/or tagging strategies (Lee, 1976b). In verbal STM, repetition inhibition, including impaired memory for repeated occurrences of an item has been attributed to two factors at recall: response suppression and/or a guessing bias. In serial recall, response suppression refers to automatic inhibition of responses for previously recalled items (such as repeated items; Burgess & Hitch, 1992; Henson, 1998; Page & Norris, 1998) while a guessing bias constitutes a natural reluctance to repeat items when guessing (Henson, 1998; Hinrichs, Mewaldt, & Redding, 1973). The finding of repetition inhibition in the current study suggests that similar factors are also at play in the visuo-spatial domain. Non-associative models of serial order are best able to characterize such factors in sequences with repetition. For instance, repeated items are argued to have competing position cues and/or activation strengths (e.g., Duncan & Lewandowsky, 2003) leading to suppression of such items and/or a bias against recalling them when guessing after they have been recalled once. Consequently, memory for the repeated instances of an item suffers. As in the verbal domain, the C-SOB model's (Lewandowsky & Farrell, 2008b) principle of novelty-sensitive encoding can also account for the impaired memory of the second occurrences of repeated locations reported in the current study. According to this principle, in the Dots Task, the second occurrences of repeated locations (items) will be encoded with less strength due to completely shared item-location representations with the first occurrences of the repeated locations (principle of novelty-sensitive encoding; Lewandowsky & Farrell, 2008b) leading to a greater number of order errors for these locations.

Crucial differences between verbal and visuo-spatial recall errors in trials with repetition

Although the current study reproduced the classic verbal repetition effects with visuo-spatial memoranda, the pattern of recall errors for the items subsequent to repeated items presents some level of challenge to the notion that serial order representations are completely functionally equivalent in these domains. Studies of repetition inhibition with verbal sequences indicate impaired memory for items immediately following the repeated items (e.g., Wickelgren, 1966). This has been attributed to increased adjacent transposition errors with the repeated items (fill-in errors). However, to test the validity of this claim, errors on subsequent items have not been analyzed while controlling for performance on the repeated items. This makes direct comparison with the current results difficult. Nevertheless, the present study reports impaired memory for the items following the second occurrence of the repeated items (S2), even on trials when the repeated items were correctly recalled (ruling out fill-in explanations). Furthermore, in contrast to the verbal domain, we found facilitated memory for the items following the first occurrence of the repeated items (S1), suggesting that modality-specific processes may be at play. Indeed, recent studies indicate that the spatiotemporal path formed by the locations of a visuo-spatial sequence affects serial recall. In particular, when a sequence of locations is organized into spatial clusters, serial recall is better when the sequence path progresses through each cluster of locations relative to alternating between different clusters (*spatial clustering effect*; De Lillo, 2004; De Lillo & Lesk, 2010). Likewise, recall accuracy is higher when the distance between locations in a visuo-spatial sequence is shorter compared to when the distance is longer (*path length effect*; Guérard, Tremblay, & Saint-Aubin, 2009; Parmentier et al., 2006). Finally, the *path crossing effect* refers to the finding that sequences of locations containing crossings in the path formed by successive locations are recalled poorly relative to ones without path crossings (Parmentier & Andrés, 2006).

Proposed interaction between visuo-spatial attention and serial order processes during repetition

In addition to spatiotemporal paths, visuo-spatial attention in general has been repeatedly investigated in working memory. Given the close link between visuo-spatial attention and working memory (see Theeuwes, Belopolsky, & Olivers, 2009, for a review), we propose that visuo-spatial attention interacts with a modality-general ordering mechanism to produce the heterogenous pattern of recall errors found here for the subsequent items (S1 and S2). We propose that when the second occurrence of the repeated item appears, participants are reminded of and anticipate the next item to be the one that followed the first occurrence of the repeated item. Consequently, the second occurrence of the repeated item may cue an overt and/or covert visuo-spatial attentional shift, to the area of the screen and/or memory space, respectively, previously occupied by the S1 item. This leads to two parallel effects. Firstly, participants will be subjected to extra encoding/rehearsal of S1 leading to improved memory for S1. Also, if attention during encoding has shifted to S1 immediately preceding and/or during the presentation of S2 then the result may be poor encoding of S2 leading to impaired memory for S2 (see Figure 5).

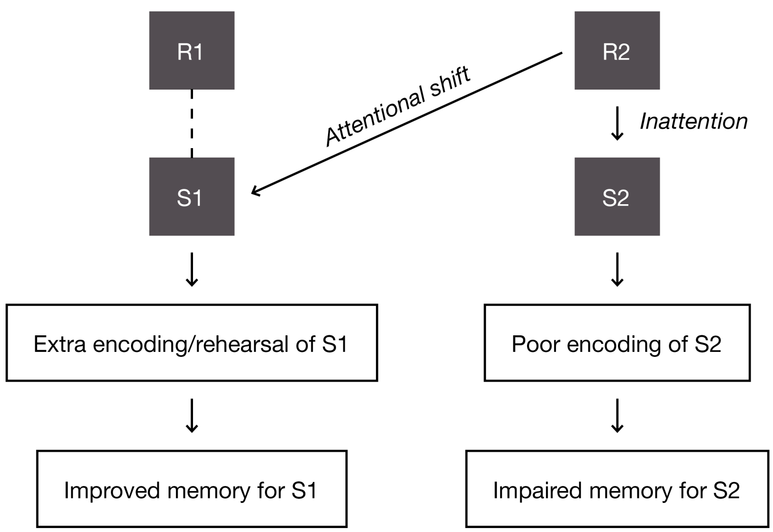

Figure 5. Proposed framework for understanding how visuo-spatial attention interacts with the ordering mechanism to produce the heterogenous pattern of recall errors for the items subsequent to repeated items (R1, first occurrence of repeated item; R2, second occurrence of repeated item; S1, item subsequent to R1; S2, item subsequent to R2). During order encoding, an initial spatial association between R1 and S1 is formed. The appearance of R2 induces a visuo-spatial attentional shift to S1 leading to two parallel effects: a) extra encoding/ rehearsal of S1, improved memory for S1 and b) poor encoding of S2, impaired memory for S2.

Such a hypothesis invokes three assumptions regarding visuo-spatial STM. First, previously encoded items in a sequence can serve as cues for subsequent items. This is in line with results from an eye-tracking study of the visuo-spatial Hebb learning paradigm in which a particular sequence was repeated every few trials. Following the presentation of a given dot location, participants fixated the next to-be-remembered location before its actual presentation, based on a previous encoding of that sequence (Tremblay & Saint-Aubin, 2009). In the present study the second occurrence of the repeated dot location may serve as a cue for the S1 location (not displayed) based on its initial encoding.

Secondly, overt or covert shifts of spatial attention to specific locations can allow for maintenance of these locations in memory. Indeed, using the Dots Task, it has been shown that participants exhibit shifts of spatial attention (manifested as eye movements) to memorized locations on a blank screen during rehearsal and that this supports serial memory performance (Tremblay, Saint-Aubin & Jalbert, 2006). Furthermore, a long line of research indicates that memory for attended locations is better than for unattended locations (e.g., Jonides, 1981; Yantis & Jonides, 1990). This accounts for extra encoding and/or rehearsal of S1 leading to facilitated serial memory performance for it, as was found in the current study.

Finally, we assume that when attention to locations being memorized is interrupted, memory for such locations suffers. In fact, Awh et al. (1998) revealed that spatial working memory accuracy declined when participants' ability to direct spatial attention to locations was impaired. This supports our account for the impaired recall of S2. There is also evidence that memory for locations is affected by distractor locations that capture attention during the retention interval. Specifically, distractor locations caused a shift in the memory representation in the direction of the distractors (Van der Stigchel, Merten, Meeter, & Theeuwes, 2007). Based on this study, if S1 serves as a distractor location immediately preceding and/or during the presentation of S2, then participants will be more likely to recall S1 in the serial position of S2 in repetition relative to no repetition sequences. A post-hoc analysis of the types of recall errors, specifically the proportion of times participants selected the S1 item in the serial position of S2 in repetition sequences versus items in corresponding positions in no repetition sequences, supported our prediction. Furthermore, participants were not significantly more likely to make adjacent transposition errors, the most common error type in sequences with no repetition, for the S2 serial position in repetition versus no repetition sequences. We take these findings as support for our third assumption and argue that the reported novel pattern of recall errors stems from interactions between visuo-spatial attention and serial order STM.

The case for separate vs. common ordering principles in visuo-spatial and verbal STM

Given that the pattern of recall errors on subsequent items in repetition sequences of visuo-spatial memoranda differs from that reported for verbal lists, it may be argued that serial order representations in these domains are functionally different. However, it must be noted that the present study reproduced the classic facilitatory adjacency effect (Crowder, 1968) and the inhibitory Ranschburg effect (Crowder, 1968). Moreover, as with verbal stimuli, the current study found impaired memory for repeated occurrences of an item, a finding that can be explained by common principles for serial order representations in the verbal and visuo-spatial domains [e.g., response suppression (Burgess & Hitch, 1992), novelty-sensitive encoding (Farrell, 2006)]. This is in line with reports of similar dynamics of the transposition error latencies in verbal and visuo-spatial serial recall which matched the predictions of a serial ordering mechanism based on common principles of serial order (Hurlstone & Hitch, 2014). We also presented preliminary evidence that the novel pattern of recall errors on subsequent items is due to spatial attentional processes. Taken together with previous reports of functional similarities between verbal and visuo-spatial serial order STM (see Hurlstone et al., 2014, for a review), we propose that visuo-spatial and verbal STM share a common ordering mechanism that is susceptible to influence from modality-specific characteristics (e.g., visuo-spatial attention, spatiotemporal path). This is in line with recent work suggesting that serial order mechanisms interact with networks that underlie item-level representations (Acheson, MacDonald, & Postle, 2011). For instance, immediate serial order recall of word lists is affected by the level of activation of items within the relevant lexico-semantic network (Poirier, Saint-Aubin, Mair, Tehan, & Tolan, 2015).

Another possibility is that serial order representations in verbal and visuo-spatial working memory may be intrinsically spatially coded. Indeed, the idea that numbers are linearly represented in the mind was proposed decades ago (Moyer & Landauer, 1967; Restle, 1970) but even recent studies suggest that the serial order of verbal items may be represented in an internal spatial frame (van Dijck & Fias, 2011) and may interact with visuo-spatial attention (van Dijck, Abrahamse, Majerus, & Fias, 2013). Therefore, if order is represented spatially, then repeated locations within a visuo-spatial sequence may interfere with spatially defined order representations (i.e., through visuo-spatial attentional mechanisms). In contrast, when verbal items (non-spatial) are repeated within a sequence, this may not necessarily disrupt the spatial representation of order. However, the notion that order representations are intrinsically spatial across verbal and visuo-spatial domains, remains to be explored in future models conceptualizing mechanisms of serial order.

To summarize, the present study found two previously unreported visuo-spatial equivalents of well-known effects in verbal STM for serial order, *repetition inhibition* and r*epetition facilitation*. However, these findings were accompanied by crucial differences in the pattern of recall errors from that of verbal STM. These affected items subsequent to the repeated items in sequences with distantly repeated items. Specifically, memory for items following the first occurrence of the repeated item was facilitated. We provide preliminary evidence that these notable differences are due to modality-specific processes in the visuo-spatial domain (i.e., visuo-spatial attention). Future research should employ eye-tracking methodologies to directly investigate the role of visuo-spatial attention on memory for serial order in sequences with repeated locations. Furthermore, the present study reports that memory for items following the second occurrence of the repeated item was impaired. Conditional analyses, controlling for accuracy of repeated items, revealed that this effect could not be attributed to in-fill or fill-in errors as previously suggested in the verbal domain. Conditional analyses must also be performed with repeated items in verbal sequences in order to test the validity of this claim and directly compare the results to the present findings in the visuo-spatial domain. In the future, we need to move beyond finding functional similarities and directly address whether the two domains share a common ordering mechanism. One possibility is to use carefully controlled dual-task designs contrasting two types of visuo-spatial interference tasks during a concurrent verbal serial order STM task: a serial order STM and a non-serial order STM (control) task. Selective, serial-order specific interference effects may reveal competing demands on a common ordering mechanism. Finally, the present study opens new avenues for investigating the nature of serial order representations by revealing a possible role for spatially-defined order coding in verbal and visuo-spatial STM. While the precise nature of the mechanism underlying serial order representations is still unclear, we propose that visuo-spatial and verbal domains are subserved by a common ordering mechanism that interacts with domain-specific processes. Such processes need to be incorporated when modeling order mechanisms in STM in order to achieve better understanding of the details of order representation.

Chapter 3

Do Verbal and Visuo-spatial STM Share a General Ordering Mechanism?

Introduction

There is an extensive body of literature stemming from behavioural, neuropsychological, and neuroimaging studies that highlight double dissociations between visuo-spatial and verbal STM representations (see Baddeley, 2007, for a review). However, this is accompanied by findings of functional equivalence between visuo-spatial and verbal domains of STM with respect to serial order processing (see Hurlstone et al., 2014, for a review). For example, in Experiment 1 we replicated classic verbal *repetition facilitation* and *repetition inhibition* effects with visuo-spatial sequences. This suggests that common ordering mechanisms may underlie both subsystems.

Given previous distinctions between item and order STM processes, Majerus et al. (2010) investigated the commonality of neural networks underlying verbal and visuo-spatial STM with respect to item vs. order processing using fMRI. They contrasted two types of STM recognition tasks, one which presented sequences of nonwords (verbal) and the other which presented sequences of unfamiliar faces (visual) for later recognition. Following a short delay, memory for either order or item information was probed. Results indicated domain-specific effects for verbal and visual STM in sensory networks specialized in processing modality-specific item information (i.e., language and face processing areas, respectively), strongest for item STM conditions relative to order STM conditions. However, results also revealed that identical neural networks (parieto-fronto-cerebellar) are activated during serial order processing in the verbal and visual STM conditions, supporting recent behavioural data showing identical serial position curves for the recall of face and word sequences (Smyth et al., 2005). In light of these results, it was argued that commonality of neural networks for verbal and visual STM therefore depends on the type of information, item vs. order, to be remembered, with modality-specific networks for item information and common neural networks for order information (Majerus et al., 2010).

This notion led to two hypotheses regarding the mechanisms of serial order within the working memory framework. According to the first, common, shared, mechanisms underlie serial order representations across different STM subsystems. Alternatively, the ordering mechanisms operate in functionally similar ways across different STM domains, but are divorced from one another. A classic approach to investigate the processing capacity of STM is to use concurrent tasks that introduce memory loads and to study the resulting interference effects. Specifically, such tasks require participants to maintain a memory load while a secondary task presents another memory load (Baddeley, 1986). Interference effects emerge when concurrent memory tasks compete for the same underlying processes and mechanisms (Allport et al., 1972 ; Brooks, 1967). However, when both tasks are presented simultaneously, performance on these tasks is confounded by general attentional demands (difficulty dividing attention between both tasks;

Meyer & Kieras, 1997; Navon & Miller, 2002). An alternative is that both tasks are presented in succession, followed by delayed recall of the initial memory load (Baddeley, 1986). Delayed recall of the initial memory load requires concurrent maintenance of this load during the secondary memory task to support successful recall (e.g., Lewandowsky, Geiger, & Oberauer, 2008), while minimizing the confounding effects of attentional demands.

One possible approach to investigate serial-order specific interference between verbal and visuo-spatial STM is to use a dual-task design that contrasts two types of visuo-spatial STM interference tasks during a concurrent verbal serial order STM task (e.g., digit sequence memory). One visuo-spatial task would maximize memory for order information and minimize memory for item information. Another visuo-spatial task would maximize memory for item (e.g., location) information (control) and minimize memory for order information. For instance, the Dots Task is particularly useful for assessing memory for serial order information because all the dot locations are provided as cues at the time of serial recall, therefore reducing the demand for item memory while maximizing the demand for order memory. However, there is a need to develop a visuo-spatial item STM task that is of comparable difficulty as a counter-part to the visuo-spatial serial order reconstruction task (the Dots Task). This is because visuo-spatial item STM is classically measured by presenting visual arrays such as spatial locations for immediate recall. As such, only memory for location (item) information is required. The Dots Task inherently requires the binding of dot locations with order information. In order to match two visuo-spatial tasks for equal STM demands, the tasks could require memory for location as well as binding of location information with a secondary property, such as order (in the serial order STM task) or symbol identity (in an item STM task).

Experiment 2a reports the findings of a study in which we aimed to devise two novel types of visuo-spatial interference tasks: one requiring serial order STM the other non-serial order STM. The tasks were titrated for difficulty level and STM demands. The visuo-spatial serial order STM task was an adaptation of the Dots Task (Jones et al., 1995) and consisted of serial presentation of an abstract symbol (Tamil syllabic characters) in different locations of the screen. Participants were required to remember the order of the locations that the abstract symbol had been presented in. The non-serial order (control) counterpart of the visuo-spatial interference task consisted of simultaneous presentation of different abstract symbols in different locations of the screen. Here, participants were required to remember the symbols in their correct locations. The classic Dots Task (Jones et al., 1995) was not used as it would not allow control of equal demands in both visuo-spatial interference tasks. For instance, if dots were used instead of abstract symbols, the serial order task would require binding of locations with order information whereas the non-serial order task would just require memory for the locations. By using abstract symbols ensured that both visuo-spatial tasks required memory for location as well as binding of location information with a secondary property, order (in the serial order task) and symbol identity (in the non-serial order task).

In Experiment 2b, we studied whether verbal and visuo-spatial STM rely on modality-general order mechanisms. We used a delayed recall dual-task design that contrasted the effect of the two novel types of visuo-spatial interference tasks from Experiment 2a on a concurrent primary verbal serial order STM task (digit sequence memory). One interference task relied on serial order STM, the other was a non-serial order STM task (control). Given previously reported functional similarities between verbal and visuo-spatial serial memory phenomena, we hypothesized a shared ordering memory mechanism for the two modalities. Based on this, we predicted greater interference effects during concurrent verbal and visuo-spatial serial order STM tasks relative to the non-serial order control condition. We also critically manipulated the degree to which the verbal serial order task relied on STM vs. LTM by presenting each digit sequence three times throughout the duration of the experiment. Based on Hebb's (1961) repetition learning effect, by the second and third presentation, the verbal serial order task should theoretically rely less on short-term serial order processes and at least in part on LTM representations of the sequence. This should reduce competition for short-term serial order processes between the verbal and visuo-spatial domains. Consequently, we predicted that during repeated presentations of the verbal serial order task, there would be less interference between concurrent verbal and visuo-spatial serial order STM tasks.

Experiment 2a: Checking the difficulty of two visuo-spatial STM tasks

Experiment 2a investigated the difficulty level of two novel visuo-spatial STM tasks: one that measured serial order STM and another that measured non-serial order (item) STM task performance. If the difficulty level of the two types of visuo-spatial tasks was not found to be significantly different, the objective was to use these as non-verbal interference tasks in a delayed recall dual-task paradigm in Experiment 2b to study their effects on a concurrent primary verbal serial order STM task (digit sequence memory).

Method

Participants

Thirty undergraduate students aged 18–25 from McMaster University took part in this study. They were recruited through the Linguistics Participant Pool at McMaster University. All participants were native English speakers with no prior familiarity with written, Tamil, syllabic characters and had normal or corrected-to-normal vision and normal hearing. All participants gave informed written consent prior to the beginning of the study and received course credit for their participation. The protocol was cleared by the McMaster University Research Ethics Board.

Stimuli

The experiment was programmed in Super Lab 4.0 and run on an iMac computer with a 21.5 inch screen with a resolution of 1920 x 1080 pixels. The visuo-spatial interference tasks were adapted from the Dots Task (Jones et al., 1995). Stimuli consisted of black abstract symbols (Tamil syllabic characters; radius of 12 pixels), either presented as a sequence (serial order task) or static display (non-serial order task), on a blank white matrix (1200 x 900 pixels). The locations of the symbols (coordinates) were randomly constructed within a 15 x 11 matrix using Adobe Illustrator. There was a restriction that the central points of two symbols must be separated by at least 150 pixels in Euclidian space. Given that 3 path crossings between successive locations leads to impaired serial memory performance in the Dots Task (Parmentier et al., 2005), sequences were constructed containing 1 or 2 path crossings only. Path crossings were included in the sequences to assert some task difficulty as a condition with no path crossings previously led to near ceiling performance in the Dots task (Parmentier et al., 2005). The sequence path connecting successive spatial locations was drawn to ensure that sequences contained no symmetry or obvious prototypical shapes. The static displays also contained no symmetry or obvious prototypical shapes.

Procedure

Participants completed two types of visuo-spatial STM tasks, serial order and non-serial order (control). The order of the conditions was counterbalanced across participants. In the serial order condition, each trial began with the presentation of a fixation cross (radius of 12 pixels) located in the centre of a blank computer screen for 1000 ms. The fixation cross was followed by a sequence of five, identical, black, abstract symbols (Tamil syllabic characters) presented one at a time (1000 ms on, 1000 ms off) in different spatial locations of the screen for later serial recognition. Following presentation of the last symbol, the fixation cross appeared for 1000 ms and then a blank screen appeared for 7000 ms (retention interval). The fixation cross appeared once again for 1000 ms, after which participants completed the serial recognition component of the serial order STM task in which all the abstract symbols were re-presented in their original spatial locations and remained on the screen while a red square moved from symbol to symbol (1000 ms on, 700 ms off) to indicate a particular sequence. Following this presentation, participants were prompted to identify whether the indicated sequence matched the previously presented order by pressing a computer key. Half of the trials were match trials, and half were mismatch trials. In the non-serial order condition, each trial began with the presentation of the fixation cross for 1000-ms in the centre of a blank computer screen. A static display of four, different, black, abstract symbols (Tamil syllabic characters) located in different spatial locations, was presented on the screen (for 10000 ms) for later visuo-spatial recognition. The fixation cross appeared for 1000 ms and then a blank screen appeared for 7000 ms. The fixation cross appeared again for 1000 ms. Next, participants completed the visuo-spatial recognition component of the visuo-spatial STM task in which an array of abstract symbols located in the previously seen spatial locations was presented for 8500 ms. Participants were asked to identify whether the presented array matched the previously presented array (correct symbol + location) by pressing a computer key. The recognition component always consisted of the same symbols and locations that were previously presented in the trial. Non-match trials consisted of an incorrect pairing of symbols and locations. Half of the trials were match trials, and half were mismatch trials.

Each condition contained 10 test trials presented in random order. The test trials were preceded by 5 practice trials presented in random order. After every 5 trials, a “break” icon appeared prompting participants to take a break if necessary. Participants were also instructed to take a 5 minute break before proceeding to the second condition.

Participants were encouraged to perform both tasks as accurately as possible. They were instructed to use visuo-spatial strategies and avoid using any verbal and/or gestural strategies. Participants were tested individually and data was collected and saved via computer responses. The dependent measure for the visuo-spatial interference tasks was accuracy of recognition (sensitivity - d prime). The experiment lasted 45 minutes.

Results

The objective of the experiment was to ensure that the difficulty level of the two types of visuo-spatial tasks (serial order STM and non-serial order STM) was not significantly different. The results can be seen in Figure 6. A planned paired t-test was conducted on the sensitivity scores between the two tasks. In line with predictions, analyses revealed no significant differences between sensitivity scores in the serial order versus the non-serial order condition [t (25) = .588, p = .562; see Figure 6]. Thus, if a difference existed, it was not significant in a sample of 30 participants. Moreover, absolute recognition performance was slightly better in the order memory condition.

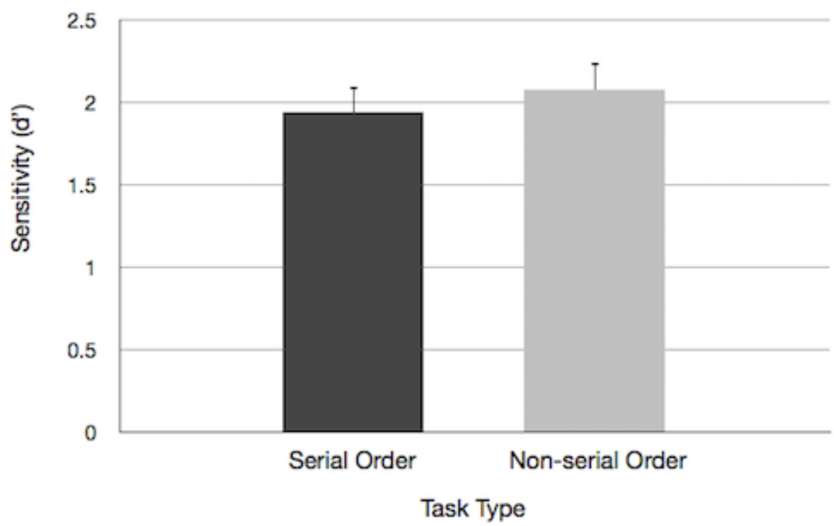

Figure 6. Visuo-spatial task accuracy as a function of task type (serial order vs. non-serial order; error bars represent standard errors).

<u>Experiment 2b: Selective interference between order STM tasks</u>

Experiment 2b investigated whether common ordering mechanisms underlie verbal and visuo-spatial STM. A delayed recall dual-task paradigm was used to contrast the effects of two types of visuo-spatial STM interference tasks (serial order vs. non-serial order) devised in Experiment 2a, on a concurrent primary verbal serial order STM task (digit sequence memory).

Method

Participants

Thirty undergraduate students aged 18–25 from McMaster University took part in this study. They were recruited through the Linguistics Participant Pool at McMaster University. All participants were native English speakers with no prior familiarity with written Tamil syllabic characters and had normal or corrected-to-normal vision. All participants gave informed written consent prior to the beginning of the study and received course credit for their participation. The protocol was cleared by the McMaster University Research Ethics Board.

Stimuli

The visuo-spatial stimuli from Experiment 2a were also used in Experiment 2b. In addition, in the digit sequence memory task, stimuli consisted of sequences of seven digits (one per second), pre-recorded by the experimenter using Audacity 2.0.6 sound editor/recorder, and presented through JVC headphones. Responses were recorded using Audacity 2.0.6 sound editor/recorder.

Procedure

Participants completed a delayed recall dual-task paradigm that contrasted two types of visuo-spatial (secondary) interference tasks during a concurrent primary verbal digit sequence memory task, serial order STM and non-serial order STM (control; see Figure 7). Each trial sandwiched presentation of a digit sequence for later recall between the encoding and retrieval phases of one of the visuo-spatial STM tasks. The order of the serial order and non-serial order conditions was counterbalanced across participants. The digit sequence stimuli were also counterbalanced across participants.

Serial Order STM + Digit Sequence Memory Task

Each trial began with the presentation of a fixation cross (radius of 12 pixels) located in the centre of a blank computer screen for 1000 ms. The fixation cross was followed by a sequence of five, identical, black, abstract symbols (Tamil syllabic characters) presented one at a time (1000 ms on, 1000 ms off) in different spatial locations of the screen for later serial recognition (visuo-spatial serial order STM task). Following presentation of the last symbol, the fixation cross appeared for 1000 ms and then participants heard through headphones a sequence of seven digits which they were asked to remember in the correct order of presentation for a later recall test (digit sequence memory task). The fixation cross appeared once again for 1000 ms, after which participants completed the serial recognition component of the Serial order STM task in which all the abstract symbols were re-presented in their original spatial locations and remained on the screen while a red square moved from symbol to symbol (1000 ms on, 700 ms off) to indicate a particular sequence. Following this presentation, participants were prompted to identify by pressing a computer key whether the indicated sequence matched the previously presented order. Half of the trials were match trials, and half were mismatch trials. Finally, the response screen for the digit sequence memory task appeared, prompting the participants to orally recall the previously presented digits in the correct order. Participants said "blank" for any digits they could not recall. After the oral response, they were were instructed to click a "next trial" icon to initiate the next trial when they were ready. Once clicked, a blank screen appeared for 1000 ms, followed by the presentation of the next trial.

Non-serial Order STM + Digit Sequence Memory Task

The procedure was repeated for the second dual-task condition with slight exceptions to the visuo-spatial component. Each trial began with the presentation of a fixation cross for 1000 ms in the centre of a blank computer screen. A static display of four, different, black, abstract symbols (Tamil syllabic characters) located in different spatial locations, was presented on the screen (10000 ms) for later visuo-spatial recognition (visuo-spatial non-serial order STM task). The fixation cross appeared for 1000 ms and then participants heard through headphones a sequence of seven digits which they were required to remember in the correct order of presentation for a later recall test (digit sequence memory task). The fixation cross appeared again for 1000 ms. Next participants completed the visuo-spatial recognition component of the visuo-spatial STM task in which an array of abstract symbols located in the previously seen spatial locations was presented for 8500 ms. Participants were asked to identify whether the presented array matched the previously presented array (correct symbol + location) by pressing a computer key. The recognition component always consisted of the same symbols and locations that were previously presented in the trial. Non-match trials consisted of an incorrect pairing of symbols and locations. Half of the trials were match trials, and half were mismatch trials. Finally, a response screen prompted participants to complete the recall component of the digit sequence memory task by orally recalling the previously presented digits in the correct order. Participants said “blank” for any digits they could not recall. After the oral response, they were required to click a “next trial” icon to begin the next trial. A blank screen appeared for 1000 ms preceding the presentation of the next trial.

The parameters of both conditions were identical with the exceptions of the visuo-spatial interference tasks. Each condition contained 30 test trials presented in random order. The test trials were preceded by 5 practice trials presented in random order. After every 10 trials, a “break” icon appeared prompting participants to take a break if necessary. Participants were also instructed to take a 5-minute break before proceeding to the second condition.

Participants were encouraged to perform both dual tasks in each condition as accurately as possible. They were instructed to use visuo-spatial strategies in the visuo-spatial interference tasks without using any verbal and/or gestural strategies. Participants were tested individually and data was collected and saved via computer responses and audio-recordings. In the digit sequence memory tasks of both conditions, each digit sequence was presented three times throughout the duration of the experiment to provide a measure of Hebbian digit sequence learning. The dependent measure for the digit sequence memory task was the number of digits recalled in the correct serial positions across repetitions (0, 1, and 2). The dependent measure for the visuo-spatial interference tasks was accuracy of recognition (sensitivity - d prime) across digit sequence repetitions (0, 1 and 2). The experiment lasted 60 minutes.

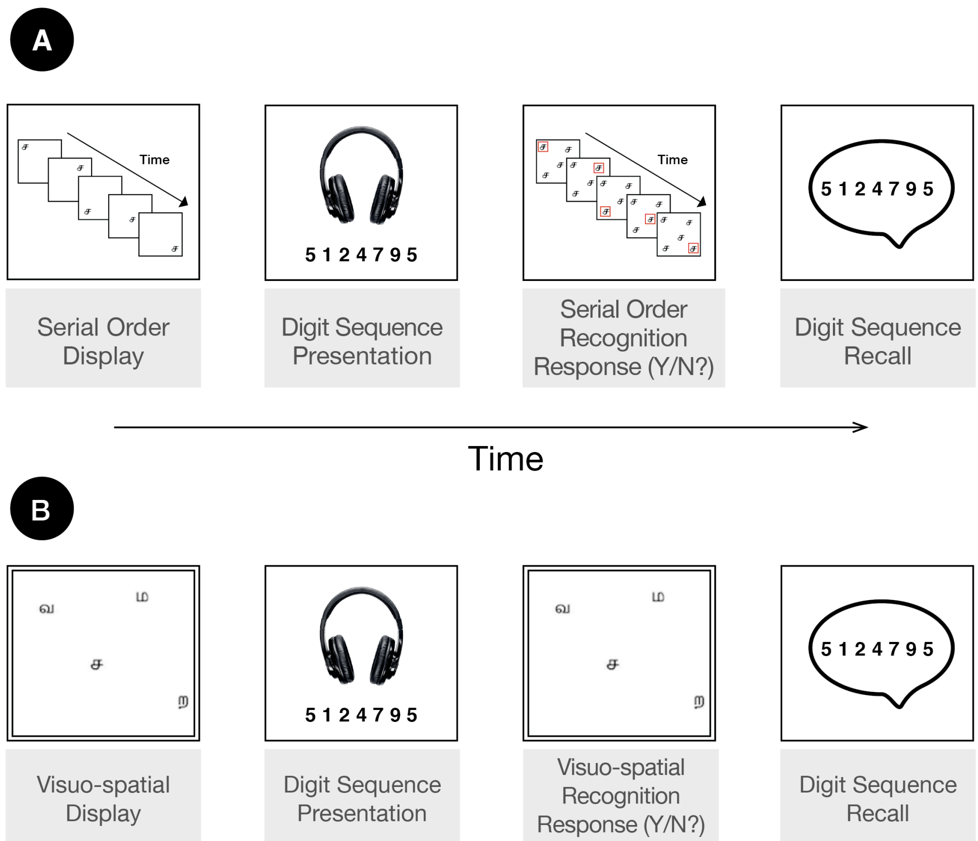

Figure 7. Illustration of the conditions of the dual-task paradigm- A) Serial Order, B) Non-serial Order.

Results

Performance in visuo-spatial interference tasks

If shared order mechanisms cause specific interference, performance in the non-serial order condition was expected to be better than in the serial order condition. A 2 (interference task type; serial order vs. non-serial order) x 3 (digit sequence repetition; 0, 1, 2) repeated measures ANOVA was conducted on the sensitivity measure for discrimination of match versus mismatch trials (d' scores) in the visuo-spatial interference tasks. Analyses showed a significant predicted main effect of task type, $F(1, 29) = 14.226$, $MSE = 15.734$, $p < 0.001$, $\eta_p^2 = 0.329$, but the effect of digit sequence repetition was not significant, $F(2, 58) = 0.281$, $MSE = 0.130$, $p = 0.756$, and neither was the interaction between the two, $F(2, 58) = 0.334$, $MSE = 0.173$, $p = 0.718$. Planned paired t-tests were conducted on the sensitivity scores between the non-serial order and serial order conditions of the visuo-spatial tasks separately for trials in which the digit sequences of the digit sequence memory task had been repeated 0, 1, or 2 times. If interference effects stemmed from shared order mechanisms in STM, they should become smaller or disappear as the verbal sequences got established in LTM. Analyses revealed that sensitivity was significantly higher in the non-serial order condition versus the serial order condition when there had been no digit sequence repetition [R- 0; $t\,(29) = 2.927$, $p < 0.01$, $d = 0.692$], and after one digit sequence repetition [R-1; $t\,(29) = 2.820$, $p < 0.01$, $d = 0.596$]. The difference between the non-serial order and the serial order conditions did not reach significance on trials with the digit sequence repeated a second time [R-2; t (29) = 2.478, p = 0.019, d = 0.452]. The Bonferroni-corrected alpha-level for the pairwise contrasts was .0167 (see Figure 8).

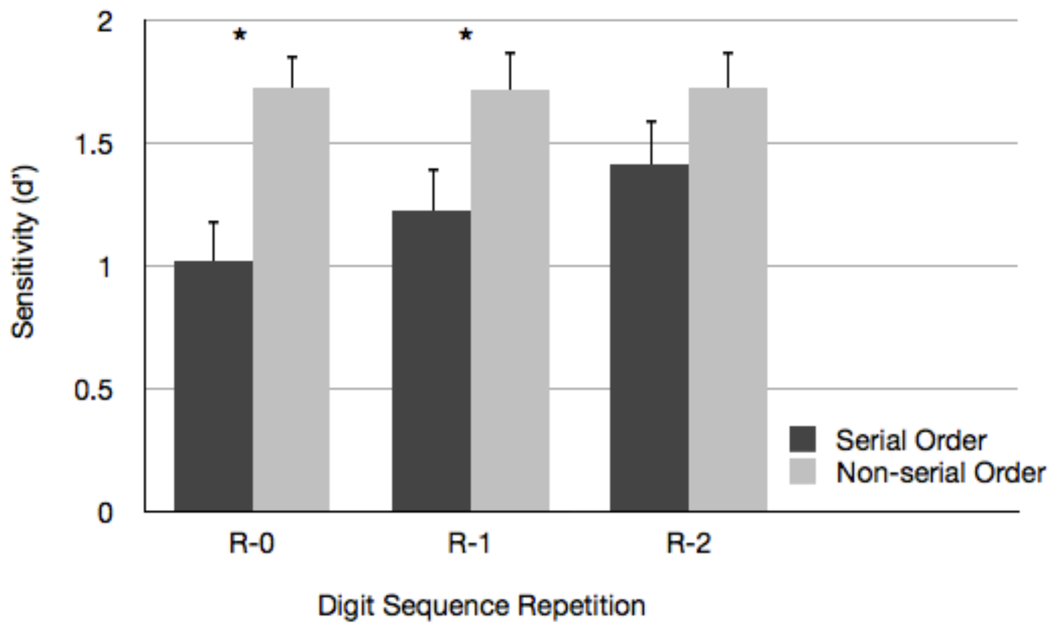

Figure 8. Visuo-spatial task accuracy as a function of digit sequence repetition (R-0, R-1, R-2) and task type (serial order vs. non-serial order; error bars represent standard errors).
* p < 0.01

Performance in digit sequence memory task

We asked, first, whether visuo-spatial memory performance in the non-serial order condition was better than in the serial order condition. We also analyzed performance in the verbal recall task. A 2 (interference task type; serial order vs. non-serial order) x 3 (digit sequence repetition; 0, 1, 2) repeated measures ANOVA was also conducted on the mean number of digits recalled in the correct serial positions in the digit sequence memory task. Analyses revealed a significant main effect of interference task type, $F(1, 29) = 9.962$, $MSE = 8.647$, $p < 0.005$,

$\eta_p^2 = 0.256$, and digit sequence repetition, $F(2, 58) = 20.962$, $MSE = 4.631$, $p < 0.0001$, $\eta_p^2 = 0.419$, but no significant interaction between the two variables, $F(2, 58) = 1.776$, $MSE = 0.288$, $p = 0.178$. Planned paired t-tests indicated that significantly more digits were recalled in the non-serial order condition relative to the serial order condition for the first digit sequence repetition [R-1; t (29) = 2.847, $p < 0.01$, $d = 0.518$], and the second digit sequence repetition [R-2; t (29) = 3.260, $p < 0.01$, $d = 0.595$]. No reliable differences were found between the non-serial order and the serial order conditions for the no digit sequence repetition [R-0; t (29) = 1.897, $p = 0.068$]. The Bonferroni-corrected alpha-level for the pairwise contrasts was .0167 (see Figure 9).

As reviewed above, a serial order learning effect (Hebb, 1961) is expected for the digit sequence memory task. That is, digit recall performance is hypothesized to improve with increasing repetitions. Contrast analyses were conducted on the mean number of digits recalled correctly across trials in which the digit sequences were repeated 0, 1 and 2 times, first for the serial order condition and then the non-serial condition. Analyses revealed that digit recall performance in the serial order condition was better for the first digit sequence repetition and the second digit sequence repetition than for the no repetition, $F(1, 29) = 7.49$, $MSE = 1.067$, $p = 0.01$, $d = 0.500$, $F(1, 29) = 10.17$, $MSE = 2.534$, $p < 0.01$, $d = 0.582$, respectively. There were no significant differences between the first repetition versus the second repetition, $F(1, 29) = 1.73$, $MSE = 0.313$, $p = 0.199$. This pattern was also seen in the non-serial order condition, where digit recall performance was better for the first repetition and the second repetition than for the no repetition, $F(1, 29) = 18.2$, $MSE = 2.885$, $p < 0.001$, $d = 0.779$, $F(1, 29) = 34.17$, $MSE = 7.0466$, $p < 0.0001$, $d = 1.067$, respectively. Performance for the second repetition was not significantly different relative to the first repetition, $F(1, 29) = 4.3$, $MSE = 0.914$, $p = 0.047$. The Bonferroni-corrected alpha-level for the pairwise contrasts was 0.0167.

The strength of the serial order learning effect (Hebb, 1961) in both conditions was computed by taking the gradient of performance across repetitions (R-0 to R-2; Szmalec et al., 2009). A planned paired t-test comparing the gradient values between the non-serial order condition and the serial order condition showed that the gradient for the serial order condition was significantly lower than the gradient for the non-serial order condition [$t\ (29) = 3.111$, $p < 0.01$, $d = 0.568$].

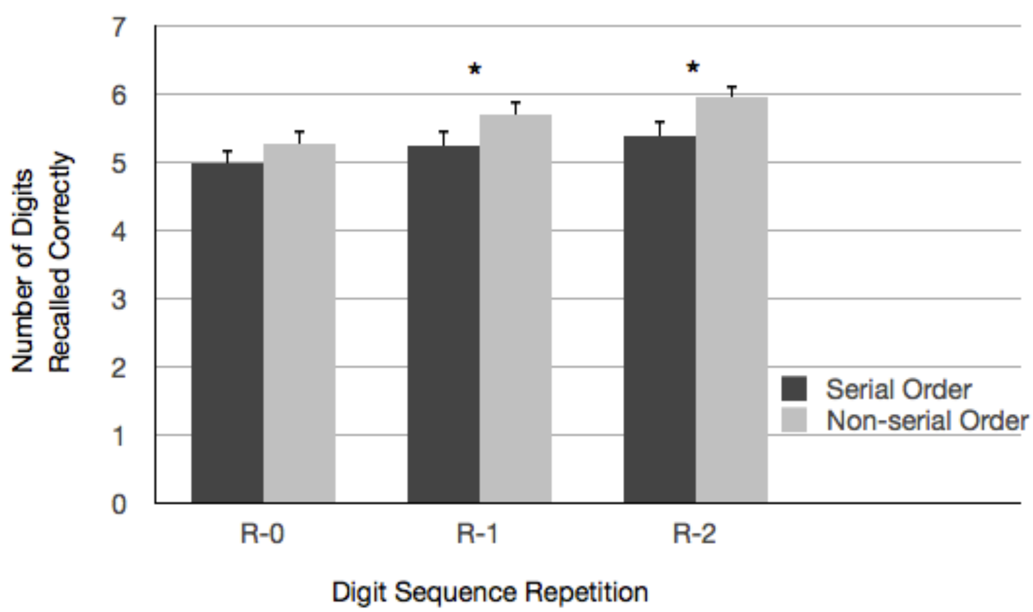

Figure 9. Digit recall task accuracy as a function of digit sequence repetition (R-0, R-1, R-2) and task type (serial order vs. non-serial order; error bars represent standard errors).
* $p < 0.01$

General Discussion

The present study developed two novel types of visuo-spatial STM interference tasks that were calibrated for difficulty level and general STM demands: one that specifically requires serial order memory and another that requires item memory (without serial order requirements). We then directly investigated to what extent common ordering mechanisms apply to visuo-spatial and verbal STM using a delayed recall dual-task design that contrasted the two types of visuo-spatial interference tasks during a concurrent primary verbal serial order memory task (digit sequence memory). As predicted, results indicated greater interference from the secondary visuo-spatial serial order STM task than the non-serial order STM task on digit recall. Likewise, there was greater interference from the primary digit sequence memory task on visuo-spatial serial order recognition than on purely visuo-spatial (non-serial order) recognition. Although the interaction factors between verbal recall and sequence repetition did not reach significance, planned contrasts between trials with different levels of repetition as well as the slopes indicating the strength of the Hebb effect supported the conclusion that serial aspects of task interference affected especially STM for digits. As participants learned the digit sequences with repeated presentations (i.e., with less demand on short-term serial order processes), there was less interference from the digit sequence memory task on visuo-spatial serial order recognition. Given that interference effects emerge when concurrent memory tasks compete for the same underlying processes and mechanisms (Allport et al., 1972; Brooks, 1967), the present results suggest that the verbal and visuo-spatial STM domains are subserved by common ordering mechanisms. The following discussion looks at first, the interference effects arising from the primary digit sequence memory task on visuo-spatial STM task performance and then, the interference effects arising from the secondary visuo-spatial STM tasks on digit recall performance.

Interference effects on visuo-spatial task performance

In light of the distinction between item information and order information in STM tasks (Burgess & Hitch, 1999; Gupta, 2003), the two secondary visuo-spatial tasks employed in the present study maximized the requirement for either order memory or item memory to allow investigation of specific serial-order interference effects arising from a concurrent primary verbal serial order STM task (digit sequence recall). Since there was greater interference from the verbal serial order STM task on visuo-spatial serial order recognition than on purely visuo-spatial (non-serial order) recognition during the no repetition and first repetition conditions, it is argued that serial-order specific interference effects emerged between the verbal and visuo-spatial tasks. That is, the interference emerged as a result of the concurrent tasks tapping a common ordering mechanism.

An alternative account would be that the serial-order specific interference effects reflect the greater difficulty of the visuo-spatial serial order STM task relative to the purely visuo-spatial (non-serial order) task. However, with extensive piloting work, we had calibrated the difficulty level in the two visuo-spatial tasks to a point at which participants appeared to be performing at the same level (Experiment 2a). Furthermore, the initial interference from the digit sequence recall on the visuo-spatial serial order task was relieved by the second repetition of the digit sequences. This is evident from participants performing similarly in the two visuo-spatial tasks by the second repetition. This would not be likely if we attribute the previous serial-order specific interference effects to the greater difficulty of the visuo-spatial serial order task as compared to the non-serial order task. Nevertheless, it may be argued that initially the visuo-spatial serial order task was more difficult than the non-serial order task but by the second repetition of the digit sequences, performance on the visuo-spatial serial order task improved due to increased practice with it. The benefit of practice would have resulted in a lack of interference between the primary verbal and secondary visuo-spatial serial order tasks by the second repetition. However, such an account is unlikely since a similar practice effect was not observed for the visuo-spatial non-serial order task. Furthermore, this view assumes that the second repetition trials occurred towards the end of the experiment to support practice effects. However, the trials of the digit sequence repetitions (R-0, R-1, and R-2) were not presented in blocked fashion and as such the second repetition trials did not necessarily always occur towards the end of the experiment allowing for the possibility of practice benefits in the visuo-spatial tasks.

The distinction between item and order information in the secondary visuo-spatial tasks allowed us to study serial-order specific interference effects between the visuo-spatial and verbal tasks. This in turn, provided insight into the debate regarding the modularity of STM systems. For instance, while some dual-task designs highlight selective domain-specific interference effects (e.g., Baddeley et al., 1975; Farmer et al., 1986; Logie et al., 1990), other studies also report interference effects between verbal and visuo-spatial tasks. For example, the requirement to perform an articulatory suppression task that consisted of counting backwards resulted in impaired performance on a spatial span task (Smyth & Pelky, 1992). Likewise, visuo-spatial tracking appeared to interfere with a verbal span task involving the recall of consonants presented out loud (Morris, 1987). One possible explanation proposes that there is a dissociation between verbal and visuo-spatial representation of item information in STM, but common ordering mechanisms employed by both subsystems (Majerus et al., 2010). A domain-specific approach to item information may explain domain-specific interference effects reported in some STM studies (e.g., Baddeley et al., 1975; Farmer et al., 1986; Logie et al., 1990), while a common ordering mechanism can also account for cross-domain interference effects such as those reported in the present study.

Interference effects on digit sequence recall performance

Greater interference from the secondary visuo-spatial serial order STM task than the non-serial order STM task on immediate verbal digit sequence recall highlights competing demands for a common ordering mechanism between the verbal and visuo-spatial domains. Moreover, given that the Hebb repetition effect (Hebb, 1961) is considered a serial-order learning effect, in which sequence information in STM gradually transforms into a LTM representation (Szmalec et al., 2012), it follows that the Hebb repetition effect observed for digit sequences should be affected by a concurrent visuo-spatial serial order STM task. As expected, while a Hebb repetition learning effect was observed for digit sequences in both dual-task conditions (i.e., with serial order and non-serial order visuo-spatial tasks), the learning effect (gradient of improvement over repetitions) was weaker in the serial order condition relative to the non-serial order condition. This supports the notion that the rate of long-term sequence learning is dependent on short-term serial order processes. As expected, while a Hebb repetition learning effect was observed for digit sequences in both dual-task conditions (i.e., with serial order and non-serial order visuo-spatial tasks), the learning effect, reflected in the gradient of improvement over repetitions, was weaker in the serial order interference condition compared to the non-serial order condition. This supports the notion that the rate of long-term sequence learning is dependent on short-term serial order processes. Specifically, learning may be dependent on the quality of the order representation set up on each repetition cycle. Recent work (Oberauer, Jones, & Lewandowsky, 2015) suggests that the Hebb effect is not modulated by the opportunity to refresh items in WM, corroborating our interpretation that it relies on specific order rather than central executive mechanisms.

Finally, the Hebbian learning of digit sequences may have led to the observed reduction of interference from the primary digit recall task on the secondary visuo-spatial serial order task by the second repetition of digit sequences. It was hypothesized that as the digit sequences were learned (i.e., with increasing repetitions), the digit recall task would rely more on LTM processes and less on immediate ordering mechanisms for successful recall of the digit sequences. If serial-order specific interference effects between the secondary visuo-spatial task and the primary digit recall task reflect competing demands for a common ordering mechanism employed by the two STM systems, it would be expected that as the digit sequences were learned, concurrent demands on a common ordering mechanism, and therefore the interference on visuo-spatial serial order task performance, would be reduced. As expected, by the second repetition of the digit sequences, participants appeared to perform equally in the two visuo-spatial tasks, which suggests that the previous interference (during the first presentation and first repetition of digit sequences) from the digit recall task on visuo-spatial serial order STM task performance was relieved. Particularly, there was a gradual reduction in effect sizes for the difference between the two visuo-spatial tasks with increasing repetitions.

While such an account lends support to the notion that a common ordering mechanism underlies verbal and visuo-spatial STM, it is important to discuss the possible role of central executive processes in explaining the relation between Hebbian sequence learning and the non-significant serial-order specific interference during the second repetition of digit sequences as noted above. Indeed, previous studies have shown the central executive, described as an attentional controller, to play a crucial role in dual-task procedures (e.g., Della Sala, Baddeley, Papagno, & Spinnler, 1995). For instance, it can be argued that as the digit sequences are learned, the capacity of the central executive to switch attention between the verbal and visuo-spatial dual-tasks increases, relieving the previously observed interference from the primary digit recall task on the secondary visuo-spatial serial order STM task. However, it would follow then that central executive processes also lead to a similar pattern of data for the non-serial order condition (i.e., improved visuo-spatial STM task performance with increasing repetitions), but this was not observed. Therefore, it is unlikely that the relation between Hebbian sequence learning and the lack of serial-order specific interference is due to central executive processes.

To summarize, a recent review (Hurlstone et al., 2014) highlighted that serial order is processed in functionally equivalent ways in the verbal and visuo-spatial STM domains. This opened the question of whether the verbal and visuo-spatial STM subsystems rely on common, shared mechanisms for serial order processing or whether they rely on ordering mechanisms that merely operate in functionally similar ways but are entirely dissociated. The present dual-task study found serial-order specific interference effects between a verbal and a visuo-spatial STM task, in support of common ordering mechanisms between the two domains. Nevertheless, given previous reports of domain-specific influences on order memory (see Experiment 1 discussion), we argue that while verbal and visuo-spatial STM domains appear to be subserved by common ordering mechanisms, such mechanisms, in turn, must interact with domain-specific properties (e.g., visuo-spatial attention). Such a conceptualization provides fruitful avenues for future research centered on unravelling the mechanisms underlying this interaction. Future research must also address whether common ordering mechanisms extend to the visual component of the visuo-spatial STM domain (i.e., the visual cache). One possibility is to replicate the present study using sequences of abstract visual patterns or unfamiliar faces instead of sequences of visuo-spatial locations.

Chapter 4

Does Serial Order STM underlie Novel Word Learning?

Introduction

There is an extensive body of literature indicting relations between serial order STM task performance and the ability to learn novel phonological word-forms (Gathercole et al., 1992; Gathercole et al., 1997; Gathercole et al., 1999; Leclercq & Majerus, 2010; Majerus & Boukebza, 2013; Majerus et al, 2009). Recent work also suggests that aspects of naturalistic word-form learning is analogous to Hebbian sequence learning (Szmalec et al., 2009; Szmalec et al., 2012). Specifically, the sub-lexical items within novel word-forms exhibit similar serial position effects as those that occur to items in immediate serial recall tasks and Hebb repetition tasks (Gupta, 2003). Also, both word-form learning and immediate serial recall are subject to influence from similar verbal factors (Papagno et al., 1991; Papagno & Vallar, 1992). However, it still remains unclear whether serial order STM mechanisms such as those employed in immediate serial recall tasks and Hebb repetition tasks also underlie vocabulary learning.

The present study aimed to address whether common ordering mechanisms underlie vocabulary acquisition and immediate visuo-spatial serial recall by replicating the investigations of Experiment 2b using a word-learning paradigm as a concurrent primary task in place of the digit sequence memory task used previously. Two types of visuo-spatial interference tasks were contrasted to probe serial order STM versus item STM (control), during a concurrent paired-associate word-learning paradigm. The paired-associate word-learning task was based on previously used learning procedures (Atkins & Baddeley, 1998; Papagno & al., 1991; Papagno & Vallar, 1992) and consisted of presenting novel Tamil word-forms with their English translation counter-parts. Given previously reported associations between serial order STM and vocabulary acquisition, we hypothesized that immediate serial recall and vocabulary acquisition both draw on common order mechanisms. Based on this, we predicted greater interference effects during a word-learning task when paired with a concurrent visuo-spatial serial order STM task relative to being paired with a STM task that did not require memory for order. The degree to which the word-learning task relied on STM was also manipulated by presenting each novel word-form three times throughout the duration of the experiment. Similar to Majerus et al. (2008), the number of repetitions was kept relatively small because we were particularly interested in how STM contributions affect early stages of word learning. Based on the assumption that the Hebb repetition learning effect (Hebb, 1961) is a laboratory analogue of naturalistic word-learning (Szmalec et al., 2009), we hypothesized that by the second and third presentation of the word-forms, the word-learning task should theoretically rely less on short-term serial order processes and, at least in part, on learned, long-term memory representations of the word-forms. This should reduce competition for short-term serial order processes between the primary word-learning task and the secondary visuo-spatial serial order task. Consequently, we predicted that with repeated presentations of the word-forms, there would be less interference between the visuo-spatial serial order STM task and concurrent word-learning task.

Experiment 3

Method

Participants

Thirty undergraduate students aged 18–25 from McMaster University took part in this study. They were recruited through the Linguistics Participant Pool at McMaster University. All participants were native English speakers with no prior familiarity with written Tamil syllabic characters and no familiarity with the spoken Tamil language. They also had normal or corrected-to-normal vision. All participants gave informed written consent prior to the beginning of the study and received course credit for their participation. The protocol was cleared by the McMaster University Research Ethics Board.

Stimuli

The visuo-spatial stimuli from Experiment 2a and 2b were used in Experiment 3. Additionally, for the paired-associate word-learning task, stimuli consisted of English word -Tamil word pairs. English words ranged from one-four syllables in length and Tamil words were three syllables in length. The tamil words were exclusively made of phonemes that are also found in English. The spoken words were pre-recorded by the experimenter using Audacity 2.0.6 sound editor/recorder, and presented through JVC headphones. Responses were recorded using Audacity 2.0.6 sound editor/recorder.

Procedure

Participants completed a delayed recall dual-task paradigm that contrasted two types of visuo-spatial interference tasks (same as in Experiment 2) during a concurrent primary paired-associate word-learning task. The visuo-spatial tasks probed serial order STM and non-serial order STM (control). Each trial sandwiched presentation of an English word-Tamil-word pair for later recall between the encoding and retrieval phases of one of the visuo-spatial STM tasks. The experiment was carried out over two days of testing. Half of the test trials from each condition (15 from serial order, 15 from non-serial order) were presented on Day 1 of testing, and the other half were presented on Day 2 of testing. The order of the conditions was counter-balanced across participants in each day of testing. The word-pairs in each condition, and in each day of testing, were also counter-balanced across participants.

<u>Serial Order STM + Word-Learning Task</u>

Each trial began with the presentation of a cue in the form of a fixation cross (radius of 12 pixels) located in the centre of a blank computer screen for 1000 ms. The fixation cross was followed by a sequence of five, identical, black, abstract symbols (Tamil syllabic characters) presented one at a time (1000 ms on, 1000 ms off) in different spatial locations of the screen for later serial recognition (visuo-spatial serial order STM task). Following presentation of the last symbol, the fixation cross appeared for 1000 ms and then participants heard an English word followed by a Tamil word presented through headphones. They were asked to remember the pair for a later recall test (novel word-form immediate recall) that would occur towards the end of the trial. The fixation cross appeared once again for 1000 ms, after which participants completed the serial recognition component of the serial order visuo-spatial STM task. In this, all the abstract symbols were re-presented in their original spatial locations and remained on the screen while a red square moved from symbol to symbol (1000 ms on, 700 ms off) to indicate a particular sequence. Following this presentation, participants were prompted to indicate whether the presented sequence matched the previously presented order of locations by pressing a computer key. Half of the trials were match trials, and half were mismatch trials. Finally, in the response component of the word-learning task, the previously heard English word was presented through headphones and participants were prompted to orally repeat the corresponding novel Tamil word (e.g., door - ?). Participants said "blank" for any words they could not recall. After the oral response, they were were instructed to click a "next trial" icon to initiate the next trial when ready. Once clicked, a blank screen appeared for 1000 ms, followed by the presentation of the next trial.

Non-serial Order STM + Word Learning Task

The same procedure was used for the second dual-task condition with slight exceptions to the visuo-spatial component. Each trial began with the presentation of the fixation cross for 1000 ms in the centre of a blank computer screen. A static display of four, different, black, abstract symbols (Tamil syllabic characters) located in different spatial locations, was presented on the screen (10000 ms) for later visuo-spatial recognition (visuo-spatial non-serial order STM task). The fixation cross appeared for 1000 ms and then participants heard an English word followed by a Tamil word presented through headphones. They were asked to remember the pair for a later recall test (novel word-form immediate recall) that would occur towards the end of the trial. The fixation cross appeared again for 1000 ms. Next, participants completed the visuo-spatial recognition component of the visuo-spatial STM task. In this, an array of abstract symbols located in the previously seen spatial locations was presented for 8500 ms. Participants were asked to identify whether the presented array matched the previously presented array (correct symbol + location) by pressing a computer key. The recognition component always consisted of the same symbols and locations that were previously presented in the trial. Non-match trials consisted of an incorrect pairing of symbols and locations. Half of the trials were match trials, and half were mismatch trials. Finally, in the response component of the word-learning task, the previously heard English word was presented through headphones and participants were prompted to orally repeat the corresponding novel Tamil word.

Participants said "blank" for any words they could not recall. After the oral response, they were required to click a "next trial" icon to begin the next trial. A blank screen appeared for 1000 ms preceding the presentation of the next trial.

Participants were encouraged to perform both dual tasks in each condition as accurately as possible. They were instructed to use visuo-spatial strategies in the visuo-spatial interference tasks and avoid using any verbal and/or gestural strategies. Participants were tested individually and data was collected and saved via computer responses and audio-recordings.

The parameters of both conditions were identical with the exceptions of the visuo-spatial interference tasks. Each condition contained 30 test trials presented in semi-random fashion. The test trials were preceded by 5 practice trials presented in random order. After every 15 test trials, a "break" icon appeared prompting participants to take a break if necessary. The trials in each condition were presented in blocked fashion such that each English word- Tamil word pair was presented three times throughout the duration of the experiment to provide a measure of Hebbian word learning across repetitions. The first block consisted of five trials that contained the first presentation of each pair, the next block consisted of five trials that contained the first repetition of each pair, and the last block consisted of five trials that contained the second repetition of each pair. After the presentation of each block, a delayed English-word cued recall test followed, in which the English words from each block were presented through headphones in random order and participants were asked to orally recall the corresponding Tamil word-forms (e.g., door - ?). At the end of each day of testing, a delayed syllable-cued recall test was administered, in which partial components (first two syllables) of the Tamil word-forms encountered that day were presented and participants were asked to orally recall the last missing syllable (e.g., ka-tha- ?). The whole experiment lasted 120 minutes, 60 minutes on Day 1 and 60 minutes on Day 2.

Measures

The dependent measure for the visuo-spatial interference tasks was accuracy of recognition (sensitivity - d prime) across word-form repetitions (0, 1 and 2). The paired associate word-learning paradigm consisted of three different measures: novel word-form immediate recall, delayed English-word cued recall, and delayed syllable cued recall. Novel word-form immediate recall was measured as the proportion of word-forms recalled correctly across repetitions (0, 1, and 2). Although recall was cued with an English word in each trial, the task can still be regarded as a measure of phonological word-form learning since participants do not necessarily need to remember the pairing in order to successfully recall the last heard Tamil word. Based on piloting work, ceiling performance was expected in this task, but it was included as a measure in order to facilitate the learning of the novel word-forms. English-word cued recall was measured as the proportion of word-forms recalled correctly across repetitions (0, 1, and 2). This was regarded as a measure of simulated vocabulary learning since the phonological word-forms had to be learned in association with their semantic meaning (i.e., the English referent). Syllable cued recall was measured as the proportion of missing syllables recalled correctly and was regarded as a measure of phonological word-form learning.

Results

Performance in visuo-spatial interference tasks

It was predicted that performance in the non-serial order condition would be better than in the serial order condition due to order-related interference. A 2 (interference task type; serial order vs. non-serial order) x 3 (word-form repetition; 0, 1, 2) repeated measures ANOVA was conducted on recognition sensitivity measures (d' scores) in the visuo-spatial interference tasks. Analyses showed a significant main effect of task type, $F(1, 29) = 14.434$, $MSE = 8.105$, $p < 0.001$, $\eta_p^2 = 0.332$, and interaction between task type and word-form repetition, $F(2, 58) = 4.496$, $MSE = 3.117$, $p < 0.05$, $\eta_p^2 = 0.134$, but the main effect of word-form repetition was not significant, $F(2, 58) = .094$, $MSE = 0.047$, $p = 0.761$. Planned paired t-tests were conducted on the sensitivity scores between the non-serial order and serial order conditions of the visuo-spatial tasks across trials in which the word-forms in the word-learning task were repeated 0, 1, and 2 times. Analyses revealed that for both the no word-form repetition (R-0) and first word-form repetition (R-1) trials, sensitivity in the visuo-spatial tasks was significantly higher in the non-serial order condition compared to the serial order condition [R-0: $t\,(29) = 3.791$, $p < 0.001$, $d = 0.692$; R-1: $t\,(29) =$

3.148, $p < 0.005$, $d = 0.575$, respectively]. For the second word-form repetition (R-2) trials, no significant differences were found between the non-serial order and serial order conditions [t (29) = 0.202, $p = 0.841$, $d = 0.037$]. The Bonferroni-corrected alpha-level for the pairwise contrasts was 0.0167 (see Figure 10).

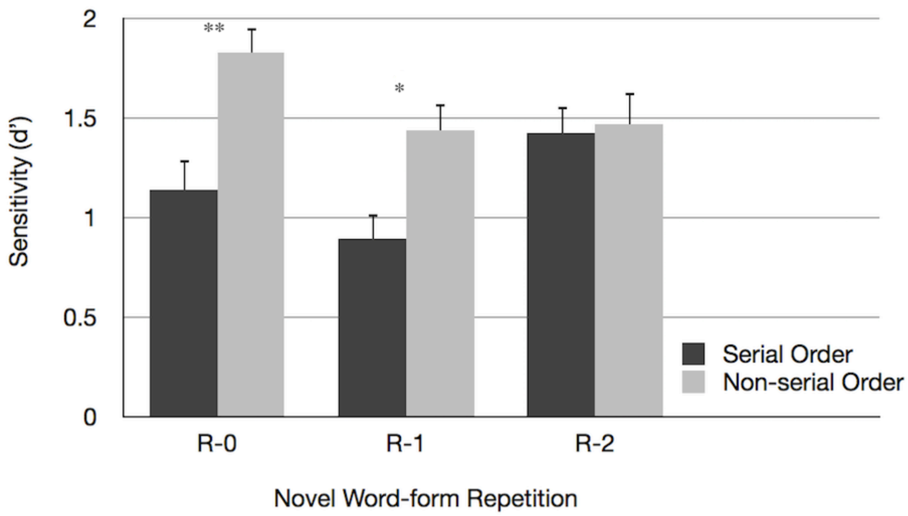

Figure 10. Visuo-spatial task accuracy as a function of novel word-form repetition (R-0, R-1, R-2) and task type (serial order vs. non-serial order; error bars represent standard errors).
* $p < 0.005$, ** $p < 0.001$

Performance in word learning tasks

<u>Delayed English-word Cued Recall</u>

Word-learning performance in the non-serial order condition had been hypothesized to be better than in the serial order condition as a result of added interference due to shared order memory mechanisms. A 2 (interference task type; serial order vs. non-serial order) x 3 (word-form repetition; 0, 1, 2) repeated measures ANOVA was conducted on the proportion of words recalled correctly in the English-word cued recall task. Analyses revealed a significant main effect of task type, $F(1, 29) = 8.146$, $MSE = 1.0125$, $p < 0.01$, $\eta_p^2 = 0.219$, and word-form repetition, $F(2, 58) = 19.798$, $MSE = 1.321$, $p < 0.0001$, $\eta_p^2 = 0.406$, but no significant interaction between the two variables, $F(2, 58) = 0.779$, $MSE = 0.067$, $p = 0.464$. Planned paired t-tests indicated that the proportion of words recalled correctly was higher in the non-serial order condition relative to the serial order condition for the first word-form repetition trials [R-1: $t\,(29) = 3.356$, $p < 0.005$, $d = 0.613$], and second word-form repetition trials [R-2: $t\,(29) = 2.670$, $p = 0.012$, $d = 0.487$]. No reliable differences were found between the non-serial order and serial order conditions for the no word-form repetition [R-0: $t\,(29) = 1.751$, $p = 0.091$. The Bonferroni-corrected alpha-level for the pairwise contrasts was .0167 (see Figure 11).

The next hypothesis relates to the Hebb repetition learning effect (Hebb, 1961) expected to be present for the novel word-forms. It was predicted that word-recall performance would improve with increasing repetitions. Contrast analyses compared the proportion of word-forms recalled correctly across trials in which they were repeated 0, 1 and 2 times, first, for the serial order condition and then the non-serial condition. In the serial order condition, recall performance was better for the first repetition and second repetition trials than for the no repetition trials [$t\,(29) = 7.761$, $p < 0.0001$, $d = 1.417$, $t\,(29) = 11.036$, $p < 0.0001$, $d = 2.017$], respectively. Recall performance was also better for the second repetition trials than for the first repetition trials [$t\,(29) = 7.215$, $p < 0.0001$, $d = 1.320$] indicating word-form learning with repetition despite order-related interference. In the non-serial order condition, recall performance was better for the second repetition relative to the first repetition [t (29) = 6.595, $p < 0.0001$, d = 1.204]. Recall performance was also better for the second repetition than for the no repetition, however, this difference did not reach significance after the Bonferroni-correction [t (29) = 2.067, $p < 0.05$, d = 0.377]. No significant differences were found between recall performance for the no repetition and the first repetition trials [t (29) = 0.506, p = 0.617]. The Bonferroni-corrected alpha-level for the pairwise contrasts was 0.0167.

The strength of the repetition learning effect for the word-forms (Hebb, 1961) in both conditions was computed by taking the gradient of performance across repetitions (R-0 to R-2). A planned paired t-test compared the gradient values between the non-serial order and serial order conditions but revealed no significant differences [t (29) = 0.124, p = 0.902]. Thus, the Hebb effect for word forms did not significantly depend on whether the secondary task required memory for order or not.

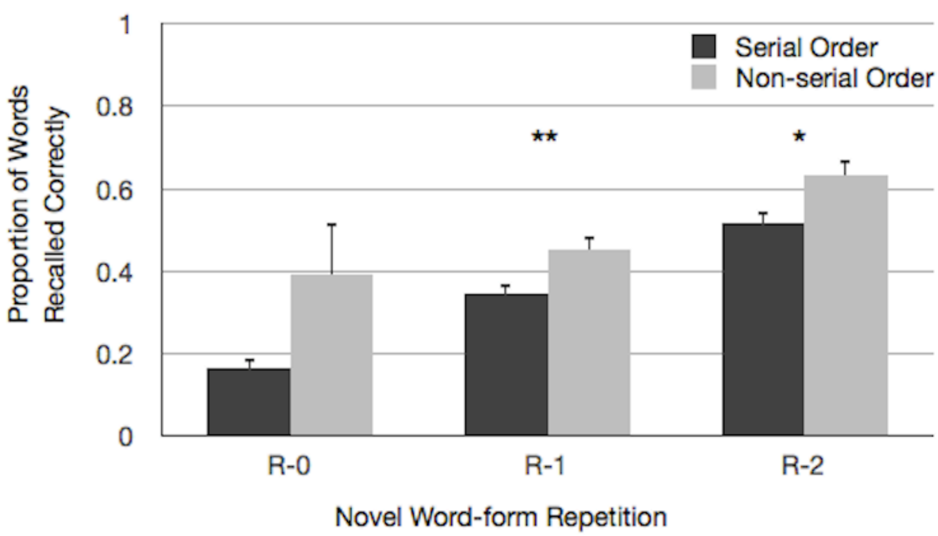

Figure 11. English-word cued recall accuracy as a function of novel word-form repetition (R-0, R-1, R-2) and task type (serial order vs. non-serial order; error bars represent standard errors). * p < 0.05, ** p < 0.005

Delayed Syllable Cued Recall

It was expected that performance in the syllable cued recall test would be better in the non-serial order condition relative to the serial order condition if word-form learning depended on an ordering mechanism. A planned paired t-test confirmed predictions, revealing that the proportion of syllables recalled correctly was higher in the non-serial order condition ($M = 0.477$, $SD = 0.185$) versus the serial order condition [$M = 0.373$, $SD = 0.180$; $t\ (29) = 3.120$, $p < 0.005$, $d = 0.705$].

Novel Word-form Immediate Recall

Novel word-form immediate recall was designed to function as a learning task. Based on piloting work, we expected performance in novel word-form immediate recall to be at ceiling. Performance in this task is shown in Figure 12. A 2 (interference task type; serial order vs. non-serial order) x 3 (word-form repetition; 0, 1, 2) repeated measures ANOVA was conducted on the proportion of words recalled correctly in the learning phase. Analyses indicated a significant main effect of word-form repetition, $F(2, 58) = 14.48$, $MSE = 9.036$, $p < 0.0001$, $\eta_p^2 = 0.334$, but not a significant effect of interference task type, $F(1, 29) = 3.302$, $MSE = 0.014$, $p = 0.08$, and no significant interaction between the two variables, $F(2, 58) = 0.467$, $MSE = 0.0007$, $p = 0.629$. Contrast analyses compared the proportion of word-forms recalled correctly across trials in which they were repeated 0, 1 and 2 times, first for the serial order condition and then the non-serial condition. In the serial order condition, recall performance was better for the first repetition and the second repetition than for the no repetition [$t(29) = 3.746$, $p < 0.001$, $d = 0.682$; $t(29) = 3.261$, $p < 0.005$, $d = 0.602$], respectively. No significant differences were found between recall performance for the first repetition and the second repetition [$t(29) = -0.701$, $p = 0.489$], both near ceiling. This pattern was also seen for the non-serial order condition, where recall performance was better for the first repetition and the second repetition than for the no repetition [$t(29) = 2.796$, $p < 0.001$, $d = 0.503$; $t(29) = 3.525$, $p < 0.005$, $d = 0.648$], respectively. Again, no reliable differences were found between recall performance for the first repetition and the second repetition [$t(29) = 0.441$, $p = 0.662$] with both close to perfect performance. The Bonferroni-corrected alpha-level for the pairwise contrasts was 0.0167. Thus, performance in the learning trials appeared to be similar during both interference tasks (see Figure 12).

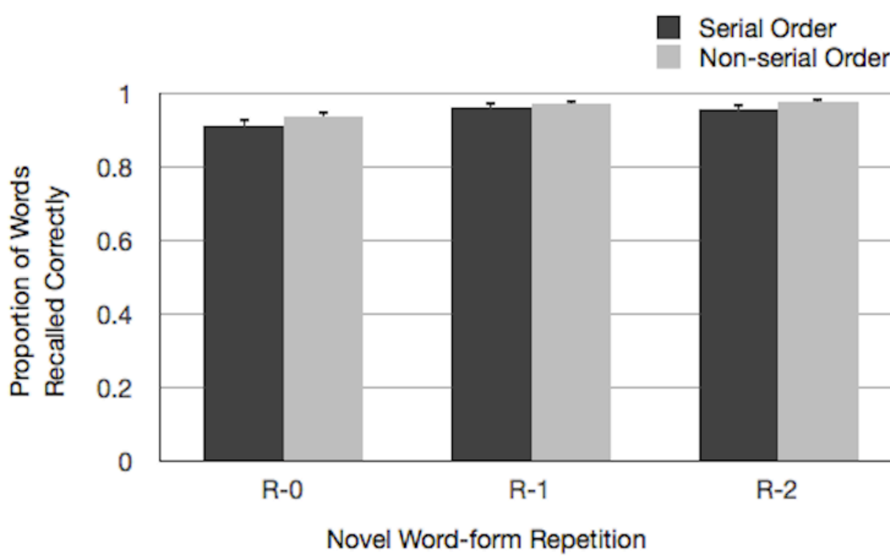

Figure 12. *Performance in the learning trials:* novel word-form immediate recall accuracy as a function of repetition condition (R-0, R-1, R-2) and task type (serial order vs. non-serial order; error bars represent standard errors).

Discussion

Experiment 3 aimed to address whether vocabulary learning was supported by serial order mechanisms by replicating the results of Experiment 2b using a paired associate foreign-word-learning paradigm as a primary task in place of the previously used digit sequence memory task. The same delayed recall dual-task design was employed. It contrasted two types of secondary visuo-spatial STM interference tasks during the concurrent word-learning paradigm. The two visuo-spatial tasks probed either serial order STM or item (non-serial order) STM. As predicted, results indicated greater interference from the visuo-spatial serial order STM task than the non-serial order STM task on word-learning ability reflected in delayed recall. From the perspective of the secondary tasks, results showed greater interference from the primary word-learning task on visuo-spatial serial order recognition than on visuo-spatial (non-serial order) recognition. However, as the word-learning task presumably came to rely less on STM processes and more on the learned representations of the word-forms in LTM with repeated presentations of the word-forms, it presented less interference on visuo-spatial serial order recognition. These serial-order specific interference effects are taken as evidence supporting the hypothesis that a shared serial ordering mechanism underlies both aspects of word-learning and visuo-spatial serial order STM task performance. Moreover, the pattern of findings in Experiment 3 was strikingly similar to that reported in Experiment 2b, despite critical differences between the word-learning task used in the current study and the Hebbian digit sequence memory task used in

Experiment 2b. This supports the assumption that the Hebb repetition effect (Hebb, 1961), described as the learning of sequence information through repeated exposures, can be used as a laboratory analogue of aspects of naturalistic word-learning (Szmalec et al., 2009; Szmalec et al., 2012). The following discussion looks at first, the interference effects arising from the primary word-learning task on visuo-spatial task performance and then, the interference effects arising from the secondary visuo-spatial tasks on word-learning performance.

Interference effects on visuo-spatial task performance

As previously mentioned, interference effects between primary and secondary dual tasks emerge when such tasks compete for the same underlying processes or mechanisms (Allport et al., 1972 ; Brooks, 1967). Therefore, the serial-order specific interference effects arising from the primary word-learning task on the secondary serial order visuo-spatial task measure during the no repetition and first repetition of the word-forms suggest that a common ordering mechanism underlies both functions. Notably, the present pattern of data for visuo-spatial task performance is strikingly similar to the results of Experiment 2b. In particular, both experiments reveal that by the second repetition of the digit sequences (of Experiment 2b) or word-forms (present experiment) in the primary tasks, participants are performing at a similar level in the two visuo-spatial STM tasks (serial order vs. non-serial order). That is, the interference from the primary verbal task on visuo-spatial serial order STM task performance during the first and second presentations of the verbal stimuli appears to be relieved by the third presentation. This further supports the argument that the two visuo-spatial tasks had been successfully calibrated for difficulty level, since equal performance between the two tasks would not be expected if one were more difficult than the other. However, as in Experiment 2b, it may be argued that the higher difficulty level of the serial order STM task compared to the non-serial one was masked after the second repetition of word-forms since participants could improve their performance on the visuo-spatial serial order task by benefiting from practice with it throughout the duration of the experiment. This would have led to the lack of interference between the visuo-spatial serial order and word-learning tasks by the second repetition. This argument was dismissed in Experiment 2b because it implied that the trials of each repetition occurred in blocked fashion such that the second repetition occurred towards the end of the experiment allowing for practice effects. In Experiment 2b, the trials of each digit sequence repetition were not presented in blocked fashion that would have allowed practice effects. However, the present experiment was critically different from Experiment 2b in that the trials of the word-form learning (repetitions) were presented in blocked fashion allowing for the possibility of practice effects in the visuo-spatial task over the duration of the experiment. Nevertheless, similar to Experiment 2b, we argue that practice effects were unlikely since similar effects were not observed for the visuo-spatial (non-serial order) task performance. Indeed, the results indicated no effect of word-form repetition.

The current results shed light on the role of visuo-spatial STM in vocabulary acquisition with respect to item versus order processing. A recent study showed that the magnitude of Hebb sequence learning of spatial memoranda (in the Dots Task) in 5 and 6- year old children correlated with performance on a nonword paired-associate learning task (Mosse & Jarrold, 2008). The explanation preferred here states that the relations between visuo-spatial sequence learning and vocabulary acquisition are at least partly dependent upon common serial order memory demands relative to item memory demands. This is consistent with the serial-order specific interference effects observed between the primary word-learning and secondary visuo-spatial STM tasks in the current study. Since the verbal and the visuo-spatial tasks are presumed to tap different STM domains for item processing, visuo-spatial STM for the visuo-spatial serial order task and phonological STM for the word-learning task, the observed task-dependent interference may be attributed to common serial ordering processes. For this reason, the visuo-spatial serial order STM task and visuo-spatial item STM task have differential effects on concurrent word-learning ability. This finding supports a growing body of evidence highlighting the distinction between item and order memory representations in the STM domains (Attout et al., 2012; Fiebach, Friederici, Smith, & Swinney., 2007; Majerus & D'Argembeau, 2011; Majerus, Norris, & Patterson, 2007; Majerus et al., 2006; Majerus et al., 2010; Marshuetz et al., 2000; Nairne & Kelley, 2004; Poirier & Saint Aubin, 1996; Saint-Aubin & Poirier, 2005).

Interference effects on word learning performance

In the current study, three different measures of word learning were used in the primary word-learning task: novel word-form immediate recall, delayed English word-cued recall, and delayed syllable cued recall. The novel word-form immediate recall and delayed syllable cued recall measures were both assumed to mainly tap the learning of phonological information. In contrast, the delayed English word-cued recall measure requires the learning of the phonological aspects of the word-form as well as the association of the phonological word-form with its English counterpart or semantic meaning (Gupta & Tisdale, 2009). According to Page and Norris (2009), serial order mechanisms are activated in phonological word learning as driving the processing of the sub-lexical units of the word in the correct order. This view is reinforced by the present data indicating greater interference from the secondary visuo-spatial serial order STM task than the non-serial order STM task on performance in both delayed word-learning measures: syllable cued recall and English word-cued recall. Although, no corresponding interference differences were observed from the secondary visuo-spatial tasks on novel word-form recall at the end of each trial, this is likely due to ceiling effects in this task. It was primarily included as a measure to facilitate word-learning across repetitions based on previous reports that the Hebb repetition effect for sequences is strongest when recall is attempted (see Page & Norris, 2009a, for a review). Taken together, the findings point to a role for serial ordering mechanisms in phonological word-form learning as well as more general vocabulary learning (i.e., learning the phonological word-form and its associated semantic meaning). The ordering mechanism is argued to drive the sequential processing of sub-lexical units of the novel word-forms during learning. This interpretation is supported by data showing that the magnitude of sequential learning of spatial and verbal memoranda correlates specifically with non-word paired-associate learning but not with word paired-associate learning (Mosse & Jarrold, 2008). That is, the association reveals a specific role for serial order STM in learning the sequential structure of the novel phonological word-form.

The present data also add support to the notion that aspects of word learning in the natural environment are analogous to the Hebb repetition effect for sequence learning (Szmalec et al., 2009; Szmalec et al., 2012). To clarify, given previous reports of Hebb repetition learning effects for novel word-forms (i.e., improved recall with increasing repetitions; Szmalec et al., 2009), the present study also expected Hebb repetition effects for the novel word-forms in the English-word cued recall task. As predicted, learning of novel word-forms improved with increasing repetitions in both the serial order and non-serial order dual task conditions. However, based on the view that during early exposure to novel words, a sequencing mechanism is employed in order to maintain the sequence of sub-lexical units within the word (Gupta, 2003; Page & Norris, 2009), it would follow then that the visuo-spatial serial order task should interfere with word learning ability more than the non-serial order task. As expected, word-learning was better in the non-serial order condition compared to the serial order condition after each repetition, reflecting competing demands between the primary word-learning and secondary serial order STM tasks for a common ordering mechanism. Moreover, these findings are directly in line with Experiment 2b which showed digit sequence learning after each repetition to be greater in the non-serial order condition relative to the serial order condition. Although Experiment 2b reported the strength of the Hebb repetition learning effect (gradient of improvement over repetitions) for sequences to be stronger in the non-serial order condition compared to the serial order condition, no such differences were found for the Hebb repetition learning of word-forms. Therefore, while participants learned more novel-word forms when performing a concurrent non-serial order STM task relative to a serial order STM task, the rate of learning over repetitions was similar in both conditions. The lack of improvement advantage for novel word-forms in the non-serial order condition may be due to the unusually high recall performance after their first presentation (see Figure 11). One possibility is that the ordering mechanism is necessary in each trial of Hebb repetition to produce new learning for a digit sequence (e.g., Experiment 2b). However, in the case of Hebbian word-learning (present experiment), it could be hypothesized that the order of sub-lexical phonemic information is mainly laid out after the first presentation of word-forms (R-0 trials). Subsequent Hebb learning is then weighted towards phonemic identity information rather than the order of phonemes (e.g., a skeleton consisting of an ordering of consonants and vowels gets filled in by more detailed phonemic information). Although this may explain why word-learning performance appeared to incur more interference from the serial-order visuo-spatial task than the non-serial order task after the first presentation of word-forms (R-0), further investigations are needed to explore the validity of this claim.

One final line of evidence that points to common ordering mechanisms between word-learning and visuo-spatial serial recall stems from the reported Hebb repetition learning effect for the novel word-forms. Similar to Experiment 2b, it was assumed that with increasingly accurate representations of the novel word-forms, the primary word-learning task would rely less on STM serial order processes and more on the learned LTM representations of the word-forms. As such, the concurrent secondary visuo-spatial serial order STM task should incur less interference from the word-learning task with each repetition, if common ordering mechanisms are employed. As predicted, by the second repetition of the word-forms, participants appeared to perform equally in the two visuo-spatial tasks, which suggests that the previous interference (during the first presentation and first repetition of word-forms) from the word-learning task on visuo-spatial serial order STM task performance was relieved. This was evident from the gradual reduction in effect sizes for the difference between the two visuo-spatial tasks with increasing repetitions.

The reliance on executive control processes are difficult to control in dual-task conditions. However it is unlikely to be a factor in explaining the current pattern of findings. It may be argued that with increasingly accurate representations of the word-forms (i.e., learning of word-forms), executive control demands for switching between the two dual tasks (word-learning and visuo-spatial STM) is reduced, relieving the previously observed interference from the word-learning task on the visuo-spatial serial order STM task. However, such an account would require similar effects of executive control on the visuo-spatial non-serial order STM task, which were not observed.

Lastly, it must be noted that the pattern of data regarding word-form learning across repetitions was strikingly similar to that seen for digit sequence learning in Experiment 2b despite critical methodological differences. Specifically, Experiment 2b measured digit sequence recall at the end of each trial, while the present experiment tested English-word cued recall after every five trials. Nevertheless, the same pattern of Hebb repetition learning effects and serial order-specific dual-task impairments were observed for novel word-forms and verbal digit sequences in the primary tasks. Taken together, these experiments readily accommodate the view that verbal sequences, such as those in Hebb repetition paradigms, and novel-word forms are learned in functionally similar ways (Szmalec et al., 2009; Szmalec et al., 2012) and are subject to similar serial-order specific interference from visuo-spatial tasks.

In conclusion, a large body of work has highlighted the importance of verbal phonological processing/storage capacities in novel word-learning (e.g., Avons et al., 1998; Baddeley et al., 1998; Gathercole & Baddeley, 1989;

Gathercole et al., 1994; Gathercole et al., 1992; Service, 1992). Namely, studies have revealed a specific link between novel word-learning and phonological STM (e.g., non-word/pseudo-word repetition; Service & Craik, 1993; Service & Kohonen, 1995). In addition, several studies have indicated relations between vocabulary acquisition and verbal serial order STM capacity (See Baddeley et al., 1998, for a review). The present study aimed to clarify the latter relation and employed a dual-task paradigm that exhibited serial-order specific interference effects between a word-learning task and a visuo-spatial STM task. These findings provide direct evidence that vocabulary learning processes and visuo-spatial serial order STM rely on common ordering mechanisms. Based on this, we argue that vocabulary acquisition depends on both verbal phonological STM capacities and domain-general serial ordering processes.

Concluding Chapter

Mechanisms of Serial Order in Working Memory and in the Language Domain

As noted in the introduction, the working memory (WM) model by Baddeley and Hitch (Baddeley, 1986; Baddeley & Hitch, 1974) consists of separate subsystems for the processing of verbal and visuo-spatial memoranda. This fractionation is supported by a wealth of behavioural, neuropsychological, and neuroimaging data that indicate double dissociations between verbal and visuo-spatial STM (See Baddeley, 2007, for a review). An "episodic buffer" is assumed to integrate information from the two sub-systems as well as LTM, and a "central executive" operates as an attentional control system. Despite reports of several serial order phenomena in both domains, the characterization of serial order processing within the working memory framework has been unclear.

A recent review (Hurlstone et al., 2014) indicated that many of the verbal serial order phenomena also exist in the visuo-spatial domain. Moreover, Hurlstone and Hitch (2014) presented evidence to show that verbal and visuo-spatial STM rely on common principles for serial order representations - a primacy gradient, response suppression, and/or position marking. Taken together, the findings suggest that serial order is processed in functionally equivalent ways in both domains. This opens the question whether the verbal and visuo-spatial STM subsystems rely on common, shared mechanisms for serial order processing or whether they rely on ordering mechanisms that merely operate in functionally similar ways but are entirely dissociated. Moreover, a growing body of evidence suggests that serial order STM capacity and novel word-learning ability are related (Majerus et al, 2009; Leclercq & Majerus, 2010; Majerus & Boukebza, 2013). A recent proposal characterizes this relation as stemming from a common reliance on STM serial ordering mechanisms (Page & Norris, 2009).

Given this data, the present project aimed first to address the domain-generality of serial order processing and second, to address the commonality of serial ordering mechanisms in immediate serial recall and vocabulary acquisition. The reported findings indicating serial-order specific interference effects between verbal and visuo-spatial STM lend support to the notion of common, shared, ordering mechanisms between the two domains. Likewise, serial-order specific interference effects between visuo-spatial immediate serial recall and word-learning also indicate that domain-general, common ordering mechanisms are applied. Taken together, we propose that common ordering mechanisms underlie verbal and visuo-spatial STM, as well as aspects of novel word-learning. In light of well-established relations between phonological knowledge and vocabulary measures (Service & Craik, 1993; Service & Kohonen, 1995), we argue that aspects of novel word-learning depend on both verbal (phonological) STM and serial ordering processes. Moreover, for the purpose of the discussion below, we assume that learning a novel word-form is similar to learning a sequence of verbal information (e.g., syllables), which in turn depends on immediate verbal serial order STM (Page & Norris, 2009). However, the findings of Experiment 3 indicate that there are differences between digit sequence learning and novel word-learning in terms of the gradients of the Hebb effect. These qualitative differences suggest that the ordering mechanism may play a larger role in the Hebb effect for digit sequence learning as compared to in novel-word learning.

A review of the above mentioned mechanisms for serial order processing (i.e., primacy gradient, response suppression, position marking) had highlighted possible candidate processes that might enable common order representations between the two STM subsystems as well as the language system (i.e, for word-learning). Given that the primacy gradient mechanism codes order information conjointly with the representations of items within the STM store, and assuming dissociable memory subsystems for verbal and visuo-spatial stimuli, it has been argued that distinct primacy gradients would be applied to represent serial order across different STM domains. With regards to response suppression, a shared mechanism invoking central executive processes in order to suppress previously recalled items in the STM domains, has been hypothesized. However, central executive processes are generally under willful control, where as response suppression has been characterized as an unconscious process. As such, it has been argued that the mechanism of response suppression also operates distinctly within the two STM subsystems (Hurlstone & Hitch, 2014). Finally, positional marking implies that order information is coded separately from item information via positional context signals (e.g., Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1999; Henson, 1998b). Therefore, it has been argued that separate subsystems for verbal and visuo-spatial memoranda can exist, while complemented by common context signals that represent serial order across different STM subsystems (Hurlstone & Hitch, 2014). Such a conceptualization readily accommodates the present findings exhibiting serial order-specific interference between a verbal STM task and a concurrent visuo-spatial STM task (Experiment 2b).

While our data support the notion of a common mechanism for the representation of serial order across different STM domains and the language system, it is important to note the influence of domain-specific processes. For instance, several studies suggest that memory for visuo-spatial sequences is supported by Gestalt organization principles of visual perception. In particular, the spatiotemporal path formed by the locations of a visuo-spatial sequence has been found to affect serial recall. For example, when a sequence of locations is organized into spatial clusters, serial recall is better when the sequence path progresses through each cluster of locations relative to alternating between different clusters (*spatial clustering effect*; De Lillo, 2004; De Lillo & Lesk, 2010). Likewise, recall accuracy is higher when the distance between locations in a visuo-spatial sequence is shorter compared to when the distance is longer (*path length effect*; Guérard, Tremblay, & Saint-Aubin, 2009; Parmentier et al., 2005). Finally, the *path crossing effect* refers to the finding that sequences of locations containing crossings in the path formed by successive locations are recalled poorly relative to ones without path crossings (Parmentier et al., 2005). Also, immediate serial recall is better for symmetrical relative to non-symmetrical sequences (Rossi-Arnaud, Pieroni, & Baddeley, 2006). In this thesis, we report the visuo-spatial equivalent of the classic verbal repetition inhibition effect (Ranshcburg effect; Crowder, 1968), in which visuo-spatial sequences containing distant repeated items were recalled less well than ones with unique items. However, the pattern of recall errors for items subsequent to the repeated items did not match that found in the verbal domain (Experiment 1). This notable difference was attributed to shifts of spatial attention caused by the repetition of items within the visuo-spatial sequence. Along these lines, previous secondary-task interference studies have revealed that memory for spatial sequences is impaired by shifts of spatial attention and task-irrelevant eye movements (Lawrence, Myerson, & Abrams, 2004; Pearson & Sahraie, 2003; Smyth, 1996; Smyth & Scholey, 1994a; Tremblay et al., 2006). Domain-specific influences are also evident in the verbal domain, where serial recall has been found to be affected by lexico-semantic knowledge (Poirier et al., 2015). Future modeling of serial order mechanisms must incorporate such modality-specific processes. In line with this notion, Majerus et al. (2010) proposed that models of STM should assume that verbal and visuo-spatial STM subsystems rely on common, shared mechanisms for serial order processing which in turn communicate with domain-specific processing substrates involved in item-level memory representations (e.g., visuo-spatial and verbal STM, lexico-semantic LTM). Furthermore, based on the findings in this thesis (Experiment 3), it is argued that aspects of vocabulary learning, may also depend on item-level phonological representations in verbal STM in addition to common serial ordering mechanisms (see Figure 13 for a conceptual structure of the serial order mechanism).

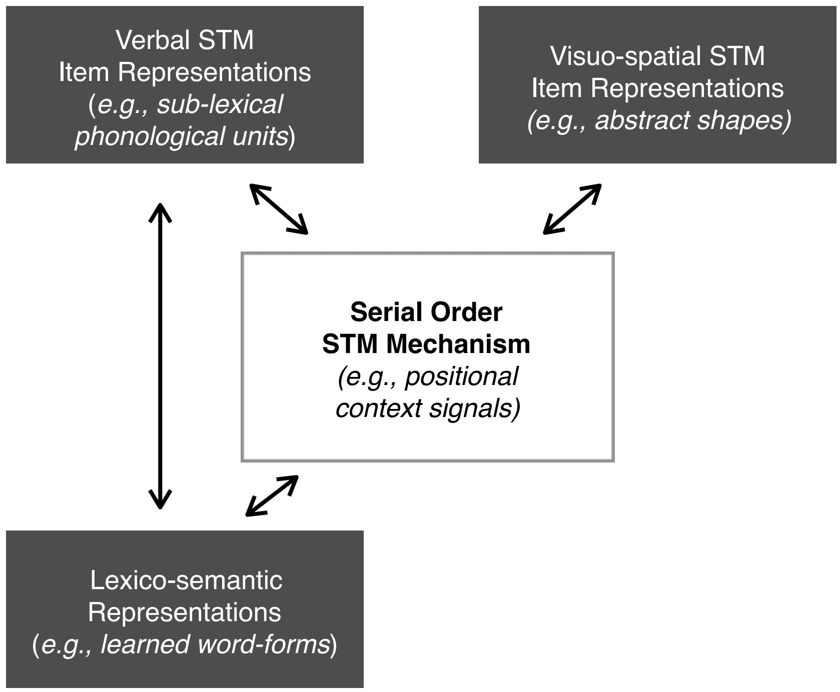

Figure 13. Conceptual framework characterizing the commonality of serial order in working memory and in the language domain. Domain-specific representations of item information are thought to interact bilaterally with a domain-general, common ordering mechanism (e.g., during immediate serial recall). Verbal item STM representations in conjunction with serial ordering mechanism interact with lexico-semantic representations in LTM (e.g., during word-learning). Specifically, repeated processing of sub-lexical phonological units in their correct serial order leads to LTM representations of whole word-forms. This conceptualization accounts for three patterns of data: a) dissociations between verbal and visuo-spatial STM subsystems, b) serial-order specific interference between verbal and visuo-spatial subsystems, and c) serial-order specific interference during visuo-spatial immediate serial recall and concurrent word-learning. Additionally, the reciprocal connections account for domain-specific and LTM effects on order memory.

The present project raises the question of what processes could be involved in a common ordering mechanism within the working memory architecture. Specifically, we must address whether serial order processing consists of a specialized substrate or whether it can be incorporated within the existing working memory architecture. The “episodic buffer” has been postulated to bind together information from different STM domains and LTM. Therefore, it has been proposed that a shared ordering mechanism based on principles of position marking may map directly onto the episodic buffer, while still remaining open to the integration of item information from different modalities as well as LTM (Hurlstone & Hitch, 2014). One productive approach is to use neuroimaging procedures to contrast STM tasks that either require serial order processing or the binding of cross-domain item information (memory for relational information), in order to address which common neural networks underlie both functions, and whether serial order processing encompasses a distinct neural substrate. Indeed previous work suggests that the hippocampus and medial temporal lobe represent the temporal order of events (e.g., Ginther, Walsh, & Ramus, 2011), and furthermore, are involved in establishing long-term representations of verbal sequences (Kalm, Davis, & Norris, 2013). Specifically, Kalm et al. (2013) have shown that voxels in the hippocampus gradually encode the identity of individual overlapping sequences over repetitions. Likewise, related research suggests that the medial temporal lobe and hippocampus are also involved in representing cross-domain relational information (Konkel & Cohen, 2009).

To summarize, the present project provided direct evidence concerning two related issues in the literature: a) that the two STM domains are subserved by common ordering mechanisms, and b) domain-general serial order STM mechanisms support vocabulary acquisition. These findings offer a novel approach to addressing vocabulary development and/or deficits that are rooted in inefficient serial order STM capacity. Critically, since serial order STM is argued to be a domain-general process, training programs can adopt a variety of non-verbal strategies to improve capacity for serial order learning and processing. This is particularly crucial for persons with specific language impairments, who have difficulty with phonological processing and thus are already at a disadvantage within the language module.

Future research must elucidate the functional role of serial order STM in novel-word form acquisition. One hypothesis suggests that serial ordering mechanisms are necessary to maintain the sequential structure of the sub-lexical items of a novel word-form (Martin & Gupta, 2004; Page & Norris, 2009). Relevant to this, it has been proposed that if sub-lexical segments of a novel word are represented as a sequence analogous to the items within STM serial recall tasks, then these sub-lexical segments within a word should exhibit the same hallmark features observed in STM serial recall tasks (e.g., classic error patterns; Gupta, 2003; Martin & Gupta, 2004). Therefore, one possibility is to study whether classic error patterns in STM serial recall tasks are also evident during the learning of novel word-forms and reflected in electrophysiological (EEG) event-related components.

Other questions that remain to be answered concern whether serial order STM plays a differential role in native language learning versus second language learning. Indeed, it must be noted that the present study tested undergraduate university students in a word-learning paradigm that may be more relevant to second language learning. This procedure required the mapping of a novel phonological word-form onto an existing word-form label in the native language, akin to second language learning. One possibility is to employ a word-learning procedure in which novel phonological word-forms must be associated to an unlabeled semantic referent (Gupta, 2003). Given that the correlations between serial order STM capacity and vocabulary acquisition in adults (Majerus et al., 2006; Majerus et al., 2008) also extend to children (e.g., Leclercq & Majerus, 2010; Majerus et al., 2006), another question of interest concerns whether serial order STM plays a different role early on in development versus later on in development. If serial ordering mechanisms are also employed to learn novel word-forms early on in development, then it may be argued that the processes underlying vocabulary development maintain their configuration throughout development. In sum, the current study opens new avenues of investigation for language learning by bridging two parallel lines of research in the working memory and language domains.

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Appendices

Appendix A: Sample visuo-spatial stimuli - Experiment 2a/b, 3

Appendix B: Sample stimuli in paired-associate word-learning task - Experiment 3

/ beauty / - / alagu /

/ bed / - / padukai /

/ earn / - / sambaathi /

/ door / - / kathavu /

/ night / - / rathiri /