WORKING MEMORY AND BILINGUALISM:
AN INVESTIGATION OF EXECUTIVE CONTROL AND PROCESSING SPEED

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Abstract

In order to investigate the possibility of a working memory (WM) advantage in bilinguals, a spatial WM task, Matrix span task, was developed and validated in Study 1. To be maximally sensitive to the specific processing differences that might be found between monolinguals and bilinguals, the task was non-verbal and based on spatial location information. The main requirement was to recall a series of locations in a fixed order, regardless of the random presentation order. The task was pilot tested with monolinguals and bilinguals in Study 2, and results showed that bilingual and monolingual young adults were matched on all the measures except for the Matrix Span task. Bilinguals scored significantly higher when the scores were calculated from the whole task, including the performance for the string length of 5 and 6. These results suggested that although bilingual young adults showed similar spatial memory capacity (forward Corsi Block), bilinguals outperformed monolinguals when the spatial task required higher levels for processing (rearranging the locations in the Matrix span task), confirming the hypothesis of the bilingual advantage in WM.

In Study 3, 49 monolingual and 45 bilingual young adults performed similarly on all measures of general intelligence, attentional control, processing speed, and attentional scope. The overall performance of the digit WM tasks showed no difference between the two groups, confirming their similar memory capacity. Against these similarities, however, there was evidence for bilingual advantages in performing the spatial WM tasks, especially when the task required higher levels of information processing demand (simple forward version), and when the attentional control demand was higher (complex sequencing version). Regression analysis showed that for monolinguals, both complex reaction time and distractor inhibition contributed to the variance in the WM performance, while for bilinguals, no clear pattern was found. Together these three studies showed bilingual advantages in spatial WM tasks with a different set of underlying abilities contributing to performance for each group. The results were discussed further in terms of their implications for the relationship between executive functions and WM.

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INTRODUCTION

Working memory (WM) refers to a limited capacity for temporarily maintaining information for use in ongoing mental operations (Baddeley & Hitch, 1974; Baddeley, 1986, 2007). The combined need for short-term storage and concurrent information processing is the hallmark of WM. As an everyday life example of WM, consider that you have less than 30 minutes to eat breakfast and take a shower. You are holding the information and plans about time in your WM and rapidly calculate the time needed for each task. You notice that making coffee will take about 10 minutes and toasting the bread will take 1 minute, and after some rapid computations about how fast you can take the shower, what time it presently is, whether or not you want to take the shower after eating, and if you want to toast the bread, you decide to make coffee before taking a shower and toast the bread after taking the shower. This rapid flow of information requires not just passive storage of facts, but generation of information and manipulation and evaluation of alternatives that are not readily captured by a passive storage system. This ability to both maintain information in a short-term store of limited capacity and simultaneously manipulate and process the information is the essence of WM.

WM underlies a broad range of cognitive abilities (see Baddeley, 1986, 2007, for reviews), and therefore plays an important role in contemporary global models of cognition (e.g., Cowan, 1995, 2005). Because of its centrality to so many domains of cognitive processing, individual differences in WM performance have been found to be related to such cognitive abilities as reading comprehension (Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Just & Carpenter, 1992), arithmetic (Adams & Hitch, 1997; Hitch & McAuley, 1991; Turner & Engle, 1989), following directions (Engle, Carullo, & Collins, 1991), problem solving (Passolunghi, Cornoldi, & de Liberto, 1999; Passolunghi & Siegel, 2001), reasoning (de Jong & Das-Smaal, 1995; Jurden, 1995; Kyllonen & Christal, 1990), note taking (Kiewra & Benton, 1988), bridge (Clarkson-Smith & Hartley, 1990), writing (Benton, Kraft, Glover, & Plake, 1984), as well as performance on the SAT (e.g., Turner & Engle, 1989), academic achievement (Gathercole, Pickering, Knight, & Stegmann, 2004; Hitch, Towse, & Hutton, 2001; Swanson, 1999), and most importantly, general intelligence (reviewed in Ackerman, Beier, & Boyle, 2005).

The relationship of WM and bilingualism is addressed in the dissertation. It has been indicated that bilingualism, defined as the regular use of two (or more) languages (Grosjean, 1992), is “more a rule than an exception on our planet” (Hartsuiker, Costa, & Finkbeiner, 2008). For example, English and French are recognized as “official languages” in Canada. But according to the 2006 census, in the Greater Toronto Area, the percentage of language spoken most often in the home was 56 for English, 2 for French, and 43 for other languages, including Chinese, Punjabi, Spanish, Italian, and more than 100 other languages. The increasing number of bilingual speakers all over the world has especially motivated growing awareness of bilingualism in research and clinical settings for the past decades and is now inside the mainstream of experimental cognitive psychology (Kroll & de Groot, 2005). Researchers agree that it is important to study not only behavior and cerebral structures associated with linguistic competence, metalinguistic knowledge, pragmatic ability, and motivation in the acquisition, learning, and use of verbal communication; but it is important also to study the cognitive consequences of bilingualism for cognition (e.g., Paradis, 2005).

A particularly exciting development in recent research is the bilingual advantage in executive control (e.g., Bialystok, Craik, Klein, & Viswanathan, 2004). Research suggests that both of their languages are active even when bilinguals are required to read (e.g., Dijkstra, 2005), hear (e.g., Marian & Spivey, 2003), and speak (e.g., Kroll, Bobb, & Wodniecka, 2006) one language alone. The activity of both languages when only one language is required, in the absence of a disruption to performance, suggests that proficient bilinguals have acquired not only linguistic proficiency but also the cognitive skill that allows them to juggle the two languages with ease (Kroll, 2008). Because WM has been highly correlated with attentional control, and bilingualism has been associated with an advantage in executive control tasks, one might expect a relationship between WM and bilingualism. Studies targeting the relationship between WM and bilingualism are necessary to test the tentative hypothesis of a bilingual WM advantage.

This introduction is organized in five parts. It begins with a brief summary about the history of memory and WM research. Next, tasks used to measure WM are reviewed with an introduction to the theoretical construct of WM. The third part summarizes underlying resources responsible for individual and developmental differences in WM performance, including executive control, focus of attention, and information processing speed. The next part summarizes the literature examining the influence of bilingualism on cognition, especially on executive control abilities and processing speed. After reviewing the current research findings on bilingual memory and bilingual WM performance, the introduction concludes with a hypothesis of a bilingual advantage in WM and a brief description of the 3 studies carried out.

Memory and WM Research: An Overview

Prior to the introduction of the term WM, theorists had distinguished between short-term and long-term memory (STM and LTM). The seminal model of memory proposed by Atkinson and Shiffrin (1968) included three memory "stores" – a sensory register, a short-term store, and a long-term store. Both STM and LTM were conceptualized as passive stores with STM having limited storage capacity and rapidly decaying traces. Information was hypothesized to flow from limited short-term storage into a large, more permanent long-term storage through strategies such as rehearsal. The notion that memory consists of two main compartments has been accepted in one form or another ever since (e.g., Craik & Levy, 1970), although many recent conceptions of human memory assume that STM is simply the activated portion of LTM (e.g., Anderson, 1983; Cowan, 1988; McClelland & Rumelhart, 1985). However, the unsatisfying aspect of such models is that they are largely structural and do not have a locus for the manipulation, transformation, and processing of information beyond rehearsal. Thus, the distinguishing feature of the WM construct as it is conceptualized today is that it integrates both the storage and the processing aspects of information, better reflecting the experience of consciousness.

In an attempt to encompass the more general notion of processes in memory, Atkinson and Shiffrin (1971) proposed a modification that involved a rather more complex STM system, comprising limited storage space and a number of control processes. The control processes could be used to encode information in LTM and to maintain information in STM. The short-term store was therefore seen as a working buffer rather than a passive storage system, and the control processes could include both verbal rehearsal and other coding strategies such as imagery. However the Atkinson and Shiffrin model (modal model) did not fully develop the notion of the control processes, and it was unclear why some processes led to better long-term retention than others.

Primary memory and secondary memory are also terms used to distinguish different types of human memory (e.g., Waugh & Norman, 1965). Williams James (1890) referred to primary memory as "the trailing edge of the conscious present", with a limited amount of information. In contrast, secondary memory was referred to as the vast amount of information stored from lifetime experiences. Waugh and Norman (1965) described primary memory as best illustrated by one's ability to recall verbatim the most recent few items in a list (recency effect). They assumed that the advantage for the most recent items occurred because those items were represented in primary memory whereas prior items, from the middle of the list, had been displaced from primary memory and entered into secondary memory. It was estimated on this basis that only a few items, approximately four, could be held in primary memory at a time (Broadbent, 1975; Cowan, 2001). However, an apparent problem for the idea of primary memory is that items at the beginning of a list also typically are recalled better than the middle items (primacy effect), although those initial items should have been displaced from primary memory and entered into secondary memory. Although criticism of the primary and secondary memory model has remained (e.g., Cowan, 2005), proponents of the more recent attentional control view of WM (e.g., Unsworth & Engle, 2007) have related these concepts to WM performance. It has been proposes that primary memory serves to maintain a distinct number of separate representations active for ongoing processing by means of the continued allocation of attention. In contrast, retrieval of information from secondary memory is a cue-dependent, competitive processes, and the key to success is ability to effectively delimit the search process to only relevant information through use of different cues and efficient strategies.

Another attempt to conceptualize human memory was provided by Craik and Lockhart (1972) with their notion of levels of processing. The idea was to emphasize the nature of processing of information rather than memory structures. Craik and Lockhart distinguished between physical features of stimuli, for example brightness and shape, which they classified as being subject to shallow levels of processing, and the semantic features such as meaning or associations, which would involve deep levels of processing. In a typical experiment by Craik and Tulving (1975), shallow processing involved classifying letters in words as being either in uppercase or lowercase, whereas deep processing involved judging whether a presented word could fit meaningfully into an incomplete sentence. Persistence in memory was related to depth of processing, in that processing material at a deep level resulted in better recall than did processing at a shallow level. Results suggested that the nature of the processing was more important than an intention to learn (e.g., Craik & Tulving, 1975). The system that allowed such maintenance was a flexible primary memory system that could deal with different processes as required by a given level (Craik & Lockhart, 1972). However, Craik and

Lockhart did not develop this particular aspect of the levels of processing approach, preferring to concentrate on the association between processing and subsequent retention in LTM.

Starting in the mid-1970s, experimental psychologists revised their perspectives on the architecture of the information-processing system, in particular shifting from an earlier focus on short-term storage, or STM systems, to a focus on WM. Baddeley and his colleagues (e.g., Baddeley & Hitch, 1974) explored aspects of the STM system using tasks that were different from the standard memory span paradigm (e.g., digit span task) of the previous several decades. Specifically, this revised paradigm was one that involved performance of two tasks at the same time (dual task paradigm). One task might be a simple span task, and the other would involve some decision making or recoding process (see Baddeley, 1998). From these kinds of experiments, Baddeley (1986, 1992) proposed a multicomponent model of WM that consists of three functionally independent subsystems: a phonological loop, which maintains speech-based information; a visuospatial sketchpad, which maintains nonverbal information; and a central executive, which coordinates cognitive operations.

Much of the research devoted to testing and refining the subcomponents of Baddeley's model has focused on the phonological loop and the manner in which speech-based material is rehearsed (see Baddeley & Hitch, 1994, for a review). The phonological loop involves temporary storage of phonological information in a form that decays over seconds unless refreshed by articulatory rehearsal, which is also believed to facilitate storage. Baddeley, Thomson, and Buchanan (1975) suggested that articulatory rehearsal explains the effect of word length on immediate recall, whereby polysyllables (e.g. university, refrigerator, opportunity) are harder to recall than monosyllables. This effect can be removed by articulatory suppression, the requirement to utter repeatedly an irrelevant word such as 'the'.

The visuospatial sketchpad is assumed to be capable of holding and manipulating visual and spatial information. Although the mechanisms involved in the rehearsal of visual and spatial information are less thoroughly investigated, it has been suggested that imagery or eye movements may play a role in maintenance of visuospatial information (Baddeley, 1992; Cornoldi & Vecchi, 2003; Logie, 1995). The use of spatial imagery in immediate recall is disrupted by tasks such as tracking a moving object (Baddeley et al., 1975; Baddeley & Lieberman, 1980), and memory for pattern and shape are disrupted by the passive processing of line drawings or even color patches (Logie, 1986, 1995).

The central executive is the most important but least understood component of the multicomponent model. It is conceptualized as a limited-capacity attentional control system. Baddeley (1996) attempted to fractionate the central executive by proposing several separate executive capacities, including those of focusing and dividing attention and possibly of attentional switching, although the latter may not be a unitary function (Baddeley, Chincotta, & Adlam, 2001). It was suggested by Baddeley and Logie (1999) that the executive should be conceptualized purely as an attentional system without capacity for storage. This, however, created problems such as how the three components of WM could be combined and then linked to LTM in the absence of any common storage system.

Baddeley (2000) recently proposed a fourth subsystem, the episodic buffer. It is described as a limited capacity system that provides temporary storage of information held in a multimodal code, which is capable of binding information from the subsidiary systems and from LTM into a unitary episodic representation. The revised model differs from the original one principally in focusing attention on the processes of integrating information with LTM, rather than on the isolation of the subsystems. In so doing, it provides a better basis for tackling the more complex aspects of executive control in WM.

Measurement of WM

Interpretation of the research findings on WM depends heavily on the tests used to measure this construct. Before introducing additional research findings on WM, a brief review of WM tasks is provided. Simple span tasks have been used extensively over the last 100 years in an attempt to gain a better understanding of memory processes and individual differences therein (see Dempster, 1981, for review). In these tasks, participants are presented with to-be-remembered items (such as letters, digits, or words) that they have to recall in the correct serial order. Recently, interest has shifted to modified versions of these tasks known as complex span tasks. Like simple span tasks, complex span tasks require participants to recall a set of items in their correct serial order, however, they differ from simple span tasks in that some form of processing activity is interleaved between the to-be-remembered items.

One type of complex span task, the dual-task paradigm, has been used widely in WM research (for a review, see Hegarty, Shah, & Miyake, 2000). In particular, this paradigm has been used within the framework of Baddeley's (Baddeley & Hitch, 1974) model of WM. In the dual-task paradigm, a cognitive task (a primary task) is performed both by itself and concurrently with a secondary task considered to tap one of the subcomponents of WM. If the secondary task disrupts performance on the primary task (relative to the condition in which the primary task is performed alone), it is inferred that the WM subcomponent tapped by the secondary task is involved in performance of the primary task. For example, the articulatory suppression technique selectively disrupts performance on verbally mediated tasks, such as immediate serial recall and mental arithmetic, which points to the involvement of the phonological loop in these tasks (Baddeley & Logie, 1999; Gathercole & Baddeley, 1993). Similarly, spatial tapping (i.e., tapping the four corners of a square in sequence) has often been used as a secondary task for the visuospatial sketchpad (particularly its spatial, as opposed to its visual aspects), and this impairs performance on various visuospatial tasks, such as mental rotation (Logie, 1995).

Recently, the dual-task paradigm has been used to examine the role of the central executive in various complex cognitive tasks. The secondary task most widely used in this context is oral random generation (Baddeley, 1986), which requires participants to continuously generate a series of numbers or letters in as random an order as possible. This task is considered to tap the central executive because it requires actively monitoring candidate responses and suppressing responses that would lead to systematic sequences, such as 1-2-3-4 or a-b-c-d (Baddeley, 1996). The mental retrieval of responses from the total number of possibilities might constitute an additional and independent source of central executive involvement (Towse, 1998). Several recent studies have shown that random generation interferes with performance on a host of complex cognitive tasks (Salway & Logie, 1995).

Hegarty et al. (2000) examined the effects of different secondary tasks on performance of visuospatial tasks. The decrement in performance on these tasks, when they were paired with secondary executive tasks, was smallest for the secondary task considered to most heavily involve the central executive and largest for the secondary task considered least demanding of executive mechanisms. The authors proposed that, when applied to the assessment of central executive involvement, the prevalent simple dual-task logic does not always apply and needs to be used cautiously when the secondary task is as complex and demanding as random number generation. Special conditions that limit application of the dual-task methodology include two inherently related factors – a response selection bottleneck and a strategic tradeoff between primary and secondary tasks. In conclusion, the results of the Hegarty et al. (2000) study provide useful constraints on the types of so-called executive tasks that may or may not be used as secondary tasks for testing the central executive component of WM, depending on the nature of the primary task of interest.

Unlike the dual-task paradigm, another type of complex span tasks aims to capture the dynamic between memory and ongoing mental processing (e.g., Case, Kurland, & Goldberg, 1982; Daneman & Carpenter, 1980). These complex WM tasks require temporary maintenance of information during a processing activity such as counting, reading, or arithmetic. For example, in Daneman and Carpenter's (1980) reading span task, participants first read a set of unrelated sentences and then attempt to recall the final word of each sentence. Reading span reflects the number of sentences that can be read and understood and followed by successful recall of all final words. Research into reading span has shown that it correlates with measures of complex cognition, and the correlations often are stronger than those using standard assessments of STM such as word span and digit span (see Daneman & Merikle, 1996). Operation span is conceptually similar to reading span, requiring individuals to calculate or verify answers to arithmetic problems and to remember these answers (or experimentally supplied words that follow each problem). Operation span also exhibits strong relationships with complex cognition, including reading skill, and this result has been used to argue that complex WM span tasks incorporate a domain-general process (Conway & Engle, 1994; Turner & Engle, 1989). In an attempt to maximize the utility of these complex WM tasks, Conway, Engle, Kane, and colleagues (Conway, et al., 2005) produced a methodological review and user's guide to WM tasks. The authors indicated that other than standardized instruments, such as intelligence test batteries, WM span tasks are among the most widely used measurement tools in cognitive psychology. They suggested that methodologically, WM span tasks have proven to be both reliable and valid measures of WM capacity. Conway et al. (2005) believe that WM capacity is an important individual-differences variable and accounts for a significant portion of variance in general intellectual ability.

However, other than the complex span WM tasks, WM tasks in the literature, such as running memory, keeping-track, and *n*-back tasks, present quite different levels of cognitive demands. Specifically, these more dynamic tasks of immediate memory require participants to monitor a continuous stream of stimuli, often of uncertain length, and to respond according to only a subset of the stimuli presented. The participants in these tasks must, therefore, continuously update their mental representation of the target items while also dropping now-irrelevant items from consideration. So, like WM span tasks, some demanding processes are required in addition to storage. For example, the running-memory span task presents stimuli in lists of unknown length, and subjects must recall only the last *n* items (the pre-specified, variable memory load). Thus, the subjects retain only the most recent *n* items that are presented and continuously drop items from the maintenance/rehearsal set once the list length exceeds *n*. Similarly, the keeping-track task presents a list of items of unknown length and from *n* categories, and participants retain only the most recent exemplar of each category. The *n*-back task presents a list of items in which participants must continuously report whether each item matches the one that had appeared *n* items ago in the stream (*n* typically ranges from 1 to 4). In a two-back task, for example, subjects must continuously maintain the last two items in the list, updating this memory set with each new item and dropping out the least recent one.

Little research has contrasted these dynamic WM tasks with other WM or STM capacity tasks. In one study, the keeping-track task appeared to be a valid index of WM capacity. Using factor analyses, Engle, Tuholski, Laughlin, and Conway (1999) showed that the keeping-track task had reasonably high loadings on the WM capacity factor (consisting of WM span tasks), low loadings on the STM capacity factor, and correlations with fluid intelligence scores of similar magnitude to those in the WM span task.

Although the *n*-back task is arguably the current "gold standard measure of WM capacity" in the cognitive neuroscience literature (for a review, see Kane & Engle, 2002), almost no behavioral research has been conducted to validate it. The only study that has compared *n*-back with other immediate-memory tasks (Dobbs & Rule, 1989) found the two-back task to correlate strongly with simple digit span and only modestly with a one-back task. Thus, the *n*-back task may be a more appropriate indicator of the construct measured by STM capacity, rather than by WM capacity tasks, but more research is obviously needed.

Although complex WM tasks are widely used in the literature, some researchers believe that both simple and complex span tests reflect the temporary storage of information (e.g., de Jonge & de Jong, 1996). De Jonge and de Jong (1996) cast serious doubts about the reliability of the complex span tests in children. They argued that because processing speed does not underlie performance on complex span tests, it is very likely that the additional processing requirements in complex span tests (reading sentences) lead only to longer intervals between the material (words) that has to be remembered (for evidence, see Towse & Hitch, 1995). Additionally, Ackerman et al. (2005) claimed that "far too little information is available that provides an account of how overall performance should be assessed" in the complex span tasks. For example, in the reading span task, the number of words recalled was used as an index of WM performance, but the performance on sentence reading was not taken into consideration for the WM evaluation.

An understanding of the tasks used to measure WM is important because they provide a basis for understanding the nature of WM. For example, there is debate about the construct of WM itself, and this discussion is highly related to the tasks used to measure WM performance. It has been proposed that the content facet of the hypothetical structure of WM has three categories: verbal, visual-spatial, and numerical (e.g., Daneman & Tardif, 1987). These three categories are reliably found in research on intelligence structure (Carroll, 1993), and since there seems to be a close relationship between intelligence constructs and WM capacity (e.g., Kyllonen & Christal, 1990), it is believed that a similar differentiation on the content facet is reasonable. However, two parallel tasks measuring WM in the verbal and the numerical domain, respectively reading span and operation span, have correlated quite highly in some studies (Turner & Engle, 1989) but relatively low in others (Jurden, 1995). A differentiation between WM with verbal and with spatial material is strongly suggested by some researchers (Daneman & Tardif, 1987; Shah & Miyake, 1996). However, recently, Swanson (1996) did not find evidence for separate verbal and spatial factors in a study with children. Oberauer, Su¨ß, Schulze, Wilhelm, and Wittmann (2000) also showed that there was no dissociation between the verbal and the numerical domain, because differentiations of WM along the content dimension were found between spatial and non-spatial tasks, but not between verbal and numerical tasks.

With regard to the function facet of WM, it is believed that central executive function is important (Baddeley, 1986). WM monitors and controls ongoing mental operations and actions, selectively activating relevant representations and processes and inhibiting irrelevant ones. WM has also been associated with the function to coordinate information elements into structures (Halford, Wilson & Phillips, 1998; Robin & Holyoak, 1995). Coordination requires simultaneous access to several distinct elements in order to attach them to their respective roles as arguments in relations, and this should be distinguished from other coordination concepts discussed in the context of the central executive of WM, e.g., the coordination of information from different sources (Yee, Hunt & Pellegrino, 1991), or the coordination of two tasks in a dual task combination (Baddeley, 1996).

Examining 23 WM tasks from the literature, Oberauer et al. (2000) confirmed that WM capacity is differentiated theoretically along two dimensions: content and function. Regarding the content facet, spatial WM was clearly distinct from the verbal and numerical content categories, although a distinction between verbal and numerical WM was not warranted. This is in agreement with the literature, in which differentiations of WM along the content dimension were mainly found between spatial and non-spatial tasks (Daneman & Tardif, 1987; Shah & Miyake, 1996; Smith & Jonides, 1997), but not between verbal and numerical tasks (Turner & Engle, 1989; Kyllonen & Christal, 1990). On the functional dimension, the category of central executive was clearly a separate function. However, the categories of simultaneous storage and transformation and of coordination could not be separated. Therefore the choice of WM tasks for a particular study is important because it could capture different content and function of WM systems. In this study, both the content and function facet of the WM construct is tailored to the research purpose. Specifically, digit and spatial WM tasks, but not tasks using actual words, were chosen as the contents for the main experimental WM tasks. Because bilinguals sometimes show disadvantage in verbal retrieval tasks, a verbal WM task might not be an appropriate measure of WM. The executive and transformational levels of processing are manipulated to examine the effect of executive control involvement in the WM tasks.

Sources of Difference in WM Performance

In 1974, Alan Baddeley and Graham Hitch first proposed a model of WM that comprised separate, limited-capacity storage and processing components. Although the multicomponent model of WM by Baddeley and Hitch (1974; Baddeley, 2000) has remained influential, a range of alternative WM models has been proposed (see Miyake & Shah, 1999 for review). Research has attempted to identify the underlying sources for individual and developmental factors for WM performance (see Conway, Jarrold, Kane, Miyake, & Towse, 2007 for review). One of the aims of the dissertation is to explore the different factors affecting WM performance. The following section will focus on several of these sources in the current literature.

Limited Mental Resources

The first investigation of the individual-difference correlates of WM measures was provided by two studies of reading comprehension reported by Daneman and Carpenter (1980). The authors found a substantial correlation ($r = .72$) between the WM measure (reading span task) and the reading comprehension measure, although the authors later agreed that "a legitimate concern about the reading span test is that it is too much like reading comprehension itself" (Daneman & Tardif, 1987). Daneman and

Carpenter (1980) assumed that WM has processing as well as storage functions; it serves as the site for executing processes and for storing the products of these processes. If the processing interfered with storage, the poor reader's less efficient processes would appear as equivalent to a smaller storage capacity. The argument has been that a major difference between good and poor readers is the efficiency of their processing, rather than static memory capacity.

In line with this view by Daneman and Carpenter, Miyake and colleagues (e.g., Shah & Miyake, 1996) construed WM as consisting of flexibly deployable, limited cognitive resources, namely activation, that support both the execution of various symbolic computations and the maintenance of intermediate products generated by these computations (Just & Carpenter, 1992). Therefore, WM constraints exist in the maximum amount of activation that one has available for allocation to the processing and storage functions. These constraints manifest themselves mainly in the form of processing slowdown, the gradual loss of critical information, or both under capacity-demanding situations. This resource-based conception of WM assumes different types of cognitive processes might be fueled by different pools of WM resources (Daneman & Tardif, 1987; Shah & Miyake, 1996). In addition to the pool of domain-general resources, another possibility is that there are one or more additional domain-specific resource pools that are relatively distinct from those supporting spatial and language processing (Shah & Miyake, 1996).

Data from both children and adults have challenged aspects of the resource-sharing account of WM (e.g., Towse, Hitch, Hamilton, Peacock, & Hutton, 2005), and some of these studies question the necessity of a resource tradeoff between storage and processing. Towse and colleagues (2005) proposed a task-switching model of WM as an alternative. According to this approach, processing and retention operations occur sequentially. As a result, retention declines with the opportunity for forgetting during intervals occupied with processing (see also Ransdell & Hecht, 2003).

Attentional Control Abilities

Hasher and Zacks (1988) suggested that adult age differences in WM abilities result from deficits in inhibitory function, or efficacy of inhibitory mechanisms (May, Hasher, & Kane, 1999). They argued that WM involves not only the storage and manipulation of "information that is along the goal path," but also inhibitory mechanisms that prevent the entrance of "off-goal-path" information (Hasher & Zacks, 1988, p.201). They hypothesized that age differences in WM result from interference caused by older adults' decreased ability to inhibit irrelevant information. A similar suggestion has been offered regarding inhibitory deficits in children (Dempster, 1992; Tipper, Bourque, Anderson, & Brehaut, 1989).

Within this framework, WM appears as an important source of individual differences in cognitive processing. Individual differences in WM are conceptualized in terms of the ability to monitor attentional resources, i.e., WM capacity (Engle, Kane & Tuholski, 1999). Engle has defined WM capacity as "the ability to control attention to maintain information in an active, quickly retrievable state" and "is not directly about memory" (Engle, 2002, p.20). Engle and colleagues argue that the WM capacity captures the mechanisms that account for most of the covariation between a variety of WM tasks, , and between tasks of higher level cognition, such as reading comprehension and reasoning. This domain-general view is also supported by research on children aged 5-19 years old (Swanson, 1996). Declines and growth in WM capacity are much more pronounced in the central executive than in storage subsystems for older adults (Park & Payer, 2006) and children (e.g., Bayliss, Jarrold, Gunn, & Baddeley, 2003; Case et al., 1982; Gathercole & Pickering, 2000; Hitch, et al., 2001; Kail & Hall, 2001).

Engle, Kane et al. (1999) argued that individual differences in performance on complex WM tasks are primarily due to differences in the central executive component of WM, whereas in the case of simple span task performance they are primarily due to differences in domain-specific abilities such as chunking and rehearsal (in particular, verbal span tasks). In the last few years, this explanation has gained greater acceptance (Friedman & Miyake, 2004). Using complex WM tasks, Engle and colleagues (e.g., Kane & Engle, 2002) have demonstrated that the performance of low span participants under interference conditions can be simulated by dividing the attention of high span participants. This is consistent with the idea that attention-control ability is the source of individual differences between high and low WM participants. They view WM as consisting of a subset of activated LTM units, some of which are highly active and are in primary memory.

Furthermore, neuroimaging studies have revealed that WM is particularly dependent on cells in the prefrontal cortex, a region of brain that traditionally has held a prominent status in high-order, complex goal-directed human behavior (Kane & Engle, 2002). Simple span tests (e.g., digit span) are considered to exhibit greater dependence on the posterior cortex (D'Esposito & Postle, 2002a). When information has to be manipulated, however, increased prefrontal activity is found (D'Esposito, Postle, Ballard, & Lease, 1999). The manipulation-related processes ascribed to the dorsolateral prefrontal cortex are fundamentally extramnemonic in nature. They play a fundamental role in the exercise of executive control of WM, but they do not govern storage per se of the information held in WM (D'Esposito & Postle, 2002b).

Focus of Attention

The concept of focus of attention in understanding WM was proposed by Cowan (1995) as a means of understanding WM. While recent literature on the link between attention and WM has focused on the control of attention, Cowan suggested that a meaningful measure of WM depends on an emphasis on another dimension of attention, i.e., the focus of attention, which is viewed as a capacity-limited attention component (Cowan et al., 2005). Cowan suggests that the focus of attention can zoom out to handle roughly four separate pieces of information or it can zoom in to focus on only one piece, and that the capacity of WM is the capacity of the focus of attention at any given moment (Usher & Cohen, 1999). A developmental study by Cowan et al. (2005) showed that scope-of-attention measures correlate well with WM and aptitude measures (American College Test composite scores for adults and Cognitive Abilities Test composite scores for children). Therefore, both the basic scope of attention itself and the management of attentional resources may be distinctive features of WM functioning.

Cowan and colleagues (e.g., Cowan et al., 2005) argued that the critical aspect of successful WM measures is that rehearsal and grouping processes are prevented, allowing a clearer estimate of how many separate chunks of information the focus of attention can circumscribes at once. Complex span tasks (such as reading span) correlate with aptitudes, according to the view of focus of attention, largely because the processing task (sentence reading) prevents rehearsal and grouping of items to be recalled. It has been shown that several attention scope measures that do not include a separate processing component, but nevertheless prevent efficient rehearsal or grouping, also correlate well with aptitudes and with complex span measures.

Cowan believes that management of limited attentional resources is a distinctive feature of WM functioning. This suggestion of an invariant capacity for processing information is very similar to the neo-Piagetian position, initiated by Pascual-Leone (e.g., 1970). In this model (Pascual-Leone, 1970, 1987), mental attentional capacity (M-capacity) increases from one to seven units (or chunks) between 3- and 15-years of age, yielding stages of 2-year duration. In particular, the model introduces a distinction between the "field of mental attention" and the "field of WM or centration" (Pascual-Leone & Ijaz, 1989). Case's model (1985, 1992), which also aimed at integrating Piaget's theory with concepts of memory and attention, suggests that cognitive development between 4-months and 19-years consists of four major stages (sensorimotor, interrelational, dimensional, and vectorial operations), each of which is divided into three substages (unifocal, bifocal, and elaborated). These substages differ by the number of elements represented, and the transition of one stage to another stage takes place by a process of hierarchical integration of executive structures. Children's capability for hierarchical integration is determined by the size of what Case labeled the "short-term storage space" (number of schemes that can be stored or processed), the growth of which is due to an increase in operational efficiency.

Processing Speed

On another view, researchers have argued that differences in information processing speed are the cause of differences in WM performance. Some of these researchers have focused on the relationship between individual differences in speed and individual differences in WM (e.g., Miller & Vernon, 1992), whereas others have focused on the relationship between age differences in speed and age differences in WM (e.g., Salthouse, 1996).

A possible explanation for the role of speed in individual and age differences in WM is suggested by the observation that the longer that words take to pronounce, the fewer that can be recalled. This may be taken to imply that any source of difference in rehearsal rate, whether it is attributable to characteristics of individual items or to age and individual variations, will affect WM. Consistent with this idea, developmental differences in children's rehearsal rates are good predictors of developmental differences in memory span (e.g., Kail & Park, 1994).

Notwithstanding its primitive status as a cognitive mechanism, speed of processing appears to be a critical variable underlying function in WM in the adult lifespan (e.g., Salthouse, 1994). Salthouse (1991) demonstrated that although many of the age-related differences in fluid cognition appear to be mediated by age-related reductions in WM, these reductions may in turn be largely mediated by age-related reductions in the speed of executing simple processing operations. This is consistent with findings in children (Kail & Park, 1994), for whom the age-related change in processing time was associated with a decrease in the time required to articulate numbers and letters, which increased their memory span. Kail and Park (1994) also found that these age-related effects were greater in early and middle childhood than in late childhood and adolescence. Fry and Hale (1996) found that the relationship between age and WM was mediated primarily by age-related improvements in speed (7-19 years old). Speed had no direct impact on intelligence and was mediated instead by WM. It is worth noting that in Hitch et al.'s (2001) study with children, controlling for speed of processing did not eliminate all age differences in 9- to 11-year-old children's WM. However, age-related changes in processing speed are well established (Kail, 1991) and appear to be a unitary developmental phenomenon. That is, processing speed improves with age across all domains of cognitive function during childhood (Kail, 1988; Kail & Park, 1992).

In sum, it is well-accepted that WM is limited in nature (e.g., Daneman & Carpenter, 1980; Sohn & Doane, 2003), to the extent that only a limited amount of information can be activated within the focus of attention (Cowan, 1995). Further, its limitations are due to different factors such as susceptibility to interference (Engle, Kane et al., 1999; Hasher & Zacks, 1988; Elliott, Barrilleaux, & Cowan, 2006), coordination efficiency (Oberauer, et al., 2000), processing speed (Salthouse & Meinz, 1995; de Ribaupierre & Lecerf, 2006) and the skill to encode the presented information in an accessible form in long-term WM (Burgess & Hitch, 2005; Ericsson & Kintsch, 1995). Although understanding of these sources is far from attained, the present dissertation aims to investigate the influence of three of these sources on WM: (a) executive control, the ability to allocate attention to the relevant task; (b) scope of attention, the ability to focus attention on task-relevant information; and (c), speed of information processing, the ability to monitor and coordinate incoming information within limited amount of time.

Bilingualism and Cognition

Bilingualism and language acquisition have been intensively studied in the literature (for a review, see Kroll & de Groot, 2005). Bilingual experience may have an impact beyond language. The important work by Peal and Lambert (1962) was among the first to show positive advantages of bilingualism on both verbal and non-verbal intelligence tests in children. The authors concluded that the experience of having two languages to describe the world gave the 10-year-old bilingual children "...a mental flexibility, a superiority in concept formation, and a more diverse set of mental abilities, in the sense that the pattern of abilities developed by bilinguals were more heterogeneous" (p. 20). Therefore, bilingualism has been systematically associated with more facility in concept formation and a greater mental flexibility (e.g., Diaz, 1985).

However, not all studies have pointed to the positive influences of bilingualism on the measurement of intelligence (for example, Darcy, 1963). Negative findings on the effects of bilingualism frequently have stemmed from differences in methods of investigation and the difficulty of separating the impact of language experience from educational, cultural, and socioeconomic status. For example, Ben-Zeev (1977) compared 5- and 7-year-old bilingual children with their monolingual peers and showed that in spite of lower vocabulary level, bilinguals showed more advanced processing of verbal material, more perceptual distinctions, a greater propensity to search for structure in perceptual situations, and a greater capacity to recognize their perceptions in response to feedback. However, when comparing 21- to 25-year-old multilingual and non-multilingual participants, Papagno and Vallar (1995) found comparable performance level across the groups on tasks assessing general intelligence and learning.

In recent decades most cognitive development studies have shown a positive influence of bilingualism. That is, learning a second language in childhood is associated with an increase in cognitive abilities and mental processes relative to those of monolingual children (for reviews see Diaz & Klingler, 1991; Francis, 1999). Bilingual advantages for cognitive abilities include intelligence (Hakuta & Diaz, 1985; Hsieh & Tori, 1993), creativity, analogical reasoning, classification skills (Diaz, 1985), learning strategies (Bochner, 1996), and thinking flexibility (Lambert, Genesee, Holobow, & Chartrand, 1993).

Despite the fact that the association between bilingualism and general intelligence sometimes shows different patterns across studies, the language-related cognitive advantages of bilingual children have been replicated (see Bialystok, 2001, 2005 for review). For example, bilinguals are more advanced than monolinguals in perceiving names as attributes of things they name (Feldman & Shen, 1971), and in understanding the arbitrary nature of name-object relations (Ianco-Worrall, 1972).

Cook (1997) reviewed the consequences of bilingualism for cognitive processing from both the Subtractive and the Additive view and concluded that the cognitive consequences of being bilingual are a question of swings and roundabouts. "The slight cost of bilingual deficit on language processing is offset by the slight gains on other cognitive processes, without mentioning all the other gains of bilingualism in people's lives." (p. 294). Cook proposed that the more complex system involving two languages may confer both benefits and losses in cognitive areas other than language. Furthermore, he suggested that bilinguals and monolinguals may think in different ways.

Currently in the research area of bilingualism and cognition, there is evidence that the bilingual advantage extends to performance on non-verbal executive function tasks, and this has been replicated recently in a wide range of age groups. Considering the bilingual advantage in certain executive functions and the close relationship between executive functions and WM, it leads to the question of whether or not the bilingual advantage could extend to WM performance. The following section will include a brief review of the literature on the influence of bilingualism on executive functions and information processing speed, followed by a summary of bilingual memory research, with a focus on the comparison of WM task performance between monolinguals and bilinguals.

Bilingualism and Executive Functions

Executive functions include higher-order cognitive processes necessary for goal-directed behavior. Although there is no consensus regarding executive function taxonomy, researchers generally agree that executive function is a multidimensional construct (Diamond, 2006; Miyake et al., 2000; Norman & Shallice, 1986), including processes such as planning, cognitive flexibility, decision making, task management, response inhibition, conflict resolution, working memory, and planning (Smith & Jonides, 1999). For example, Miyake et al. (2000) proposed three central components:

inhibition, updating, and switching. Inhibitory control involves ability to resist a prepotent response to a stimulus and instead give an appropriate one. Updating generally refers to the updating and monitoring of information in WM. Switching ability reflects cognitive flexibility, and is the ability to shift back and forth between mental sets.

Previous research has demonstrated that active use of two languages leads to a bilingual advantage in non-verbal executive function tasks across the life span. For children as young as 2.5 years old, bilinguals showed better performance on the Luria tapping task (Barac, Bialystok, Agnes, & Poulin-Dubois, 2008); 5- to 7-year old bilingual children made fewer errors on the Flanker task (Bialystok, Luk, & Feng, in preparation; Mezzacappa, 2004; Yang & Lust, 2005), and responded faster on the Simon task (Marcoux, Colozzo, & Johnston, 2005; Martin-Rhee & Bialystok, 2008) . Carlson and Meltzoff (2008) showed better performance of bilingual children on tasks that appeared to require managing conflicting attentional demands, for example, the dimensional change card sort task (also in Bialystok & Martin, 2004). Advanced development of bilinguals relative to their monolingual peers has also been evident on theory of mind tasks (Bialystok & Senman, 2004; Goetz, 2003; Kovacs, in press).

For young adults, bilinguals showed fewer global switching costs in an adapted number version of the Stroop task (Bialystok, Feng, & Cepeda, submitted). Similarly, using the Attention Network Task (ANT), Costa, Hernandez, and Sebastián-Gallés (2008) showed that young adult bilinguals benefited more from the presentation of an alerting cue and were also better at resolving conflicting information. In elderly bilinguals, an advantage has been shown on the Simon (Bialystok et al., 2004) and Stroop tasks (Bialystok, Craik, & Luk, 2008). It has also been found that bilingualism is one of the protecting factors for cognitive aging, such that elderly bilinguals showed symptoms of dementia four years later than monolinguals did, when they were equivalent on all other measures (Bialystok, Craik, & Freedman, 2007).

Language research has shown consistently that both languages are always active for bilinguals (e.g., Costa, 2005; Dijkstra, Grainger, & Van Heuven, 1999; Hoshino & Kroll, 2008). Therefore a control mechanism is necessary for bilinguals to assure that the appropriate language is used in certain conditions when communicating. It has been proposed that this control mechanism is the ability to inhibit or ignore the non-target language (Abutalebi & Green, 2007; Green, 1998). Bialystok and colleagues (e.g., 2001; Bialystok, Craik, & Ryan, 2006) interpreted the advantage of bilinguals on non-verbal executive function tasks as result of the constant exercise of attentional control that provides bilinguals with an enhanced ability to ignore distracting and irrelevant stimuli. This cognitive ability is believed to have generalized from experience in managing the use of more than one language over the lifespan.

These bilingual advantages have been demonstrated using a wide variety of tasks for which the specific executive function demands differ. Bilinguals outperformed monolinguals on conditions involving conflict, but conditions for which conflict was not central were performed similarly by all participants, implying a role for attentional control to resolve the conflict. For example, using the ANT task, Costa and colleagues (2008) found that bilinguals performed better on conditions requiring conflict resolution and alertness, with no group differences on conditions requiring orientation, which is also considered to be part of executive functions. Until now, it was not clear whether the influence of bilingualism would extend to all components of executive functions or only to some.

Bilingualism and Processing Speed

As cognitive flexibility may be a core advantage of bilingual experience (e.g., Peal & Lambert, 1962), and better performance is usually most evident on tasks that require resolving conflicts under time pressure, another alternative is that processing speed may provide a common mechanism underlying a bilingual performance advantage. In a study by Kohnert and Windsor (2004), 8- to 13-year old monolingual and bilingual children were given simple and choice versions of auditory- and visual-RT tasks, with each task including four levels of motor difficulty, but invoking minimal cognitive demands by having participants respond with the preferred or nonpreferred hand or foot. Results revealed no significant differences between language groups in each of the four tasks. The relative increase in cognitive demands when children were required to make a decision about stimuli as well as perceive and encode the stimuli is well in line with previous literature indicating longer RT in choice than simple nonlinguistic tasks (Cerella & Hale, 1994). However, the bilingual children were significantly slower than the monolingual children on a picture naming task (Windsor & Kohnert, 2004). Another study that examined 5-7-year-old monolinguals and bilinguals on the Trail Making task (Bialystok, submitted) showed a bilingual advantage in completion time. School-age bilingual children took less time to complete the both the Trails A and Trails B tests, although the difference score (usually an index of executive control in neuropsychological assessment) showed no group differences.

The Kohnert and Windsor (2004) study might be the only one that has administered standard elementary cognitive tasks to bilingual samples. Previous research has shown faster responses for bilinguals in non-verbal executive function tasks for children (e.g., Martin-Rhee & Bialystok, 2008), young adults, and elderly adults (e.g., Bialystok et al., 2004). In all these tasks, bilingual and monolingual groups have been matched on other background measures, such as general intelligence. Many of the tasks that are sensitive to bilingualism rely on speed of response, either by using RT directly as a performance measure or by imposing time constraints on the participant. However, it should be noted that even though bilingual RTs are faster in certain non-verbal executive function tasks, they are consistently slower in processing speed tasks involving verbal stimuli, for example, color word naming (Johnson, 1986). Nonetheless, when asked to categorize color patches by button pressing, there were no group differences. The slower response time for bilinguals in naming tasks might be explained by the complexity of the bilingual mental lexicon (Heredia & Brown, 2006): it takes more time to search for a target in a more complex system.

Based on the few studies available in the literature, it appears that bilingualism is associated with faster RTs in some conflict conditions in cognitive RT tasks. There is not enough empirical evidence, however, to conclude that bilingualism has an effect on information processing speed. Bilingualism seems to influence speed performance in some tasks but not others. In the non-verbal domain, it appears that bilinguals have faster

RTs in the more complex non-verbal processing speed tasks, but showed performance similar to monolinguals in simple non-verbal processing speed tasks. More research in this area is needed to draw conclusions about possible effects of bilingualism on information processing speed.

Bilingualism and WM

Since WM performance has been highly correlated with attentional control abilities, and bilingualism has been associated with an advantage in certain executive function tasks involving conflict resolution and set switching. Thus some positive influence of bilingualism on WM may be expected. Recent studies have found some positive influences of bilingualism on cognitive abilities, but the relationship between bilingualism and WM is still far from clear. In this section, a brief review of bilingual memory research will be provided, followed by discussion of the most recent research findings on bilingual WM.

Bilingual Memory

Bilingual memory research over the past two decades has focused on the questions of whether there is a single memory store for both languages (i.e., a common, language-independent conceptual representation for the words in their two languages) or, instead, whether separate memory stores for each language (i.e., separate, language-specific representations for the words of two languages) (for review, see Heredia & McLaughlin, 1992; Heredia & Brown, 2006; Hummel, 1993; Kroll & de Groot, 1997). In contrast, earlier research suggested the dual coding of bilingual memory (e.g., Paivio & Lambert, 1981). By this view, there are two verbal systems and a common imagery system that are all partially interconnected but capable of functioning independently. Independence implies additive effects in such tasks as free recall, and interconnectedness implies that a target item in memory can be retrieved from any of the three codes, provided that there is no ambiguity about the retrieval modality.

It seems, however, that in the literature there is no clear boundary between "bilingual memory" research and "bilingual lexical organization" research. For example, in the review of "bilingual memory" by Heredia and Brown (2006), the starting question was "How do bilinguals represent their languages in memory? Do bilinguals organize their languages in separate or in shared memory systems?" (p.225). The authors continued to review several bilingual memory/lexicon representations models such as the revised hierarchical model and the distributed model. Hummel (1993) pointed out that many of the bilingual memory research paradigms are "designed in the attempt to identify the nature of the bilingual lexicon" (p. 267). This is also confirmed by the basic methodology involved in bilingual memory research, which involves having participants learn bilingual (e.g., house-*casa*) and monolingual (e.g., house-home) word pairs followed by either a free recall or a recognition task.

To illustrate, Tulving and Colotla (1970) administered a recall task in which monolingual, and bilingual lists were presented for later recall. They found that memory for items from the bilingual list was worse than the monolingual list, and the authors concluded that semantic information is less easily accessed when encoded in two languages. The results were used as support for separate systems of lexical storage, one for each language. However, other researchers (e.g., Liepmann & Saegert, 1974) claimed that the same results could be explained in terms of the interdependent view. They proposed that the lower level of recall from bilingual lists could be attributed to the difficulty in discriminating the language tags associated with words from each language. Language tags, in this view, constitute an additional memory load. Therefore, words from each language are organized in one system, but the extra memory burden imposed by language "tags" leads to differences in recall across mixed-language and unilingual lists.

Schrauf and Rubin (2000) demonstrated that autobiographical memories appeared to be encoded in a language-specific manner, as predicated by the encoding specificity principle. With respect to bilingual eyewitness memory, Shaw, Garcia and Robles (1997) showed that cross-language misinformation effects are comparable to same-language misinformation effects. This finding suggests that misinformation presented in one language can contaminate the other language.

The debate about separate or single memory system for the bilingual mind has continued, and many factors have been identified to affect the interpretation of bilingual memory performance. Durgunoglu and colleagues (Durgunoglu & Garcia, 1989; Durgunoglu & Roediger, 1987) showed that conclusions about the manner in which bilinguals organize their two languages – in one memory or in two memories – depends on the processing required by the type of memory task. Conceptually-driven tasks such as free recall showed language-dependent performance, whereas data-driven tasks such as priming or fragment completion showed language-specific effects, thus supporting the language-independent memory model. Similarly, Snodgrass (1984) suggested that episodic memory tasks are more likely to produce evidence for the independence of two languages, and tasks involving semantic memory are more likely to produce evidence for interdependence, because they are more likely to access a common, more abstract level of representation.

Kroll and de Groot (1997) also pointed out that the architecture of the bilingual's mind may be a reflection of the level of expertise in the L2 and the context in which the L2 was acquired. It should also be noted that, as Hummel (1993) suggested, studies using discrete lexical items provide information about bilinguals' episodic memory, but they provide very little information about their semantic memories, the knowledge of the world, regardless of whether this knowledge is readily expressible in words.

However fruitful, bilingual memory research so far has almost ignored one important question: what is the impact of bilingualism on memory/WM performance when compared with monolinguals? Very few studies have addressed this issue and the studies have yielded conflicting results, with some studies showing an advantage and others showing a disadvantage or no effect. For STM, some studies (e.g., Cook, 1981) have demonstrated that bilingual children have a shorter digit span than monolingual children. Magiste (1980) also reported that bilingual children read digits more slowly and showed a higher error rate in recalling two-digit numbers in both forward recall and backward recall compared to monolinguals. In contrast, Haritos (2002) showed that for 6-10 year olds, bilinguals outperformed monolinguals on a delayed recall test of everyday event stories.

Ransdell and Fischler (1987) showed that for young university students, there was no language group difference on a free recall test of high-frequency words. Although bilinguals and monolinguals had the same accuracy in a recognition test of high-frequency words, bilinguals responded more slowly in the recognition of abstract words but not in the recognition of concrete words. Makarec and Persinger (1993) showed that monolingual and bilingual young adults had similar performance on both the digit span task and forward Corsi block test (Milner, 1971). They also found that bilingual men, but not women, displayed a verbal memory weakness. However, studies of multilingual adult participants (Papagno & Vallar, 1995) have found that they had better performance in verbal STM (auditory digit span and nonword repetition) but did not differ from monolinguals in visuospatial STM tasks (forward Corsi block test).

With respect to LTM, positive effects of bilingualism were found in children of 8 – 17 years on both episodic memory (sentence recall) and semantic memory (category and letter fluency) tasks (Kormi-Nouri, Moniri, & Nilsson, 2003; Kormi-Nouri et al., 2008), with the effect being more pronounced for older than younger children. However, using adult subjects, bilinguals were shown to have lower performance on semantic memory (more evident for category fluency than for letter fluency) compared with monolinguals (Rosselli et al., 2000; Gollan, Montoya, & Werner, 2002). However, when the language proficiency of the bilingual group was matched for the monolingual group, bilinguals showed the same performance on category fluency and even better performance in letter fluency (Bialystok et al., 2008).

Bilingual WM

Recently, researchers have started to examine the role of WM in the acquisition of a second language (e.g., Miyake & Friedman, 1998), or the language-specific impact of different languages on WM tasks. For example, Lanfranchi and Swanson (2005) showed that phonological STM is language-dependent but that WM operated primarily as a language-independent system. These findings are consistent with Harrington and Sawyer (1992), who hypothesized that WM tasks in individuals' first language (L1) and second language (L2) draw from a general system related to the executive functions. They found no significant difference between WM span scores in L1 and L2, as well as a moderate, significant relationship between the two. The finding supports the claim that WM performance is not language-specific but reflects a more general ability to process information (Osaka & Osaka, 1992; Osaka, Osaka, & Groner, 1993).

However, these studies of bilingual WM all compared performance with bilingual and unilingual conditions within bilingual samples. There have been only a few WM studies comparing bilingual and monolingual samples. Therefore, the explicit relationship between bilingualism and WM is not clear at this stage, pointing to a need for research to provide a greater understanding of the bilingual WM system.

The few studies comparing bilingual WM performance with monolinguals have not revealed a very clear pattern. Siegel and colleagues (Abu-Rabia & Siegel, 2002; de Fontoura & Siegel, 1995) presented monolingual and bilingual children of 9-14 years with a WM task similar to reading span, that require children to supply the final missing word presented orally and then to repeat all the missing words from the set, with the set size ranging from 2 to 5. The monolingual and bilingual groups were found to perform similarly when matched on reading achievement tests. Similarly, Gutierrez-Cellen, Calderon, and Weismer (2004) found that for 8-year-old children, there were no significant differences between fluent bilinguals and monolinguals on an auditory version of the reading span task (i.e., listening span task). In contrast, Marcoux, et al. (2005) showed that for 8- to 10-year-old children, bilinguals performed better on complex verbal tasks. In the verbal tasks, children heard lists of words, and they had to group those words by size of referent ('fit in the box or not') before recall.

In one study with young adults, no group difference was found on the operational span and counting span tasks (Bialystok & Feng, in press). Similar results have shown that for university students, monolingual and bilingual groups had similar performance on the reading span task (Ransdell, Barbier, & Niit, 2006). In one recent study on monolingual and bilingual young adults, a bilingual advantage on the counting span task was found, together with a smaller build-up of proactive interference in a STM task (Nikolova, 2008). Other studies showed no difference in single-task WM measures, including n-back tasks, a transformational alpha span task, or a sequencing span task (Bialystok et al., 2004). In fact, in one study, bilinguals showed a disadvantage in the Alpha span task when they scored lower than the monolingual group on a standard receptive vocabulary test (Bialystok & Feng, in press). Although these widely used measures of WM did not show much sensitivity to bilingualism, it is notable that all these tasks are verbal tasks for which bilinguals are disadvantaged (Michael & Gollan, 2005). Therefore, for bilingual participants, these tasks might not be reliable measures of pure WM, but instead reflect other abilities such as language proficiency, or speeded retrieval of verbal information.

When using non-verbal tasks, Marcoux et al.(2005) showed that for 8- to 10-year-old children, bilinguals performed better on a spatial WM task, in which children first saw novel shapes presented in a 4 X 4 grid and had to group the shapes by category (e.g., shape) before recalling. For adults, spatial memory measures such as the Forward Corsi Block test did not show differences in either young or old participants. However, the backward Corsi Block test showed a bilingual advantage in one study of young adults (Bialystok et al., 2008). It is difficult to draw any conclusions from these conflicting results, and studies targeting the relationship between bilingualism and WM are necessary to test the tentative hypothesis of a bilingual WM advantage.

The Present Dissertation

The above review of research in the areas of both WM and bilingualism points to the possibility of a positive influence of bilingualism on WM performance. In the current study monolingual and bilingual young adults will be the target groups. If the theoretical account of the underlying factors for individual differences in WM performance is valid, by comparing these two groups on measures of WM, it may be possible to find different patterns of performance and therefore shed light on the underlying mechanisms of the bilingual WM system.

Based on the theoretical construct of WM proposed by Oberauer et al. (2000), both digit and spatial WM tasks will be manipulated for their information processing and executive control demands. One initial hypothesis is that in the simple span task, participants of different language background will show more discrepancy for WM tasks requiring higher levels of information processing (transformation of information) than for passively recalling information. Bilingual advantage will be evident on transformational WM tasks and indeed, it is expected that the two groups will not perform differently from each other in the passive memory task. Recall in complex span tasks is also expected to show language group differences, because the complex WM task places higher demands on executive control. Bilinguals will outperform monolinguals in complex span tasks.

In order to investigate a potential WM advantage for bilinguals, spatial WM tasks (Study 1, 2, and 3) and digit WM tasks (Study 3) were chosen for the dissertation. A spatial WM task was designed and evaluated in Study 1 with a sample of monolinguals. The aim of Study 1 was to validate a WM task potentially sensitive to the bilingualism effect. Using this new task, the impact of bilingualism on WM subsequently was pilot tested in Study 2. The relationship between WM and bilingualism was further investigated in Study 3.

Bilinguals might be at disadvantaged in WM tasks using actual words as stimuli, because these tasks also tap other factors such as language proficiency and therefore might not be pure measures of WM for bilinguals. Therefore WM tasks using actual words as materials will be avoided to eliminate the possibility of confounding the advantage of bilingualism on non-verbal executive function with its disadvantage on verbal retrieval. For example, in a proactive interference memory task requiring the recall of words (Bialystok & Feng, in press), bilingual and monolingual young adults recalled the same number of words; however, it was the receptive vocabulary score and not the language experience that predicted the performance on this verbal memory task. The avoidance of WM tasks using actual words as stimuli leads to the problem of generalization of the bilingual influence on WM based on the results from the dissertation, and this issue should be further investigated in future research.

It is widely agreed in the literature that it is impossible to achieve consensus on a definition of bilingualism. Depending on the target age groups and the research aims, researchers define bilingualism differently. For example, according to Grosjean (1989), a bilingual is someone who can function in each language according to given needs. For the current research purpose, bilinguals are defined as individuals who have been using two languages constantly on a daily basis since a very young age (about 5-6 years old), most likely speaking the dominant language of the country at work/school, while speaking another language at home with parents/friends, and using each language with relatively equivalent frequency.

STUDY 1: VALIDATION OF THE MATRIX SPAN TASK

The purpose of Study 1 was to design and evaluate a measure of spatial WM sensitive to potential differences in bilingual participants. Because the backward Corsi Block test has shown some bilingual advantage in previous research, a novel, spatial transformational WM task, the Matrix span task, was developed. The Matrix span task was designed to impose greater processing load than the backward Corsi Block test because it requires transforming items in a complex spatial configuration. Participants viewed series of 2-7 black dots in the cells of a 5 X 5 matrix, with two trials for each string length. The main requirement was to remember all the locations where a dot appeared and recall those locations in a fixed order (from left to right, from top to bottom), rather than the order of presentation. Performance was measured with two scores: the strict score (scored up to the longest string length at which participants failed both trials) and the total score (scored for all the trials in the entire task). The strict score has been used to assess performance in memory tests (e.g., Wechsler, 1997a); the total score was included to capture the performance in conditions (i.e., long string length of 5, 6, and 7) that involve more controlled processing (Unsworth & Engle, 2006; 2007).

The important question is whether this new Matrix span task can provide a measure of the same underlying cognitive construct as the traditional spatial memory measures such as the Corsi block task, and more importantly, whether the Matrix span task can provide a new complex span measure of spatial WM. To evaluate the validity of the new task, other "traditional" memory tasks were administered in addition to the Matrix span task, and the relationship among these tasks was assessed using principal component analysis procedures. In addition, the relationship between response formats in paper-and-pencil and computer-based Corsi block tasks was explored. There are several studies using computerized Corsi block tests (e.g., Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; Vandierendonck, Kemps, Fastame, & Szmalec, 2004), but it is not clear whether the computerized version of the task is a valid measure of spatial WM.

Memory Task Selection

In the memory literature, simple and complex span tasks have been used to measure STM and WM separately, although recently it has been argued that both tasks measure the same basic cognitive processes, but to a different extent (Colom, Rebollo, Abad, & Shin, 2006; Unsworth & Engle, 2006, 2007). Simple span measures refer to tasks that assess how many items can be repeated back in order in which only to-be-recalled items are presented and no additional processing is required. For example, forward Digit span (Wechsler, 1997a) has been used widely in the literature and is an example of a simple span task. Among the many complex span tasks, perhaps the most common is the backward Digit span from the Wechsler Adult Intelligence Scale (Wechsler, 1997a), in which memory capacity is measured by how many numbers presented auditorily in a string can be reported in reverse order. Another example is the Letter-Number Sequencing task from the Wechsler Memory Scale (Wechsler, 1997b). In this task, subjects are presented with a string of letters and digits that are interspersed (e.g., “G81BT5”). The task is to repeat the sequence back in alpha-numeric order (e.g., “BGT158”), and therefore requires mental manipulation and transformation of the information presented. Moreover, research with older adults has often relied on an *n*-back procedure, in which subjects are continuously presented with a series of items such as digits, letters, or locations, and they must compare the current item with the item that was presented one, two, or three items earlier, depending on the value assigned by the experimenter (Smith & Jonides, 1999).

Recently, dual-task WM span measures (especially reading span, operation span and counting span) have come to dominate the measurement landscape of WM, although they have been used primarily to investigate individual differences in healthy young adults (for a review, see Conway et al., 2005). These dual-task measures of WM are based on the assumption that in order to most effectively measure WM capacity (Engle, 2002), a task must include a demanding secondary task to compete with information storage. Questions remain open, however, regarding the structure of these WM tasks. In the reading span task, for example, the participant reads a series of sentences aloud (the primary task) and then is asked to report the last word in each sentence (the secondary task). However, very little information is available that provides an account of how overall performance should be assessed. Instead, the typical procedure (e.g., Daneman & Carpenter, 1980) is to focus only on the secondary task. A review of the literature (Conway et al., 2005) indicates that participants are not specifically instructed about task priorities and typically, performance on the primary task is not taken into account, and only data from the secondary task are reported. Investigators do not know, for example, how two individuals who obtain the same score on the secondary task but differ in accuracy on the primary task might differ in overall capabilities captured by these tasks.

Another question for these dual-task measures of WM is whether the secondary task should present additional stimuli to be processed or simply require some mental transformation of the target memory items for the primary task. Engle, Tuholski et al (1999) tested subjects on the backward word span task, in which target words were recalled in the reverse order from that in which they had been presented, in addition to other WM and STM span tasks including operation span, reading span, counting span, and word span tasks . Factor analyses showed that backward word span grouped with the STM tasks, rather than with the WM span tasks, indicating that a mental transformation alone might not be enough to turn an immediate-memory task into a WM task (see also Hutton & Towse, 2001; Park et al., 2002). In contrast, Oberauer et al. (2000) found that simple transformation span tasks seemed to measure the same construct as did WM span. They tested subjects in a backward digit span task and an alpha span task (Craik, 1986), in addition to reading span and counting span tasks. Alpha span required recall of target words in alphabetical order, rather than in their presentation order, and so, like backward span, presented a secondary processing task without secondary stimuli. Here, the correlation between reading and counting span ($r = .66$) was only slightly stronger than their correlations with the transformation tasks (mean $r = .60$), suggesting that all of these span tasks may reflect a single construct. The source of the discrepancy between the Engle and the Oberauer findings is not obvious, so further research is needed to determine the importance of interfering stimuli, in addition to interfering processing, to the measurement of WM. Indeed, Oberauer, Süß, Wilhelm, and Wittmann (2003) tested subjects in Brown-Peterson-like tasks (Brown, 1958; Peterson & Peterson, 1959), in which subjects were first given a short list of items, then engaged in a rehearsal-preventing activity during the retention interval, and finally were asked for recall of the items. The authors found that the Brown-Peterson-like tasks correlated with WM span measures with mean *r* of .59. In fact, their WM span, transformation span (backward digit and alpha span), and Brown-Peterson tasks all loaded onto a single factor, although these tasks are structurally heterogeneous in subtle ways.

In the present study, only transformation span tasks were chosen as measures of WM, instead of dual-task WM measures to avoid inclusion of interfering stimuli while keeping the interfering processing in the measurement of WM. Furthermore, based on one investigation that has provided important insights into relations between WM and intellectual abilities, reported by Oberauer et al. (2000), memory tasks were selected from two domains: verbal/numerical and spatial. Therefore, the tasks chosen for inclusion in Study 1 are: traditional and computerized Corsi Block tests as spatial memory (forward version) and WM (backward version) measures, alpha span and sequencing span tasks as transformational verbal WM measures, and the new Matrix span task as a transformational spatial WM measure.

Method

Participants

Sixty-two young adult participants (mean age = 20.0 years; *SD* = 2.1; age range 18-26 years; 33 males and 29 females) completed the study. All participants were monolingual speakers of English with no extended exposure to any other language throughout their lives, according to the initial screening. Participants provided written informed consent for their involvement in the study. Thirty participants were undergraduates at York University and received course credit for an introduction to psychology course. Thirty-two were young adults living in the Greater Toronto area and received $10 dollars per hour for their participation in the study.

Tasks

A total of seven WM measures, one vocabulary measure, and one fluid intelligence measure were administered. The WM tasks were given to participants in a fixed order: Corsi block test (both forward and backward version), alpha span task, Matrix span task, sequencing span task, computerized Corsi block test (both forward and backward version), Cattel Culture Fair IQ Test, and Peabody Picture Vocabulary Test – III B. All tasks were administered over the course of one session of approximately one hour. The order in which tasks were run was fixed, with the order of two versions (forward version and backward version) of each set of tasks counterbalanced so that each version was run in each position equally often.

Working Memory Tasks – Validation Measures

Alpha span task (Craik, 1986). The alpha span task is a measure of verbal WM. Lists ranging in length from two to eight words are presented orally at the rate of one word per second. Words are presented in random order, and participants are required to repeat the words back in alphabetical order. The task begins with a list of two words and proceeds by presenting two trials at each list length and increasing the length by one upon completion of the pair. Testing continues until the participant makes an error in both trials at a given list length. In the scoring system, one point is awarded for each item recalled in a correctly ordered pair; the paired word can either precede or follow the scored word. For example, if a list of four items is recalled correctly, the score is four points; if the correct recall sequence for a list of four items is "apple, car, hotel, rabbit" and the participant recalls "apple, card, hotel, rabbit" he or she would receive two points – one each for hotel and rabbit. "Apple" does not receive a point because "apple-card" is not a correct pair. The alpha span test score is the total number of points awarded across all presented lists, and the alpha span test span is the maximum length at which the participant makes at least one trial correct.

Sequencing span task (Bialystok et al., 2004). The sequencing span task is similar to the alpha span test but uses strings of double-digit numbers ranging from 11 to 99 that are presented in random order; the participant's task is to repeat back increasingly long strings of numbers in the correct order. No number was repeated across any of the strings, and no pairs of numbers in the presentation strings appeared in their correct ascending order. The string lengths of double-digits range from 2 to 10 numbers. Testing continues until the participant makes an error on both trials at a given list length. The responses were scored using the procedure described above for the alpha span test.

Corsi block test (Corsi, 1972). The Corsi block test is a measure of spatial memory. Nine wooden cubes are located at random positions on a wooden board. The cubes are numbered 1-9 on the examiner's side (who can therefore present the pattern required and check the correctness of the response). During the presentation phase, the examiner indicates positions and then asks the participants to repeat the sequence in either a forward or backward order. In the backward version, participants are asked to indicate the positions starting from the last and going back to the first. The task begins with a list of two positions and proceeds by presenting two trials at each list length and increasing the length by one upon completion of the pair. Testing continues until the participant makes an error on both trials at a given list length. In the scoring system, one point is awarded for each position recalled in a correctly ordered pair. For example, in the forward version of the Corsi block test, if a list of four positions is recalled correctly, the score is four points; if the correct recall sequence for a list of four positions is "4, 7, 2, 9" and the participant recalls the position "4, 8, 2, 9" two points will be given – one each for position 2 and 9. Position 4 does not receive a point because position "4-8" is not a correct pair. The Corsi block score is the total number of points awarded across all presented lists, and the Corsi block span is the maximum length at which participant achieves at least one trial correct.

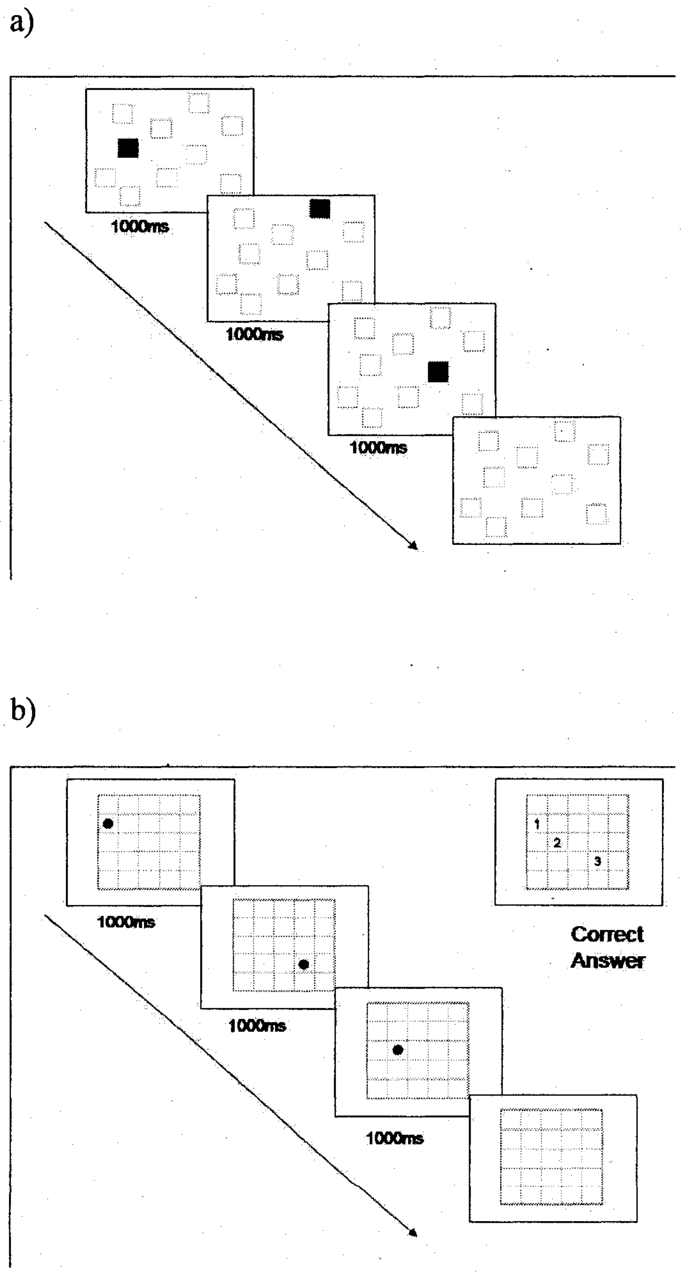
Working Memory Tasks – Experimental Measures

Computerized Corsi block test (Luo, 2005, personal correspondence). In the computerized version of the Corsi blocks test, participants are shown a set of 10 squares (displayed as white squares with a black border) in random positions on the computer screen and asked to remember the order in which they are presented (indicated by a change in color). The squares are each 1.1inch X 1.1inch and are presented on a 12 X 9–inch color monitor Pentium 4 Dell C840 laptop with a white background. Participants sit approximately 50cm in front of the screen and place their right hand on the mouse. The experiment was controlled by a program running in E-prime 1.1 (Schneider, Eschman, & Zuccolotto, 2001), and one square at a time turned red for 1000ms. Immediately after the presentation of a sequence, the cursor became visible on the computer screen and participants were asked to repeat the order by clicking on the squares using the mouse. Participants had unlimited time to respond (see Figure 1a for a schematic description of the stimuli), and every time the participants gave a response by clicking on a square, the square turned yellow for 100ms. There were two practice trials, with two squares and three squares, respectively. After the practice trials, the sequences ranged in length from 2 to 10 squares, with 2 trials at each sequence length. In the forward version of the computerized Corsi block test, the correct answer requires starting from the squares flashed first to the last, whereas in the backward version of the test, the participant is asked to respond by starting from the square presented last and going back to the first. Testing continued until participants made an error on both trials of a given list length. The responses were scored using the procedure described above for the traditional version.

Matrix span task. The Matrix span task is a measure of spatial WM designed to incorporate a transformational component as in the alpha span and sequencing span task. Participants see a sequence of dots in one of the cell locations in a 5 X 5 matrix. The main requirement was to remember all the dot locations and recall those locations after the presentation in a specified order (from left to right across the rows, from top to bottom down the rows), regardless of the order in which they were presented. The presentation showed a 5 X 5 matrix in the center of the computer screen; the height and width of each cell of the matrix was 4cm. Squares arranged in a black grid were presented on a 12 X 9 – inch color monitor Pentium 4 Dell C840 laptop with a white background. The experiment was controlled by E-prime (Schneider et al., 2001). One black dot (radius = 0.8 inch) at a time was displayed for 1000ms in the cells of the matrix followed by a blank matrix for 500ms. Dot locations were never repeated within a set; each of the 25 cells appeared in black approximately equally often in the task. Once the presentation of dots was completed, participants had unlimited time to respond with pen on a blank 5 X 5 matrix on a sheet of paper. They were asked to order those locations using Arabic numbers, in the order defined by left to right and top to bottom through the matrix rows (see Figure 1b for a schematic description of the stimuli). Participants wrote one number in each matrix cell that had contained a dot, with the number indicating its order. There were two practice trials with two cell locations and three cell locations respectively. After the practice trials, the sequences progressively increased in length from two to seven dot displays for a total of 12 trials, with 2 trials at each sequence length.

As in other memory tasks, participants attempted to reproduce the sequence of dot locations in the correct order. In the scoring system, if a list of three positions was recalled correctly, the position score is three points and the order score is two points, resulting in a score of five for that trial. For example, in Figure 1b the correct answer is displayed in the right hand corner. All participants continued to the list length of seven. The span for the Matrix span task is the maximum length at which a participant was correct on at least one trial. The strict score of the Matrix span task is the total number of points awarded across all lists up to and including the shortest string length at which both trials were failed. The total score of the Matrix span task is the total number of points awarded across all presented lists (list length 2-7). For example, if a participant made errors on both trials for string length of 5, the strict score would be the sum of the points up to and including string length of 5; and the total score would be the sum of the points up to and including string length of 7. In both scoring schema, the discrepancies between the correct answer and the positions given by participants were also calculated in terms of x-axis and y-axis, resulting in a discrepancy score in x-axis, a discrepancy score in y-axis and a total discrepancy score when combining them.

Figure 1. Example of a) the computerized Corsi block test and b) the Matrix span test.



Vocabulary and Fluid Intelligence Measures

Peabody Picture Vocabulary Test – Third Edition B (PPVT-III; Dunn & Dunn, 1997). PPVT-III is a standardized test of receptive vocabulary. The test consists of a series of plates, each containing four pictures. The experimenter names one of the pictures, and the participant indicates which picture illustrates that word by naming the number presenting the picture. The initial item is determined by the participant's chronological age. The items become increasingly difficult, and testing continues until the participant makes at least 8 errors out of 12 items in a set. The score is determined by tables that convert the raw score (number of highest items achieved minus the total number of errors) to a standard score corrected for the age of the participant. The mean of the standard score is 100 with the standard deviation of 15. The test was administered in English to all participants.

Cattell Culture Fair Intelligence Test (Cattell & Cattell, 1960). The Cattell Culture Fair Intelligence Test is a nonverbal test of general intelligence. The test is composed of four separate and timed paper-and-pencil subtests: series, classification, matrices, and conditions. Following the standard instructions, participants were allowed 2.5 to 3 minutes to complete each subtest. When time expired for a subtest, participants were instructed to stop working on that subtest and begin the next. At no point were participants allowed to go back to work on previous subtests. The raw score for Cattell Culture Fair Intelligence Test is the sum of all correct answers across all four subtests, and the raw scores are converted into standardized IQ scores based on age of the participants.

Results

Reliability Analyses

Descriptive statistics for all the measures are presented in Table 1 with the means, standard deviations, ranges, skewness and kurtosis for each measure. For ten of the participants, the vocabulary test was not administered because they were unavailable for the whole testing session. The vocabulary tests were always administered last, so these participants were missing the vocabulary test scores.

Test reliability was assessed by calculating coefficient alpha (Cronbach, 1951) across all the tests. Cronbach's alpha is an index of reliability associated with the variation accounted for by the variable that is being measured (O'Rourke, Hatcher, & Stepanski, 2005). Reliability of all tests including vocabulary and intelligence was satisfactory, with Cronbach's alpha of .75 (Nunnally, 1978). When only the memory/WM measures were included, the Cronbach's alpha was .77.

Four t-tests were conducted to compare the performance between forward and backward tests in both block version and the computerized version of the Corsi block tests. The results showed that for the span measure, which represented the longest string of locations individuals could correctly recall, there was a difference between forward and backward tests for traditional Corsi block, $t(61) = -2.20, p < .04, d = 0.26$. Participants had higher spans on backward tests of the traditional Corsi block compared with their spans on forward tests. However, the scores for forward and backward tests were similar, $t(61) = -1.97, p = .06, d = 0.25$, with only a trend toward higher scores in the backward Corsi. In the computerized version of the tasks, the difference between forward and backward tests was significant for both span ($t(61) = 6.06, p < .0001, d = 0.78$) and score ($t(61) = 6.11, p < .0001, d = 0.78$). Participants showed significantly higher spans and scores on forward tests of the Corsi block computerized version. In contrast with the results for the traditional Corsi block test, in the computerized version, backward tests were harder than forward tests, suggesting that backwards tests had greater processing demand.

For the Matrix span test, in both the strict and the total scoring system, the discrepancy scores on the horizontal line were significantly greater than those on the vertical line (strict: $t(61) = 8.19, p < .0001, d = 1.02$; total: $t(61) = 12.97, p < .0001, d = 1.7$).

Validity Analysis

Correlations between all tests for memory, WM and intelligence are presented in Table 2. The two verbal WM tasks were correlated with each other but not with the spatial WM tasks, with the exception that the sequencing span test was correlated with backward Corsi block and the total score for the Matrix task. The alpha span test was correlated with PPVT but not the intelligence measure, whereas sequencing span showed no correlation with either the PPVT or the intelligence scores.

The spatial WM measures were correlated with each other and were all correlated with intelligence ($r = .28 – .37$) but not with vocabulary measures. All four versions of the Corsi block tests were intercorrelated, except that the traditional backward Corsi block test was only marginally correlated with the computerized test in the backward version ($r = .24, p = .07$). For the Matrix span task, both the strict and total scores of the task were significantly correlated with all Corsi block tests.

Performance in the Matrix span task was correlated with spatial WM performance measured by Corsi block tests, but the question remains as to the extent to which they estimate a common construct. To achieve better insight into the commonalities underlying these measures, a principal component analysis was performed on all seven memory tests to further explore the validity of the Matrix span task.Table 3 displa ys the component loadings after applying a varimax (orthogonal) rotation. Principal component analysis extracted two components on the basis of substantial eigenvalues (greater than 1: component 1 = 2.99; component 2 = 1.35),whic h together explained 62% of variance, when excluding the backward Corsi block test score from the analysis.

In interpreting the rotated factor pattern, a measure was said to load on a given component if the factor loading was .45 or greater for that component, and was less than .45 for the other (O'Rourke et al., 2005). An initial analysis showed that backward Corsi block test score loaded on both components 1 and 2, and to eliminate this problem, the backward Corsi block test score was deleted from the final analysis. Using these criteria, five measures were found to load on the first component and two measures loaded on the second component. Therefore principal component analysis suggested a two-factor model. The first component attracts high loadings on the variables from Corsi block tests and the Matrix span test, representing the spatial component of WM. The second component shows high loadings of scores of the sequencing span and alpha span, and it represented mainly the verbal component of WM.

Table 1. *Descriptive Statistics for All Measures in Study 1*

Measure (n = 62)		*M*	*SD*	Range	Skew	Kurtosis
Alpha span task (Max Score = 70)	Span	5.0	0.9	2-8	0	2.07
	Score	32.7	9.9	4-58	0.01	0.27
Sequencing span task (Max Score = 108)	Span	3.7	0.7	2-5	0.18	-0.43
	Score	17.6	5.4	4-30	0.30	-0.11
Corsi block test (Forward)	Span	5.5	1.0	4-8	0.07	0.52
	Score	37.9	11.8	16-80	0.57	1.84
Corsi block test (Backward)	Span	5.9	1.0	3-8	-0.25	0.23
	Score	41.3	13.0	8-73	0.09	0.11
Computerized Corsi block test (Forward)	Span	6.4	0.9	4-5	-0.50	0.41
	Score	48.0	11.8	25-73	-0.17	-0.39
Computerized Corsi block test (Backward)	Span	5.7	1.0	3-8	0.01	-0.32
	Score	39.5	11.5	12-73	0.31	0.34
Matrix span task (Max Score = 96)	Span	3.9	1.4	2-7	0.56	-0.02
	Strict Score	35.2	21.0	6-85	0.88	0.19
	Strict X-Off[2]	7.3	4.7	0-25	0.93	1.64
	Strict Y-Off[2]	3.4	2.9	0-16	1.79	5.18
	Total Score	57.8	14.1	26-85	-0.01	0.32
	Total X-Off[2]	27.6	13.3	2-53	0.16	-0.73
	Total Y-Off[2]	11.7	10.1	1-56	2.59	8.36
Peabody Picture Vocabulary Test – III[1]	Standard	107.5	7.9	90-125	-0.10	-0.59
Cattell Culture Fair Intelligence Test	Standard	113.9	12.8	85-140	-0.31	-0.32

Note 1. n = 52.

Note 2. X-Off = the discrepancy score on horizontal dimension; Y-Off = the discrepancy score on vertical dimension.

Table 2. *Correlation Matrix and Reliabilities for All Measures in Study 1 (n = 62)*

	Verbal Working Memory		Spatial Working Memory						Vocabulary	Fluid Intelligence
Target Measures[12]	1	2	3	4	5	6	7	8	9	10
Verbal WM										
1. AST	–									
2. SST	.34**	–								
Spatial WM										
3.CorsiFor	.11	.15	–							
4.CorsiBa	.13	.40**	.39**	–						
5.ComCorsiFor	-.05	.05	.36**	.34**	–					
6.ComCorsiBa	.00	.06	.33**	.24	.56***	–				
7.StrictMatrix	.06	.19	.36**	.35**	.51***	.42***	–			
8.TotalMatrix	.10	.32*	.42***	.33**	.48***	.51***	.76***	–		
Vocabulary										
9.PPVT[3]	.27*	-.16	.02	-.04	.10	-.11	.10	-.01	–	
Fluid Intelligence										
10. Cattell	.19	.06	.30*	.28*	.37**	.28*	.34**	.35**	.40**	–
Cronbach's alpha with variable deleted[4]	.80	.77	.75	.75	.73	.74	.72	.70	–	–

* $p < .05$; ** $p < .01$; *** $p < .001$.

Note 1. AST = Alpha span task; SST = Sequencing span task; CorsiFor = forward Corsi block test; CorsiBa = Backward Corsi block test; ComCorsiFor = forward computerized Corsi block test; ComCorsiBa = backward computerized Corsi block test; StrictMatrix = Matrix span task (strict score); TotalMatrix = Matrix span task (total score); PPVT = the standard score of PPVT-III; Cattell = the standard score of Cattell Culture Fair IQ test

Note 2. For all working memory measures, only scores were used in calculating correlations.

Note 3. For PPVT-III, n = 52.

Note 4. The Cronbach's alpha value when the given variable was deleted from the calculation.

Table 3. *Component Loadings from Principal Component Analysis of Memory Test Scores in Study 1 with Varimax Rotation.*

	Components		h^2
Memory Measures	1	2	
Alpha Span	-.04	**.80**	.65
Sequencing Span	.16	**.79**	.65
Forward Corsi Block	**.59**	.18	.38
Backward Corsi Block[1]	–	–	–
Forward Computerized Corsi Block	**.79**	-.15	.65
Backward Computerized Corsi Bclok	**.76**	-.09	.58
Matrix Span (Strict)	**.81**	.14	.67
Matrix Span (Total)	**.83**	.26	.76

Note: $n = 62$. Commonality estimates appear in column headed h^2.

[1] Backward Corsi Block score was not incorporated into this analysis.

Discussion

To validate the new Matrix Span task, 62 monolingual university students completed a battery of memory tasks in addition to the receptive vocabulary and general intelligence tests. The memory tasks included alpha span, sequencing span, forward and backward Corsi Block test, the computerized version of the Corsi test in forward and backward versions, and the Matrix span task. Correlational analysis and principal component analysis suggested that these WM measures reflect separate (verbal and spatial) constructs and the Matrix span task reflected a common construct as other spatial tasks. The seven memory measures used in Study 1 constituted two sets of memory tests – namely, spatial (component 1) and verbal (component 2). The findings of principal component analysis highlighted the differences between the tests in two domains. The Matrix task also correlated with Cattell Culture Fair Intelligence Test ($r = .34, p < .01$), but not with PPVT ($r = .10$, n.s.). On the basis of theoretical considerations combined with the results of this analysis, it would seem that the Matrix span test is a valid measure of spatial WM. This task was therefore used in Study 2 to investigate a potential bilingual advantage in WM.

Before discussing the results in detail, some methodological limitations need to be considered. First, the sample in Study 1 was small (n = 62), so the results, particularly those for the principal component analysis, require cautious interpretation. Secondly, only monolingual young adults (age 18 – 25) attending university were investigated. Therefore, the homogeneity of the sample means that the variance among tests results was relatively small and correlations might therefore underestimate the relationships between the variables.

WM performance has been shown to be correlated with IQ in a number of studies (see Ackerman et al., 2005 for a review). In Study 1, neither the alpha span task nor the sequencing span task correlated with the IQ score. Possible explanations for this finding include the small sample size and the smaller variance in the scores for these two tests compared with the spatial measures, because both factors could serve to reduce the correlation. Another explanation could be that the IQ test used is a non-verbal reasoning task, and therefore the correlation between IQ score and spatial measures showed their shared content variance in non-verbal tasks. However the alpha span task, but not the sequencing span task, still correlated with the vocabulary measure. This likely was because the alpha span task uses actual words as stimuli, whereas the sequencing span task uses double-digit numbers. In contrast, all the spatial memory scores were correlated with participants' performance on the IQ test, and none of the spatial memory measures correlated with scores on a standardized receptive vocabulary task. This makes sense, because all the spatial memory tasks were non-verbal. As one of the spatial measures, the Matrix span task correlated with general IQ measure but not with a vocabulary measure. This pattern of correlation confirms that as a spatial WM task, Matrix span predicts general intelligence without tapping knowledge of the verbal domain.

The correlations among all the memory tasks showed an interesting pattern: The two verbal tasks were correlated even though they were using stimuli from different domains, namely, words and numbers. The alpha span task did not correlate with any of the spatial memory tasks, and the sequencing span task correlated only with the backward Corsi block test and the total score for the Matrix span task. This is consistent with the literature, where differentiations of WM according to content domain have been mainly found between spatial and non-spatial tasks (Daneman & Tardif, 1987; Shah & Miyake, 1996; Smith & Jonides, 1997), but not between verbal and numerical tasks (Turner & Engle, 1989; Kyllonen & Christal, 1990).

The spatial memory tasks were correlated with each other except that the correlation between the backward Corsi block test and the computerized version of the backward Corsi Block test failed to reach significance. It is not clear which aspects of spatial memory are tapped by the backward Corsi block, but it is related to forward Corsi block regardless of the modality of the tests. In the results, the forward and backward version of the Corsi block tests did not differ from each; only the computerized version of the Corsi block tests showed the expected difference in which the backward version was harder than the forward version. It may be suggested therefore that, at best, the backward Corsi is still sensitive to the same aspects of spatial memory as measured by forward Corsi block, but the computerized backward Corsi block tests may tap different aspects of spatial memory compared with the computerized forward Corsi block test and may place higher processing demands on the participant.

The results for the block version of the Corsi block tests in Study 1 were consistent with previous findings that while the forward digit span task elicited better performance than the backward digit span task, there were no differences in the forward and backward versions of the Corsi block tests in either healthy young adults or neurological patients (Beblo, Macek, Brinkers, Hartje, & Klaver, 2004). Also, some participants in Study 1 reported that they found backward Corsi easier than forward, despite the transformation component, because in the backward version, they could recall the last few locations in the sequence and could get partial marks, especially for the longer list-length. Therefore, for the block version of the Corsi block test, the backward Corsi block test requires no additional executive processing compared to the forward version, which represents primarily the storage component of spatial WM. Therefore the use of the backward version of the Corsi block as spatial WM measure should be reconsidered, and the computerized version of the Corsi block tests might be a better choice for measuring spatial WM.

The results revealed the Matrix span task to be valid and the validity of the Matrix span task was determined by its correlations with the other WM tasks. Although the correlations were generally moderate, this likely was due to the highly selected sample. In the principal component analysis, the Matrix span task shared one component with the forward Corsi block, forward and backward tests of the computerized Corsi block, but not alpha span or Sequencing span task, which belonged to the second component. This further confirms the Oberauer et al. (2000) findings that verbal/numerical and spatial tasks represent different aspects of the construct of WM.

On average, participants could remember as many as four locations and report them back in the required order. The Matrix span task was more difficult than the Corsi block tests, partly because in Corsi there were 9 randomly located positions, whereas in the Matrix span test there were 25 locations. Also, presentation of the Matrix span test was on the computer screen, but the response was required on paper using a blank Matrix. This re-configuration of the presentation might also contribute to the difficulty of the task. Although the span was lower in the Matrix span task than in the Corsi block tests, this might not be due to the inability to follow the instruction, but to the inability to recall the locations in the correct order. The position scores in the Matrix task represent the correctly recalled locations regardless of the order information, when the rearranging of spatial information was not included in the evaluation of the task performance. The position scores showed that the participants maintained the same level of performance in the Matrix span task as in other spatial memory tasks that do not require rearranging of spatial information. Although the Matrix span task was cognitively more demanding compared with the Corsi block tests, it nevertheless showed a wider range of performance and was determined as valid.

Each location in the matrix was assigned an x-axis value and a y-axis value by considering the matrix as a co-ordinate system with the bottom left corner positioned at the origin. The x-axis value represents the order of the cell from left to right in each row, and the y-axis value is the order of cell from the bottom to the top. For example, for the cell located in the second row from the bottom and third column from the left, the x-axis value is 3 and the y-axis value is 2. Errors in recalling location were determined by the x-off scores and y-off scores for each location recalled: the x-off score is the discrepancy between the x-axis value for the participant's response and the x-axis value for the actual presented location; the y-off score is the discrepancy of y-axis value for the participant's response and the y-axis value for the actual presented location. The results showed that the sum of the difference between the responses and the actual locations were greater on the horizontal dimension than on the vertical dimension, so participants were more accurate in recalling the location on the vertical dimension (y-axis) than on the horizontal dimension (x-axis). This pattern of results showed that participants were more attentive to the spatial information in the vertical dimension, possibly because the vertical information is more distinctive than the highly confusable horizontal dimension, so the participants remembered the more distinctive information better. This is also consistent with the fact that in the visual cognition field, individuals direct more primary attention to the vertical axis (y-axis) than they do to the horizontal axis (x-axis) (e.g., Shelton, Bowers, & Heilman, 1990). As a whole, the Matrix span task provides a valid alternative measure of spatial WM.

STUDY 2: BILINGUALISM AND THE MATRIX SPAN TASK

Having established the validity of the Matrix span task in Study 1, in Study 2 the WM performance of monolingual and bilingual young adults was examined using the Matrix span task, together with some of the other tasks from Study 1. The goal was to explore the effect of bilingualism in transformational spatial WM. Bilinguals were expected to have the same capacity for short-term storage in the Corsi block test but to outperform monolinguals in the Matrix span task which involves controlled processing during the transformational retrieval of spatial location information. To measure simple spatial memory span and verbal WM performance, the Corsi block task and alpha span task were also administered to the participants. It was hypothesized that bilinguals would show better performance only in the Matrix span task and not in the Corsi block task or in the alpha span task.

Method

Participants

Forty-four young adults participated in Study 2 in return for introductory psychology course credits. Based on the Language Background Questionnaire (LBQ; see Appendix A) filled out by each participant prior to testing, 22 of the participants were monolingual speakers of English (mean age = 21.4, *SD* = 3.1), and 22 of the participants were classified as bilingual (mean age = 20.3, *SD* = 2.5). There were 11 females and 11 males in the monolingual group and 7 females and 15 males in the bilingual group, with no difference in the gender distribution between the two groups, $\chi^2(1) = 1.50, p = .22$. The bilinguals reported using English and another language on a daily basis, and all bilinguals started using two languages actively by the age of 7 at the latest. For the bilingual participants, the non-English language used mostly in the home environment included Cantonese (4), Hindi (2), Italian (2), Korean (2), Portuguese (2), Punjabi (2) and Albanian, Farsi, French, Hebrew, Persian, Russian, Sinhalese, Spanish (one speaker for each language).

Tasks

All participants were tested individually with the tasks presented in a fixed order: Language Background Questionnaire (LBQ), Matrix Span task, alpha Span task, non-computerized forward Corsi block task, and PPVT-III A (Dunn & Dunn, 1997). The same Matrix Span task, alpha Span task, Corsi block task (forward version only) and PPVT-III used in Study 1 were used in Study 2. The LBQ was filled out by the participant to indicate the extent to which they used each language in a variety of settings, the age of the acquisition of the language(s) they speak, and the degree to which each language is used daily. The alpha span task and Corsi block task were included as verbal WM and simple spatial memory measures. All the tasks were administered to the participants in a single session of about half an hour.

Due to some technical problems, responses for the string length of 7 in the Matrix span task were missing for four monolinguals and six bilinguals. Therefore for these participants, their total scores for the Matrix span task were treated as missing. All of these participants completed the task up to the string-length of 6, because their individual spans ranged from 3 to 5, it was possible to calculate their strict scores and there were no missing data for the strict scores.

Results

The mean scores and standard deviations for the memory and vocabulary measures are reported in Table 4. A series of one-way ANOVAs comparing the two language groups indicated that there were no language group differences in years of education, the alpha span task, or the Corsi block test, all *F*s < 1; although monolinguals usually have higher vocabulary scores than the bilinguals, it was not the case for the group of participants in this study, $F(1, 42) = 1.01$, n.s.

Table 4. *Mean Scores and SDs on All Measures by Language Group in Study 2*

Variable	Monolingual *n* = 22	Bilingual *n* = 22
Years of Education	13.0 (1.4)	12.3 (0.5)
PPVT-III Std. Score	102.8 (9.2)	100.1 (8.5)
Forward Corsi Span	5.6 (0.9)	5.7 (0.6)
Forward Corsi Score	36.7 (10.0)	36.5 (6.5)
Alpha Span	4.7 (0.8)	4.5 (0.7)
Alpha Score	27.6 (8.0)	26.9 (7.6)
Matrix Span	4.1 (0.8)	4.3 (1.1)
Matrix Strict Score	31.4 (15.9)	39.7 (18.6)
Matrix Total Score	53.0 (13.4)	61.9 (8.5)

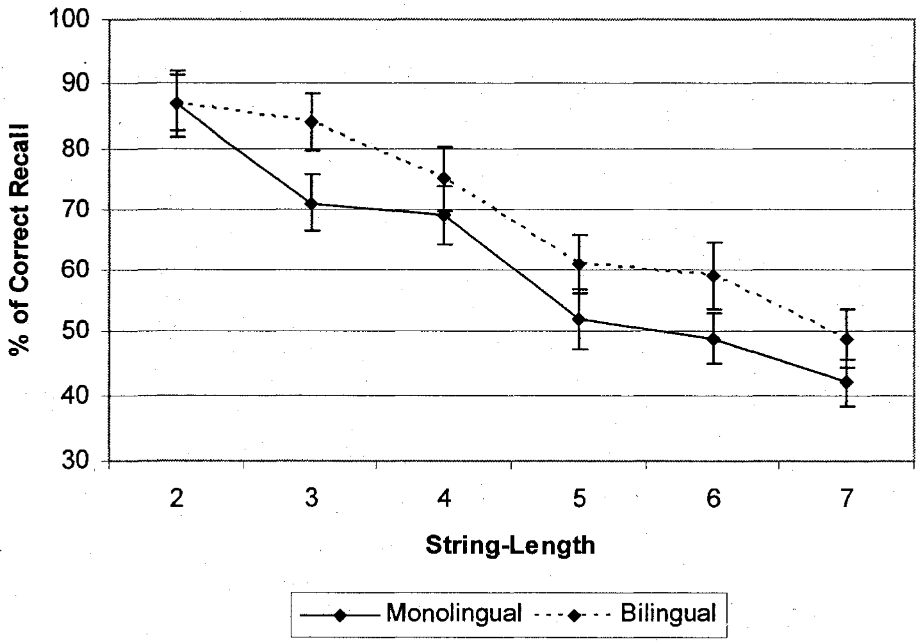
Note. For Matrix total score, n = 18 for monolinguals and n = 16 for bilinguals.

For the Matrix Span task, both groups showed an average string length of 4 as the maximum length at which they could recall at least one trial correctly, Fs < 1. A two-way ANOVA of language group (monolingual, bilingual) and scoring conditions (strict, total) showed a significant main effect of conditions for score, $F(1, 32) = 108.25, p < .0001, \eta^2 = .32$. For most of the participants, the total score, which includes the scores for the entire task, was always higher than the strict score, which ended at the string length where participants first failed at both trials. There was a main effect of language group, $F(1, 32) = 5.06, p < .03, \eta^2 = .12$, in which bilinguals scored significantly higher than monolinguals. The interaction between language group and scoring condition was not significant, Fs < 1. T-tests comparing the strict score and total score between the groups respectively showed that bilinguals performed the same as monolinguals on the strict score, $t(42) = -1.59$, ns.; but bilinguals scored higher than monolinguals on the total score, $t(32) = -2.29, p < .03, d = 0.82$.

The percentage of correct recall was calculated from the number of locations recalled in the correct serial position. The score obtained in each condition was divided by the maximum score for that condition and the result multiplied by 100. For example, for string length 4 (maximum score 7 for each trial), if the participant obtained a score of 12 for the 2 trials, then the percentage of correct recall would be 12 divided by 14 (7 + 7), which produces a percentage score of 86%. Figure 2 shows the probability of recall for each language group for each string length. A 2 X 6 two-way ANOVA for language group and string length (2, 3, 4, 5, 6 and 7) was conducted and the results showed significant effect of string length, $F(5, 155) = 30.1, p < .0001, \eta^2 = .36$, suggesting that percentage of correct recall decreases with increases of list-length. There was a main effect of language group, in which bilinguals outperformed monolinguals when comparing their percentage of correct recall at each string length, $F(1, 32) = 4.84, p < .04, \eta^2 = .05$. There was no interaction between string length and language group, *F*s < 1. Contrasts showed a decline in percentage of correct recall from string-length 2 to 3, $F(1, 32) = 4.21, p < .05$ and no decline from string-length 3 to 4, $F(1,32) = 1.21, p = .28$, but there was a significant decline of performance from string-length 4 to 5, $F(1,32) = 14.34, p < .0007$, the comparison between string-length 5 to 6 showed no decline, *F*s < 1, and there was only a marginal decline of performance from string 6 to 7, $F(1, 32) = 3.40, p = .08$. This pattern showed that participants started with correctly recalling almost all the locations when the string length was 2 (90%), and maintained good correct recall (> 70%) when the string-length was shorter than their average span length of 4. Although there was a decline of performance from string-length 4 to 5, participants somehow maintained their performance (50% - 60%) when the string length was 5 or 6; and finally when asked to recall the locations of 7 locations in a certain order, participants' performance level was decreased (< 50%).

The effect of list-length on monolinguals and bilinguals was examined again only on list-lengths 3-6 because the average span was 4 and the standard deviation for the span measure was about 1 for both language groups. Therefore the performance in list-length 2 and 7 was beyond 2 standard deviations of the average string length and actually the performance in list 2 was at ceiling (90% of correct recall). For this middle range where the data are properly distributed, a 2-way ANOVA of language group and list-length showed that the probability of correct recall was higher for bilinguals, $F(1, 39) = 6.97$, $p < .02$, $\eta^2 = .07$, and both groups showed the same decline of performance with increases of list-length, $F(3, 117) = 20.59$, $p < .0001$, $\eta^2 = .23$, because the interaction of language group and list-length was not significant, *F*s < 1. Contrasts showed the same pattern as in the previous analysis in which all list-lengths were included in the analysis: a significant decline from list-length 4 to 5, $F(1, 37) = 21.44$, $p < .0001$, and no change for the performance from list-length 3 to 4 or the decline from 5 to 6, both *F*s < 1.

Figure 2. Percentage of correct recall for each string-length in the Matrix span task in Study 2 by language group. Error bars represent standard error of the mean.



Discussion

The results from 22 bilinguals and 22 monolingual university students showed that the two groups performed similarly on alpha Span task, forward Corsi Block task and PPVT-III, but not on the Matrix Span task. However, bilingual young adults scored significantly higher in the Matrix Span task than monolinguals, especially on the total scores; although both groups showed an average string length of 4 as the maximum length at which they could recall at least one trial correctly. Bilinguals, however, had a significantly higher percentage of correct recall for all the list-length of 2 – 7.

These results suggest that although bilingual young adults showed similar spatial memory capacity (forward Corsi Block), they performed better than monolinguals when the spatial memory task placed a higher demand for processing (rearranging the locations), especially when the amount of information was beyond the average span (string length 5, 6 and 7). Both groups experienced difficulty when the list-length was greater than the maximum length at which they could recall correctly for at least one trial, but bilinguals outperformed monolinguals in all these difficult conditions that placed higher demands on controlled processing of spatial location information. Unsworth and Engle (2006) also suggested that performance at longer list lengths in a memory task reflects the retrieval of information from secondary memory and better predicts higher-order cognitive functions.

Because there were missing data for 10 participants (4 monolinguals and 6 bilinguals), for the total scores of the Matrix span tasks, the ANOVAs reported in the results section were rerun using data only for the subgroup of participants with no missing data. This is to eliminate the possibility that the subgroup of 18 monolinguals and 16 bilinguals were not equivalent on the background measures. The results showed that like for the whole sample, the subgroup of monolinguals and bilinguals had the same performance in alpha span, Corsi block and PPVT tasks. The strict scores for the Matrix Span task were not different between the two language groups, but the bilinguals scored higher than the monolinguals on the total scores. So even for the subgroup of participants, bilinguals' higher scores in the Matrix span task seemed to be affected by bilingualism but not the general better memory task performance. However, it should be noted that for either the entire group or the subgroup of bilinguals, they did have equivalent vocabulary scores as the monolinguals. Usually young adult bilinguals score lower on the vocabulary tests (e.g., Bialystok & Feng, in press). Therefore it is still possible to that the higher scores for bilinguals in the Matrix span task reflected factors other than bilingualism, such as language proficiency in English.

These results are consistent with the hypothesis of a bilingual advantage in spatial WM and also suggest that the potential bilingual advantage might be more evident when the amount of information is beyond the individual capacity level, therefore requiring participants to use their abilities of attentional control to coordinate the multiple processes of information storage and processing (rearranging spatial locations in the case of Matrix span task). Previous research has shown a bilingual advantage in executive control, so the results of Study 2 provide another example of bilinguals' better control ability in a WM paradigm. But the sample size of Study 2 was small and this WM advantage was only evident in one novel spatial WM task. It remains a question that whether the same pattern of results will hold for other WM tasks more widely used in the WM literature. In Study 3, the relationship between bilingualism and WM is further examined with WM tasks placing different demands on controlled processing, and the questions of whether the different WM performance could be explained by factors such as processing speed or attentional focus were explored.

STUDY 3: BILINGUALISM AND WORKING MEMORY

Study 2 showed bilingual advantage in a spatial WM task. Study 3 was designed to further investigate the relationship between WM and bilingualism. The first major goal was to specify the extent to which bilingual advantage is evident in WM measures, and the second major goal was to examine the factors affecting WM performance for monolinguals and bilinguals, including executive control, processing speed, and attentional scope.

In Study 3, monolingual and bilingual young adults were compared on both spatial and digit WM tasks. The cognitive load of the WM measures was manipulated by independently varying the demands for attentional control (simple and complex task) and information processing demand (serial recall and transformational/sequencing recall). The information processing demands were lower in serial/forward memory tasks as a measure of short-term storage, whereas the demands were higher in the transformational/sequencing WM tasks which were based on the alpha span paradigm (Craik, 1986). A complex WM task paradigm was implemented in which successful recall required maintenance in memory of digits or spatial locations and their associated colour information. Compared with simple WM tasks, the complex paradigm placed higher demands of attentional control. There were altogether four conditions that reflected the combination of two levels of attentional control (simple, complex) with two levels of information processing demand (forward, sequencing).

The important question was whether bilingual young adults would perform better on WM tasks, and if so, at what levels of the manipulation would this difference be apparent. It was hypothesized that the bilingual advantage would be evident for these young adults only in the WM tasks that require higher levels of attentional control (complex task) or higher levels of information processing (transformational recall). This hypothesis follows from empirical evidence showing a bilingual advantage in tasks that place high demand on executive control. Both spatial and digit WM tasks were included in the study to represent WM constructs based on different content information. The same hypotheses stated above were made for both digit and spatial WM tasks.

Although there are many sources for limitations on individual and developmental differences in WM, there is little agreement on how the specific source affects WM performance. So far no model of WM has incorporated more than one factor affecting WM performance in one study. The current study examined three such potential sources of individual differences in WM: (a) executive control, (i.e., ability to control attention to the relevant task); (b) speed of information processing, (i.e., ability to monitor and coordinate incoming information within a limited amount of time); and (c) scope of attention (i.e., capacity of the focus of attention on task-relevant information). Therefore, measures of these constructs were included. Although a bilingual advantage is expected in the executive control measures, no empirical evidence has been offered for differences in measures of attention scope, therefore the hypothesis is that this measure will not differ across language groups. It is also expected that within the domain of processing speed, a simple reaction time (RT) task will not show a pronounced between-groups difference. However, it is hypothesized that the group difference will be greater for RT tasks with higher information processing load and attentional control demand as opposed to tasks with low load for stimulus-response (S-R) rules. Finally, individual variance in the information processing speed tasks within each participant in the bilingual group is expected to be smaller than that for the monolinguals, indicating more consistent performance by the bilinguals when attentional control demand of the tasks increase.

Although it is expected that performance on executive control, information processing speed, and attention scope tasks will be related to WM performance, of particular interest is how the performance on each of the tasks that tap different factors affecting WM performance will be related to overall WM performance, and whether these relationships will be affected by language experience. It is possible that the relationship between WM performance and the factors affecting WM performance (i.e., executive control, processing speed, and attentional scope) will be different for monolinguals and bilinguals. However, no clear hypotheses could be generated based on existing literature.

Method

Participants

In total 114 young adults participated in return for introductory psychology course credit. Based on the Language Background Questionnaire (LBQ) filled out by each participant prior to testing, there were 49 monolingual speakers of English (mean age = 20.2, *SD* = 1.7) and 45 bilinguals (mean age = 19.7, *SD* = 1.5). A further 20 participants could not be classified as monolingual or bilingual and were included in only some of the data analyses, as explained in the Results section. There were 29 females and 20 males in the monolingual group and 30 females and 15 males in the bilingual group, with no difference in the gender distribution between the two language groups, $\chi^2(1) = 0.56$, $p = .45$.

In the LBQ, both the experimenter and the participant gave a rating of the level of bilingualism for the participant on a 5-point scale in which 1 meant "entirely monolingual" and 5 meant "entirely bilingual." The experimenter's judgement was based on the reported ratio of usage of each language on a daily basis. A rating of 5 indicated the most balanced usage between the two languages. A rating of 3 indicated ambiguous situations in which participants had some experience with another language for a certain period of time in their lives but the usage was not balanced; for example, the other language was used only in particular situations. The ratings of bilingualism by participants and experimenter are presented in Table 5. Twenty participants were not assigned into either language group because their bilingualism rating was about 3. Correlational analysis on rating of bilingualism by participants and the experimenter showed that the ratings were significantly correlated, $r = .85$, $p < .0001$.

For monolinguals and bilinguals, a two-way ANOVA of language group and rater (participant, experimenter) showed that the self-ratings by the participants and the ratings by the experimenter were not different, Fs < 1; however, the ratings for the two language groups were significantly different, $F(92) = 1050.53$, $p < .0001$, with bilinguals receiving higher ratings in the levels of bilingualism. The interaction between language group and rater was significant, $F(92) = 9.11$, $p < .004$. For monolinguals, their self-rating was higher than the ratings by the experimenter, but for bilinguals, there was no difference between the judgement of the participant and the experimenter. This was probably because monolinguals tended to give themselves higher ratings in the level of bilingualism when they had taken language courses, but the experimenter's rating was based on the balanced usage of each language.

The bilinguals all spoke English in the community and at school and a non-English language at home on a daily basis throughout most of their lives, with the age at which English language had been acquired and begun to be used regularly ranging between 4- to 7-years old. Active regular usage of both languages equivalently started between 5 and 12 years of age. Twenty-nine of the 45 bilinguals claimed English to be their dominant language. Six of the bilinguals learned both languages at home before beginning formal schooling, with the remaining bilinguals speaking the non-English language at home and then learning English in formal school settings afterwards. Bilinguals' non-English languages included Cantonese (11), Tamil (5), Vietnamese (4), Urdu (3), Farsi (3), French (2), Hindi (2), and Armenian, Gujurati, Hakka, Hebrew, Italian, Khmer, Kutshi, Persian, Polish, Punjabi, Russian, Somali, Spanish, Telugu, and Turkish (one speaker for each language).

Table 5. *Means and SDs for the Ratings of Bilingualism in the LBQ by Language Group in Study 3*

Ratings	n	Participant	Experimenter
Monolingual	49	1.3 (0.8)	1.0 (0.1)
Bilingual	45	4.0 (0.7)	4.2 (0.4)
Unclassified	20	3.0 (0.8)	2.8 (0.4)

Tasks

Background Measures

Language background questionnaire (LBQ). This questionnaire was adapted from the LBQ used in Study 2, with more detailed questions to indicate the extent of language use in a variety of settings, age of acquisition of the language(s) spoken at home and in formal school environment, and age of the start of active use of the language(s) spoken. If the participants had not been born in Canada, language experience prior to arrival in Canada was also probed in detail in terms of the country they stayed (only for participants arriving in Canada after the age of 5, including 5 in the monolingual group and 17 in the bilingual group).

Raven's Advanced Progressive Matrices (RAPM; Raven, Raven, & Court, 1998). A computerized 12-item RAPM version (Bors & Stokes, 1998) rather than the complete set was used to assess general intelligence. Previous research has shown that the correlation between the short-form RAPM scores and scores on the Abstraction subtest of the Shipley was .61; the test-retest reliability of the short-form RAPM was .82 (Bors & Stokes, 1998). Instructions and 3 practice items were given before testing. RAPM is a test of inductive reasoning in which participants are given an item that contains a figure (with three rows and columns) with the lower right-hand entry cut out, along with eight possible alternative solutions. Participants choose the solution that correctly completes the figure (across rows and columns). There is no time limit to complete the test, and accuracy rather than speed was stressed in the instructions. The total number of items completed correctly is the score for the test.

Working Memory Tasks

The main experimental tasks were the digit and spatial WM tasks, each including four conditions that reflected the combination of two levels of attentional control (simple, complex) with two levels of information processing demand (forward, sequencing). In both the digit and spatial tasks, the forward task required recall of stimuli (i.e., digits or spatial locations) in the same order as they were presented. The sequencing condition required recall in a specified order, namely, ascending order for the digit tasks and matrix order for the spatial task. On the control dimension, the simple tasks required participants to recall only the stimuli (i.e., the digits or the spatial locations). In contrast, the complex tasks required participants to recall not only the stimuli, but also additional color information. Therefore, compared with the simple tasks, complex tasks placed extra demand of control of attention over items of different colors, because participants had to recall the stimuli in different color sets separately. In all the WM tasks, the string length increased from 2 to 8 in the simple condition and from 2 to 7 in the complex condition, with two trials at each string length. Both tasks were programmed in E-prime (Schneider et al., 2001) and presented on a Dell Latitude C840 laptop computer with a 15-inch monitor. After presentation of a string of digits or spatial locations, participants were asked to recall the information with no time limit.

Digit WM tasks. In the digit WM tasks, individual digits (1-9 in 32 point Arial bold font) were presented on the computer screen for 1 second each. Immediately after each digit series, three question marks appeared on the screen signalling that the participant was to recall the digits and report them orally in the order required by the condition. In the simple forward task, participants recalled the strings in serial order of presentation. The simple sequencing task was a transformational WM measure in which strings of digits were to be recalled in ascending order. The Complex digit WM tasks were adapted from the Letter-Number Sequencing subtest from the Working Memory Index in WAIS-III (Wechsler, 1997a), with digits randomly presented in different colors (red or blue). Participants were asked to recall digits of each colour separately in serial order (forward task) or in ascending order (sequencing task), with question marks in red or blue signalling which colour was to be recalled first. A pseudo-random procedure was used so that for half of the trials participants recalled red digits first and in the other half they recalled blue digits first.

For all digit WM tasks, testing began with a sequence of two digits, and the sequence increased by one digit after every second trial, producing two trials for each string length, to a maximum of 8 digits for simple tasks and 7 digits for complex tasks. The span measure was recorded as the longest string length at which the participant could recall all the digits in the correct order for at least one of the trials. The strict score was calculated by awarding one point for each digit recalled in the correct order in each digit string up to and including the string length of one more than the span. Computation of both the span and the strict score ended when the participant failed both trials at a given string length. Testing continued until participants had completed the entire cycle of stimuli, however, regardless of errors in earlier trials. A total score, therefore, also was calculated by awarding one point for each correct digit response in the entire task. The maximum score was 70 for the simple tasks and 54 for the complex tasks.

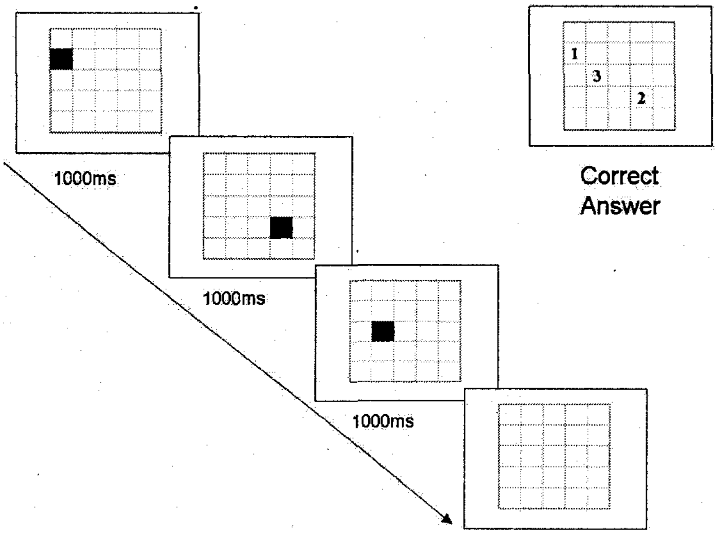
For each string length, like in Study 2, a percentage correct recall score was calculated by dividing the score participants earned in both of the two trials for that string length by the maximum score for that length and multiplying by 100. In the complex tasks, the second half of recall could have involved even higher levels of attentional control compared with the first half. To capture the potentially different recall performance in the first and second half of the complex task, percentage scores were calculated separately for the first and second halves of the task. For example, for string length 4, if the first trial was red 4, blue 8, blue 5, and red 7 and the participant recalled the string correctly, the score would be 2 for the first half and 2 for the second half. If the second trial was blue 9, red 7, blue 2, and red 6 and the participant recalled 9 and 3 for blue digits and 7 and 6 for the red digits, then the score would be 1 for the first half and 2 for the second half. In this example, the percentage score would be (2 + 1) / (2 + 2), producing 75% for the first half, and (2 + 2) / (2 + 2), producing 100% for the second half.

Spatial WM tasks. In the spatial WM task, a 5 X 5 matrix (1.8 inch X 1.8 inch) was presented on the computer and in each presentation one of the cells was filled in with red or blue. The matrices were presented one at a time, and at the end of the series, participants were asked to recall the locations of the coloured squares. Each matrix was shown for 1000 ms and was followed immediately by the next presentation. In the simple tasks, after the final presentation, the mouse cursor became visible on the screen and the next stimulus was a blank matrix in which the participant indicated the correct positions by pointing to the matrix cells with the mouse. In the complex tasks, after the final presentation, flashes of red or blue (250ms) signalled which colour was to be recalled first. The cursor then became visible and participants indicated the correct matrix cell locations on the screen using the mouse. As in the digit tasks, a pseudo-random procedure was used so that for half of the trials participants recalled red sequences first, and in the other half participants recalled blue sequences first.

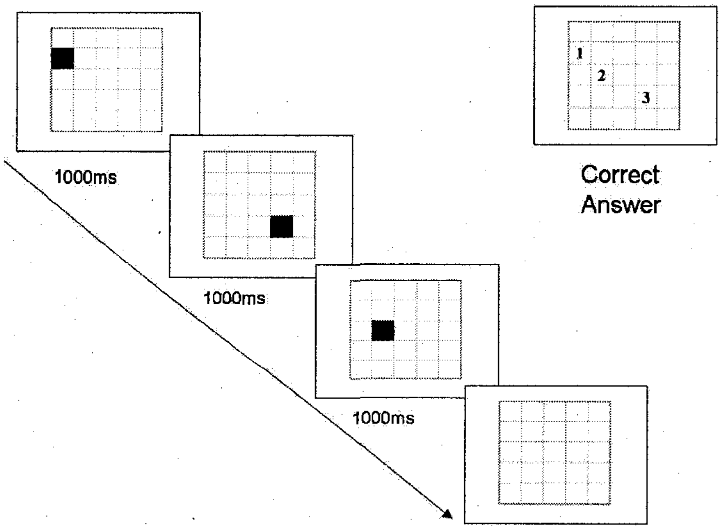
In the simple forward task (Figure 3a), participants indicated the order in which the stimuli were presented. In the simple sequencing task (Figure 3b), participants recalled the string of locations in the order proceeding from the left to right across the rows of the matrix, and from top to bottom through the columns, in other words, the order of reading print. In the complex tasks, both red and blue squares were presented and participants recalled the positions of the filled cells for each colour separately in the required order (complex forward task, Figure 3c, or in the matrix order, Figure 3d). The span, strict score, total score, and the percentage score were calculated in the same way as described for the digit WM tasks.

Figure 3. Example trials of the spatial WM tasks in Study 3 in a) simple forward task; b) simple sequencing task; c) complex forward task; and d) complex sequencing task.

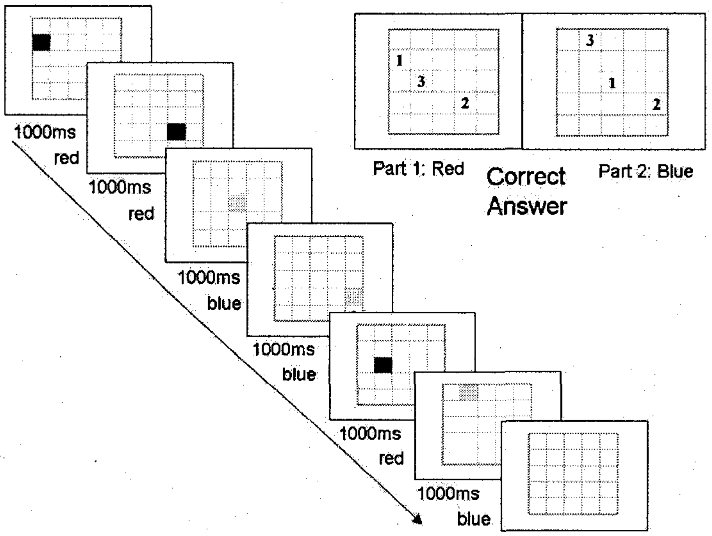
a) Simple forward spatial task



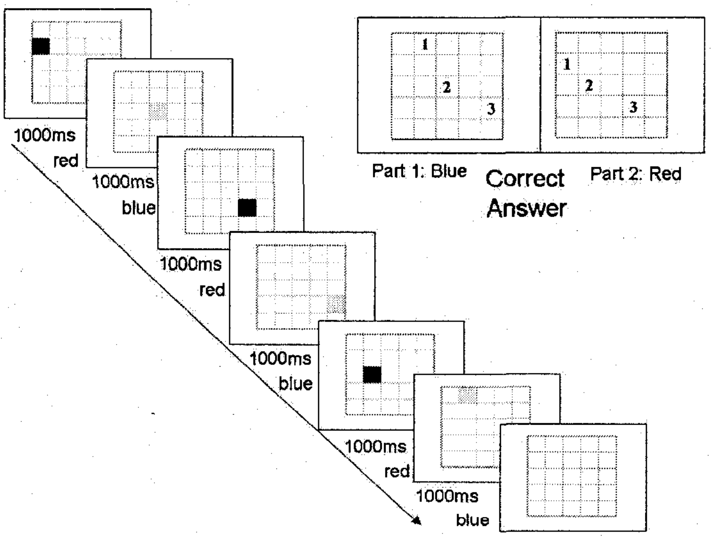
b) Simple sequencing spatial task



c) Complex forward spatial task



d) Complex sequencing spatial task



Tasks Measuring Factors Affecting WM Performance

Executive control tasks. The tasks measuring the general executive control capacity included Random Number Generation (RNG) and the incompatible S-R mapping level of the 2- and 4-choice processing speed tasks (presented in the next section). The RNG has been the most frequently used task for examining the central executive in Baddeley's (1986) WM model and has been always used to measure the general executive function in Miyake and colleagues' (2000) executive function model. In the RNG task (adapted from Miyake, et al., 2001), participants heard computerized beeps at the rate of one beep per 800ms and were asked to say a number from 1-9 for each beep such that the string of numbers produced was in as random an order as possible. The importance of maintaining a consistent response rhythm was emphasized during the instructions, and participants received a brief practice of 10 beeps before testing. The first 100 valid responses were recorded by a digital recorder.

The randomness of the generated sequence was analyzed using the RgCalc program (Towse & Neil, 1998), which produces "randomness" indices that tap different underlying executive control processes (Friedman & Miyake, 2004; Miyake et al., 2000). The randomness indices used in this study include the "inhibition indices" measuring the ability to resist producing stereotyped sequences (such as counting) and the "updating indices" measuring the tendency to cycle through the number set and use all responses equally often. The inhibition indices include Turning Point Index (TPI), Adjacency, Runs and Random Number Generation (RNG); and the updating indices include Redundancy, Coupon, and Repetition Gap (RG), all produced by the RgCale program (Towse & Neil, 1998). The indices of Phi 2-7 were not included in the analyses because they assess the tendency to avoid repeating responses at various intervals (e.g., “1, 1” or “1, 5, 1”), and previous research has suggested that this may be an automatic process that does not require limited capacity responses (Friedman & Miyake, 2004).

Processing speed tasks. The information processing speed tasks included simple and choice reaction time (RT) tasks following the rationale of Hick (1952) and Wilhelm and Oberauer (2006), using 1-, 2-, and 4-choice conditions. The tasks were programmed in E-prime (Schneider et al., 2001), and the E-prime response box was used to collect responses. There were six squares, each 1.5 inch X 1.5 inch, presented with one in the middle of the screen and the other five in a line at the bottom corresponding to the five keys on the response box placed in front of the monitor. Following a random inter-stimulus interval (ISI) ranging from 600ms to 1200ms, the middle square became coloured. Participants responded by pressing the appropriate key according to the stimulus-response (S-R) mapping rule for that condition, and RTs were recorded from the stimulus onset. Stimuli remained visible until participants responded, and immediately after the response the ISI began and then the next trial followed.

In the 1-choice condition (simple RT task), the centre square became black and the participants were asked to respond by pressing the middle key of the E-prime response box using the index finger of their dominant hand. There were 6 practice trials and 21 testing trials. In the 2-choice condition, the centre square became either red or blue, and in the 4-choice condition, the target square was red, blue, yellow, or green. The choice RT tasks (2- and 4-choice condition) each included four different S-R mapping rules: the first condition was a simple RT task that only required rapid acquisition of sensory input; in the compatible S-R mapping condition, the stimulus was to be matched with a key according to the cue on the computer screen; in the arbitrary S-R mapping condition the S-R rule was arbitrary and so participants were required to temporarily store this information. The incompatible S-R mapping condition involved an extra component of executive control, because it required matching stimuli with responses according to arbitrary S-R rules regardless of the misleading cue presented on the computer screen.

For example, in the 2-choice simple RT condition, participants were asked to respond by pressing either the left or the right key on the response box using the index finger of their dominant hand regardless of the colour of the centre square. In the compatible S-R mapping condition (Figure 4a), when the correct response for a blue square was to press the very right key on the response box and the correct response for a red square was to press the very left key on the response box, a blue square was always displayed to the very right in the row of squares and a red square to the very left, to indicate the S-R mapping rule. In the arbitrary S-R mapping condition (Figure 4b), there was no coloured square displayed on the screen and therefore no cues to facilitate a correct answer. Participants had to remember an arbitrary rule of "for a red square, press the left key; for a blue square, press the right key." In the incompatible S-R mapping condition (Figure 4c), when the correct response for a red square was to press the right key and the correct response for a blue square was to press the left key, a blue square was always displayed above the response key designated for a red square. Therefore, participants had to ignore the misleading cues in this condition. The 4-choice condition used the same paradigm as in the 2-choice condition but placed higher WM demands for the S-R rules. The arbitrary and incompatible S-R rule mapping conditions of the choice RT tasks are not pure measures of processing speed (Wilhelm & Oberauer, 2006), and bilinguals' better executive control may be evident in these conditions because they involve higher levels of attentional control, at least when memory load is highest (4-choice condition).

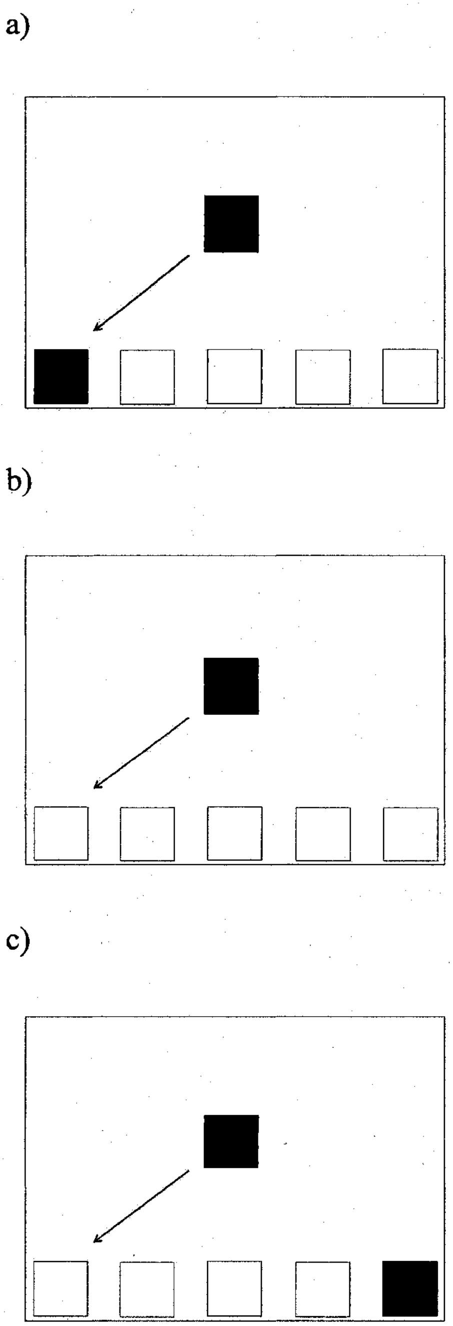
In both the 2-choice and 4-choice RT tasks, the association of a coloured square and the response key were changed from one condition to another to eliminate the possibility of overlearning over the three complex RT conditions. For example, in the 2-choice RT task, if the blue square was associated with the response of the right key in the compatible S-R mapping condition, in the following arbitrary S-R mapping condition, blue square was then associated with the left response key; and finally in the incompatible S-R mapping condition, a blue square was associated with the right response key.

In the choice RT tasks, for both 2-and 4-choice tasks, each condition began with instructions and practice that focused on the given S-R mapping. There were 12 practice trials and 42 testing trials for each 2-choice condition and there were 24 practice trials and 84 testing trials for each 4-choice condition. Both RT and accuracy data were recorded for each trial. In the 2-choice condition, the assignment of the S-R mapping rule for red/blue to the left/right key was counterbalanced among participants, therefore there were 2 versions of the 2-choice RT tasks; in the 4-choice condition, the assignment of S-

R mapping rule for the 4 colors to 4 side keys on the response box was also counterbalanced and resulted in 4 versions of the 4-choice condition task.

Attention scope task. Digit running memory task (adapted from Mayes, 1988) was used as measurement of the capacity for focused attention. There were two lists of practice items and nine lists of digits (1-9) randomly presented on the computer screen. The digits were in 32 point Arial bold font and were presented for 800 ms each followed by a blank screen of 200ms ISI. The length of the digit string lists ranged from 12 to 20 items and participants were not informed of the list length to be presented. Therefore, attention was constantly required for successful performance. When the list ended, participants were asked to recall as many digits as they could, beginning with the last one presented in backward order through the list. The responses were recorded using a digital recorder. The average number of digits correctly recalled in the backward order starting from the last digit for each sequence was used as the running memory span.

Figure 4. Example trials in the choice RT tasks in Study 3, when the arrow indicating the correct response is the very left key on the response box, in the a) compatible, b) arbitrary, and c) incompatible S-R mapping condition.



Procedures

All participants were tested individually with tasks presented in a fixed order: Language Background Questionnaire, digit and spatial simple WM tasks (part 1), 1- and 2-choice processing speed task, digit and spatial simple WM tasks (part 2), running memory task, digit and spatial complex WM tasks (part 1), Random Number Generation task, digit and spatial complex WM tasks (part 2), and 4-choice processing speed task. Both the information processing level (forward, sequencing) and the content (digit, spatial) of the WM tasks were counterbalanced: half of the participants got the forward tasks in part 1 the other half of the participants got the sequencing tasks in part 1; also half of the participants got the digit tasks before the spatial tasks and the other half always got the spatial tasks before the digit tasks. The two versions of the 2-choice processing speed tasks and the four versions of the 4-choice processing speed tasks were given to participants equally often. In both the 2- and 4-choice tasks, the four conditions were always given in the fixed order: simple RT, compatible S-R mapping, arbitrary S-R mapping, and incompatible S-R mapping. At the end of the testing session, all participants were given RAPM and PPVT-III (Dunn & Dunn, 1997) in addition to all the experimental tasks. PPVT-III was the same as used in Study 1 and 2. All participants were tested in a single session of about one hour and a half.

Results

Prior to conducting data analysis, all the data were preprocessed for data trimming and outlier analyses. With respects to the first goal of Study 3, the ANOVAs comparing the two language groups were then presented to examine different performance by monolinguals and bilinguals. The 20 participants who were classified as neither monolinguals nor bilinguals were excluded from these group comparisons. Subsequently, principal component analyses based on the data from all the participants regardless of language group (including the 20 unclassified participants) were conducted, to explore the construct of WM as well as the multiple measures of factors affecting WM, namely, attentional control, processing speed, and attentional scope. Finally, based on the results of the principal component analysis for attentional control, processing speed, and attentional scope measures, four component scores from principal component analysis were entered into a multiple regression model as dependent variables for the whole sample and then for each language group separately. The potential factors affecting WM performance were entered as predictors. The aim of this regression model is to illustrate the second goal of Study 3, that is, to examine how each factor affecting WM contributes to overall WM performance and how the contributions of different factors differ between the two language groups.

Data Trimming and Outlier Analyses

The 20 participants whose experimenter's rating of bilingualism level prevented their classification into the monolingual or bilingual groups were not included in any of the ANOVAs but were included in the principal component analyses when language group was not a factor of interest. Data screening was used to eliminate outliers from the subsequent analyses.

For the RT measures in the processing speed tasks, all RTs for error trials and all RTs less than 150 ms and greater than 2000 ms were excluded from analyses. Thus 1.7 %

RT data were excluded from the subsequent analysis. Also for the RT tasks, the first two trials in each condition were treated as warm-up trials and therefore not included in the analysis. In each condition, an accuracy of 70% was set as inclusion criterion (otherwise treated as missing data), and this deleted less than 1% of all the data. For RTs in each condition, observations of more than 3 *SD*s from the group means were eliminated from the analysis without replacement. This trimming further affected no more than 1.8% of the observations for any condition.

For the measures in the WM tasks, the observations of span measures that were more than 3 *SD*s from the group means were also eliminated without replacement (including span, strict score, and total score for the participant) and this procedure affected less than 2.1% of the observations in all the memory measures. The effect of this trimming procedure did not differ between monolingual and bilingual groups.

ANOVA

One-way ANOVAs were first used to compare monolinguals and bilinguals on all tasks and measures. The mean scores and standard deviations (*SD*s) for the background measures, running memory, 1-choice simple RT task, and seven randomness indices for the RNG task are reported in Table 6. For background measures, there was no difference between monolinguals and bilinguals in years of education, $F(1, 92) = 1.88, p = .17$, or the general intelligence test, Fs < 1, but the monolinguals scored higher in vocabulary score, $F(1,91) = 5.44, p < .03$. For the measure of attentional scope, monolinguals and bilinguals had the same spans in the running memory task, Fs < 1. In the simple RT in the 1-choice RT task, the two groups also were similar in coefficient of variances, *F*(1,

92) = 1.22, $p = .27$, and RTs, *F*s < 1. Monolinguals and bilinguals had the same baseline processing speed. For the measures of general executive control in the random number generation task, one-way ANOVA showed no language group difference on all the seven indices generated in the RNG task (RNG: $F(1, 92) = 1.57$, ns.; TPI: $F(1, 92) = 1.96$, ns.; Adj: $F(1, 92) = 1.85$, ns.; Runs: *F*s < 1; Redundancy: $F(1, 92) = 1.41$, ns.; Coupon: *F*s < 1; RG: $F(1, 92) = 1.22$, ns.). These results so far indicated that the monolinguals and bilinguals in Study 3 were equivalent on all measures of intelligence, attentional scope, simple RT, and general executive control, with monolinguals scoring higher in the receptive vocabulary test.

Table 6. *Mean Scores and SDs on Vocabulary, Intelligence, Running Memory, Simple RT, and Random Number Generation Task by Language Group in Study 3*

Variables	Monolingual $n = 49$	Bilingual $n = 45$
Years of education	13.8 (1.2)	13.5 (0.8)
PPVT-III std. score	103.9 (8.7)	99.3 (10.4)
Raven's Matrices score	5.3 (2.6)	5.6 (2.9)
Running Memory span	3.0 (0.9)	3.0 (0.7)
1-choice RT task, RT(ms)	209 (19)	204 (23)
1-choice RT task, CV	0.3 (0.3)	0.4 (0.3)
Random Number Generation	0.33 (0.04)	0.35 (0.05)
Turning Point Index	0.9 (0.1)	0.8 (0.1)
Adjacency	0.3 (0.1)	0.4 (0.1)
Runs	1.3 (0.5)	1.4 (0.6)
Redundancy	0.02 (0.02)	0.02 (0.01)
Coupon	18.1 (5.5)	17.3 (3.7)
Repetition Gap	8.7 (0.2)	8.6 (0.3)

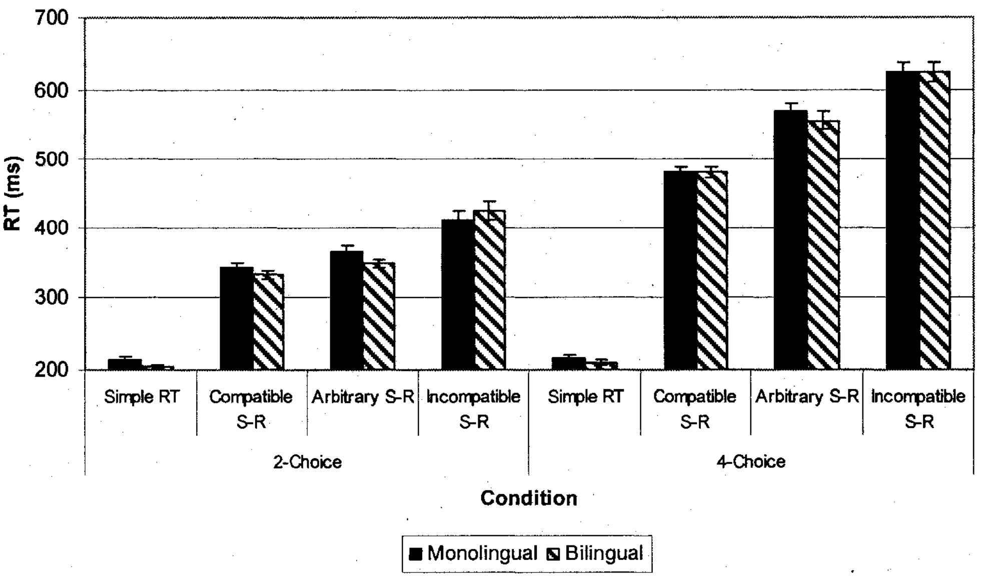
Note: CV = coefficient of variance

In the 2-choice and 4-choice processing speed tasks, the mean accuracies ranged between 92% and 100% in the 2-choice condition, and between 93% and 100% in the 4-choice condition, with no language group differences in any of the conditions, *F*s < 1. The mean RTs were calculated from the median RT for each participant in each condition and are presented in Figure 5a for the 2- and 4-choice condition. A three-way ANOVA of choice (2-choice, 4-choice), S-R mapping condition (simple RT, compatible, arbitrary, incompatible), and language group (monolingual, bilingual) showed a main effect of number of choices, $F(1, 79) = 1003.7$, $p < .0001$, with RTs in the 2-choice condition faster than in the 4-choice condition. There were main effects of S-R mapping condition, $F(3, 237) = 1143.25$, $p < .0001$, with each inter-condition difference significant, $p < .0001$, showing that the compatible S-R mapping condition elicited slower responses than the simple RT condition, followed by slower responses in the arbitrary S-R mapping condition, and the slowest responses in the incompatible S-R mapping condition. There was an interaction between number of choices and mapping condition, $F(3, 237) = 187.24$, $p < .0001$: the RT difference between 2- and 4-choice condition was the smallest for the simple RT condition, followed by compatible S-R mapping condition, and it was greatest in both arbitrary and incompatible S-R mapping, with no difference between these two conditions. There was no main effect of language group or any interactions with language group, all *F*s < 1.

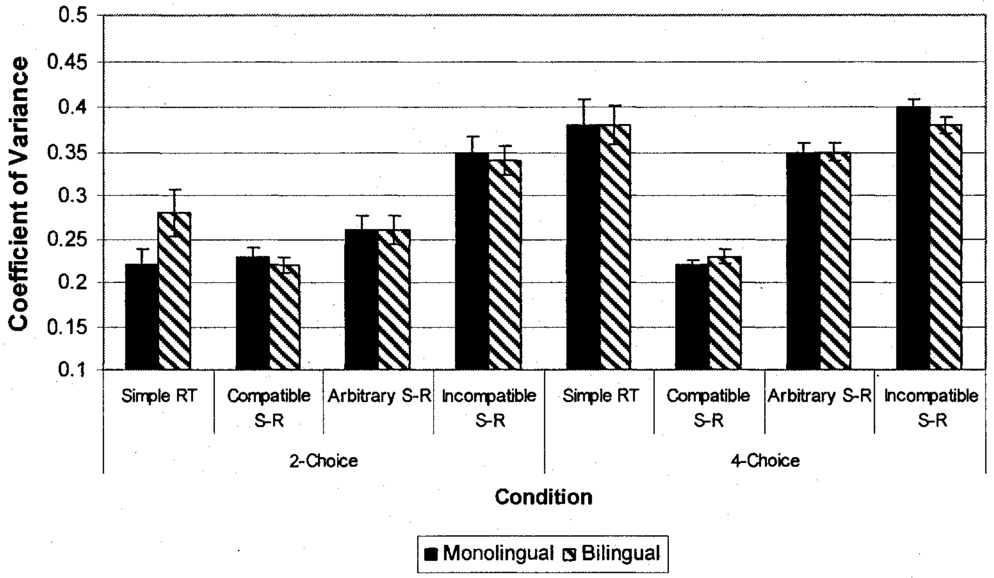
Coefficient of variance (CV), an individual's standard deviation (*SD*) of RT divided by his or her mean RT, is also used as index of speed performance (e.g., Segalowitz & Segalowitz, 1993). The same three-way ANOVA on the CV data showed the same patterns of results as the RT data, with no main effect of language group, *F*s < 1. In the choice-RT tasks, bilinguals and monolinguals showed similar speed and variability of speed, in both the simple RT conditions and the more complex RT conditions with compatible, arbitrary, and incompatible S-R mapping rules.

Figure 5. Mean of median RTs (a) and coefficient of variances (b) for the 2- and 4-choice processing speed tasks in Study 3 by language group and S-R mapping rules.

a)



b)



Data reported in Table 7 indicate the mean spans for WM in the simple forward, simple sequencing, complex forward, and complex sequencing condition, for both the spatial (Table 7a) and digit (Table 7b) versions. Two three-way ANOVAs for complexity (simple, complex), processing level (forward, sequencing), and language group were carried out on the data for spatial and digit tasks separately. For the spatial tasks, there were main effects of complexity, $F(1, 80) = 48.09, p < .0001$, processing level, $F(1, 80) = 15.80, p < .0002$, but no interaction between them, *F*s < 1. In the spatial WM tasks, spans in the forward version were lower than in the sequencing version, and the spans for complex tasks were lower than in the simple tasks. There was no main effect of language group, and neither of the two-way interactions with language were significant, all *F*s < 1. However, a 3-way interaction of language group, complexity and processing level was significant, $F(1, 80) = 8.89, p < .004, \eta^2 = .01$: for bilinguals, the span difference between the forward and sequencing versions was greater in the complex tasks than in the simple tasks; whereas for monolinguals, the span difference between forward and sequencing version was greater in the simple tasks than in the complex tasks. This pattern could be possibly because bilinguals scored higher than monolinguals on span, the maximum number of items recalled in the correct order, in the simple forward version of the spatial memory task, $F(1, 80) = 7.32, p < .009, \eta^2 = .09$.

For the span scores of the digit tasks, there were main effects of complexity, $F(1, 78) = 39.83, p < .0001$, processing level, $F(1, 78) = 30.03, p < .0001$, and a significant interaction between them, $F(1, 78) = 12.21, p < .0009$. In the digit WM tasks, spans in the forward version were lower than in the sequencing version, and the spans for complex tasks were lower than in the simple tasks. The span difference between sequencing version and forward version was greater in the simple tasks than in the complex tasks. There was no main effect of language group, and neither of the interactions with language was significant, all *F*s < 1.

Strict and total scores in the spatial memory tasks are presented in Figures 6a and 6b. Three-way ANOVAs for task complexity (simple, complex), processing level (forward, sequencing), and language group were carried out on the data for strict scores and total scores separately. For the strict scores, there were main effects of complexity, $F(1, 80) = 83.64, p < .0001$, and processing level, $F(1, 80) = 22.32, p < .0001$, with no interaction between them, *F*s < 1: scores in the forward version were lower than in the sequencing version, and the scores for complex tasks were lower than in the simple tasks. There was no main effect of language group, $F(1, 80) = 1.73, p = .19$, but there was a three-way interaction of language group, task complexity, and processing level, $F(1, 80) = 5.19, p < .03, \eta^2 = .06$: monolinguals showed a greater score difference between forward and sequencing versions in the simple tasks than in the complex tasks, whereas bilinguals showed the opposite pattern. This interaction was possibly driven by the fact that the bilinguals scored higher in the simple forward version of the spatial memory task, $F(1, 80) = 6.58, p < .02, \eta^2 = .08$.

The results of the analysis of total scores showed a similar pattern as that found for the strict scores: there were main effects of task complexity and processing level with no significant interactions (see Appendix A for full analyses). However for the total score, the main effect of language group was marginally significant, $F(1, 80) = 3.27, p =$

.07, $\eta^2 = .04$, with a trend that bilinguals scored higher than monolinguals in the total scores of the spatial tasks. There was no three-way interaction of language group, task complexity, and processing level, $F(1, 80) = 1.05, p = .30$. Unlike for the strict scores, the total scores for bilinguals were significantly higher than monolinguals in the sequencing version of the complex task, $F(1, 80) = 4.85, p < .04, \eta^2 = .06$. There was also a trend that bilinguals scored higher in the simple forward version of the spatial memory task, $F(1, 80) = 2.90, p = .10, \eta^2 = .03$.

The strict scores and total scores data for the digit tasks (Figure 7a and 7b) showed the same complexity and processing level effects as in the spatial tasks, and there was no main effect of language group in either the strict scores or total scores. Bilinguals and monolinguals scored similarly in the digit tasks. However, unlike in the spatial tasks, there was an interaction of complexity and processing level for both the strict and total scores. The score difference between the forward version and sequencing version was greater in the simple tasks than in the complex tasks. Also unlike in the spatial tasks, neither of the three-way interactions of language group, complexity and processing level was significant. For completeness, the corresponding analyses on the digit memory score data are presented in Appendix B.

To summarise the data on WM tasks for both spans and scores, complex tasks elicited worse performance than simple tasks; contrary to the hypothesis, forward tasks elicited worse performance than the sequencing tasks. In the digit tasks, the difference between forward and sequencing version was more evident in the simple tasks, but in the spatial tasks, this difference was of equal size in both simple and complex tasks. This pattern was also unexpected but could possibly show that the digit complex tasks were not as demanding as the spatial complex tasks because the digit complex tasks almost washed out the difference between sequencing and forward tasks. There were no main effects of language group in any of the analyses, but some significant interactions in the analyses of the spatial tasks indicated bilinguals' better performance in the simple forward spatial task and the complex sequencing spatial task. These results are as hypothesized and will be further interpreted in the Discussion.

Table 7. *Mean spans and standard errors by language group and task type for a) spatial memory tasks; and b) digit memory tasks*

a) Spatial memory tasks

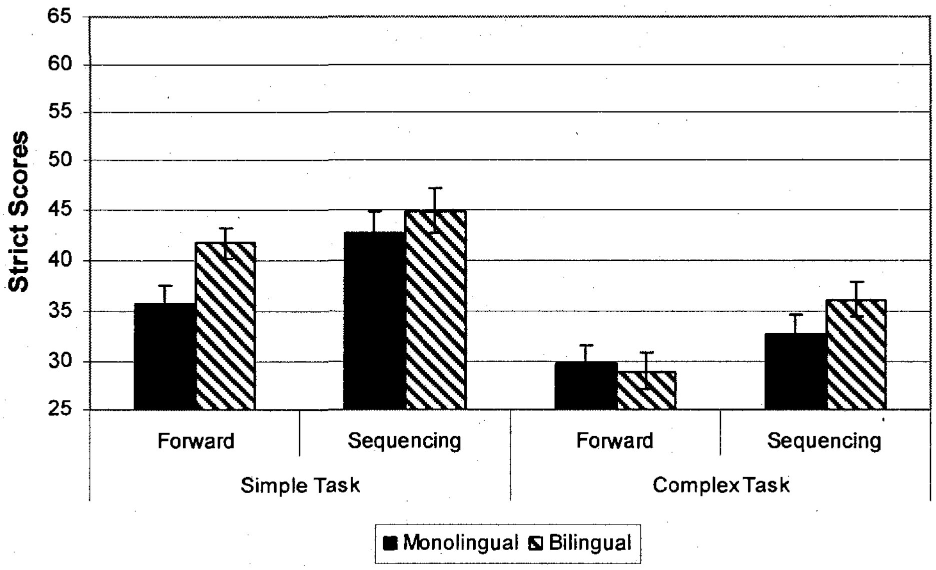
	Simple Task		Complex Task	
	Forward	Sequencing	Forward	Sequencing
Monolingual	5.2 (0.2)	5.8 (0.2)	4.9 (0.2)	5.1 (0.2)
Bilingual	5.7 (0.1)	6.0 (0.2)	4.6 (0.2)	5.3 (0.2)

b) Digit memory tasks

	Simple Task		Complex Task	
	Forward	Sequencing	Forward	Sequencing
Monolingual	5.7 (0.1)	6.6 (0.2)	5.2 (0.2)	5.3 (0.2)
Bilingual	5.8 (0.2)	6.8 (0.2)	5.3 (0.2)	5.6 (0.2)

Figure 6. a) Strict scores and b) total scores for the spatial WM tasks by language group in Study 3

a) Strict scores for the spatial tasks



b) Total scores for the spatial tasks

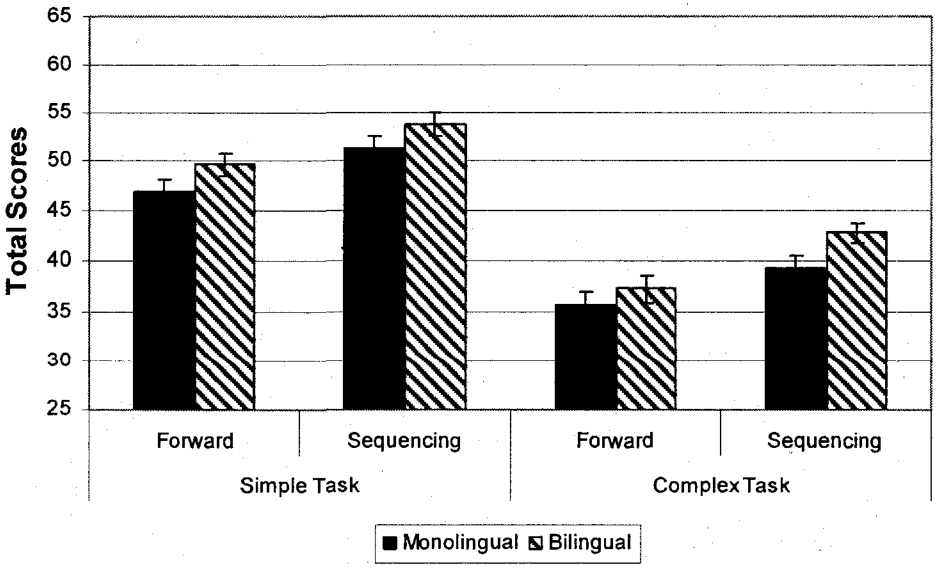
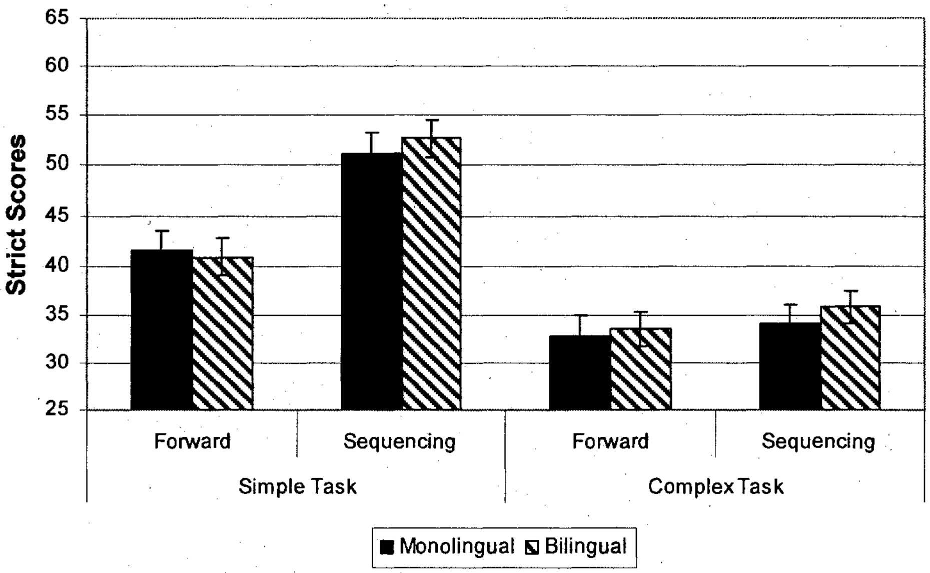
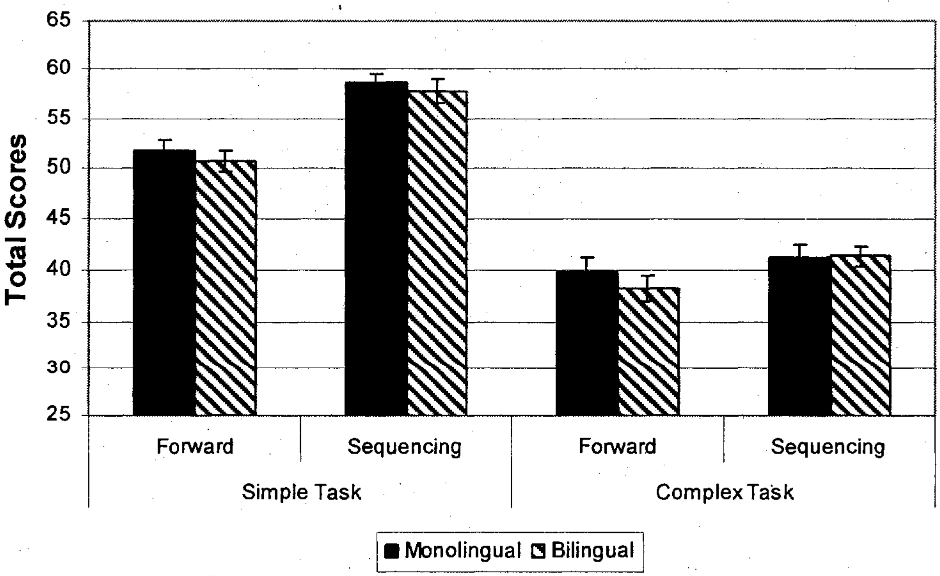


Figure 7. a) Strict scores and b) total scores for the digit WM tasks by language group in Study 3

a) Strict scores for the digit tasks



b) Total scores for the digit tasks

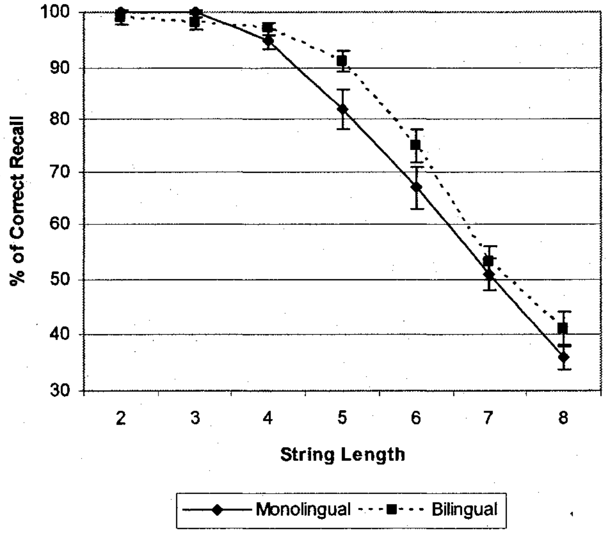


Figures 8 and 9 present the percentage of correct recall for each string length for the spatial and digit tasks separately. Two-way ANOVAs for language group and string length (2-8 for simple task and 2-7 for complex task) were carried out on these data separately for the eight memory task conditions – simple or complex and forward or sequencing versions of both the spatial and digit tasks. Full results for these analyses are presented in Appendix C. The complex sequencing spatial task revealed a significant language group effect, $F(1, 80) = 5.00, p < .03, \eta^2 = .06$, in which bilinguals performed significantly better than monolinguals. The string length effect was also significant, $F(6, 480) = 84.27, p < .0001$, with each inter-condition difference significant, $p < .0001$, because the recall percentage decreased as the string length increased. There was no interaction between language group and string length, Fs < 1. Analyses on all other task conditions showed a similar pattern but there was no significant language group effect, although string length effect was always significant.

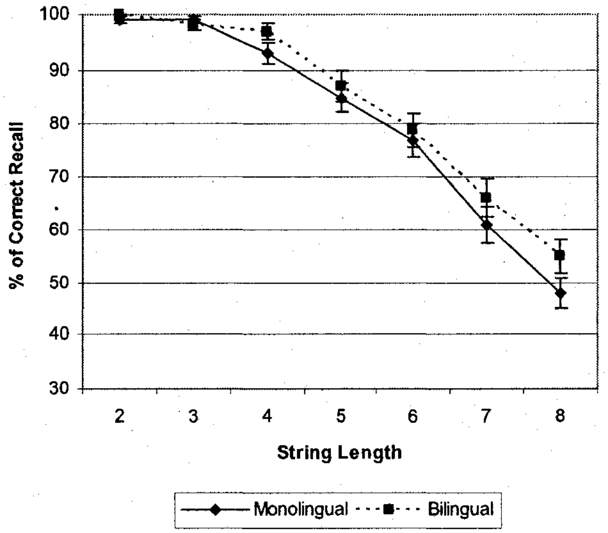
For the complex tasks, there were two parts to the recall corresponding to the two colour cues, so percentage scores were calculated separately for each part (Figures 10 and 11). Again, in the complex sequencing spatial task, bilinguals performed better in both part 1, $F(1, 80) = 4.17, p < .05, \eta^2 = .05$, and part 2, $F(1, 80) = 4.58, p < .04, \eta^2 = .05$. There was no interaction between language group and string length, both Fs < 1. Analyses of the other task condition showed no language group difference in either the first or second half of the recall.

Figure 8. Percentage of correct recall for each string length in spatial tasks in Study 3 by language group: a) simple forward; b) simple sequencing; c) complex forward; and d) complex sequencing.

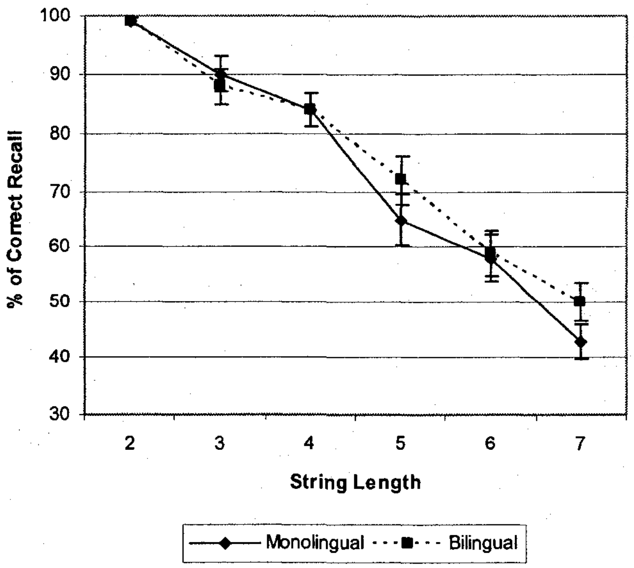
a) Simple forward spatial task



b) Simple sequencing spatial task



c) Complex forward spatial task



d) Complex sequencing spatial task

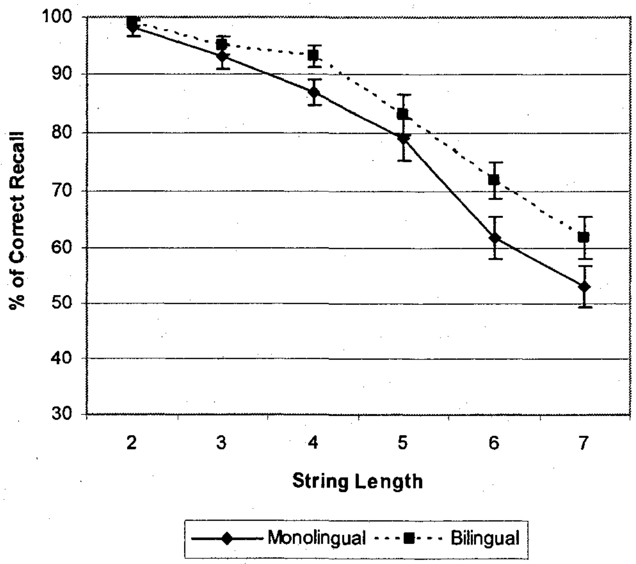
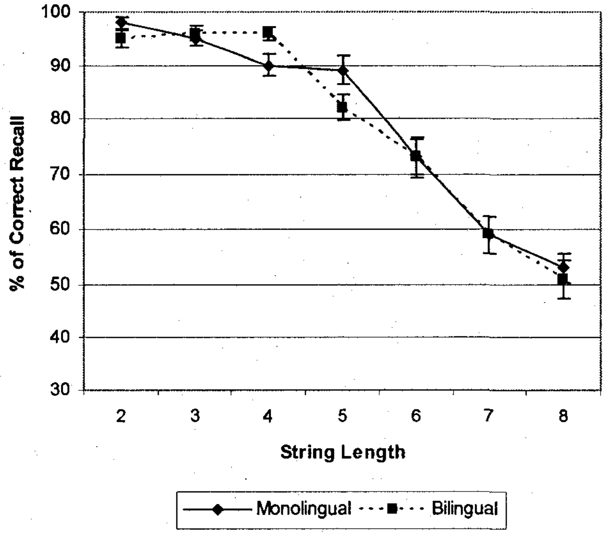
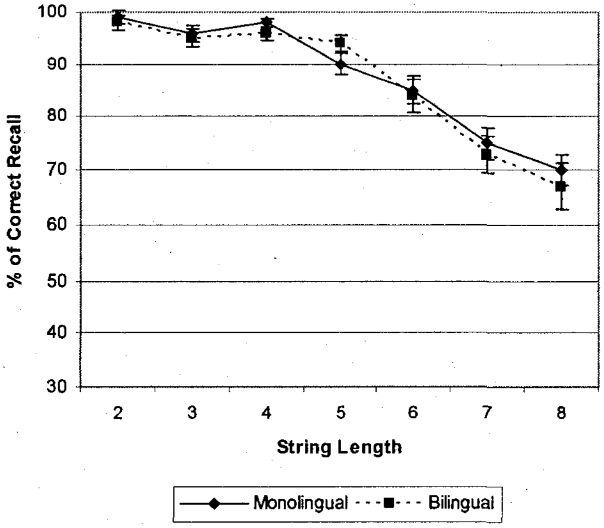


Figure 9. Percentage of correct recall for each string length in digit tasks in Study 3 by language group: a) simple forward; b) simple sequencing; c) complex forward; and d) complex sequencing.

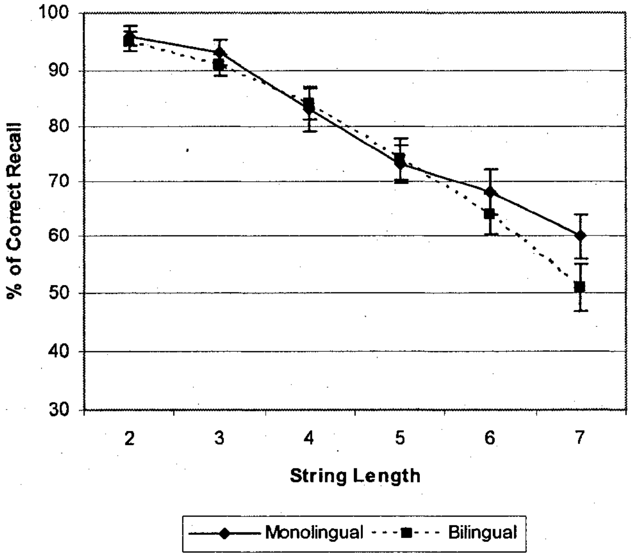
a) Simple forward digit task



b) Simple sequencing digit task



c) Complex forward digit task



d) Complex sequencing digit task

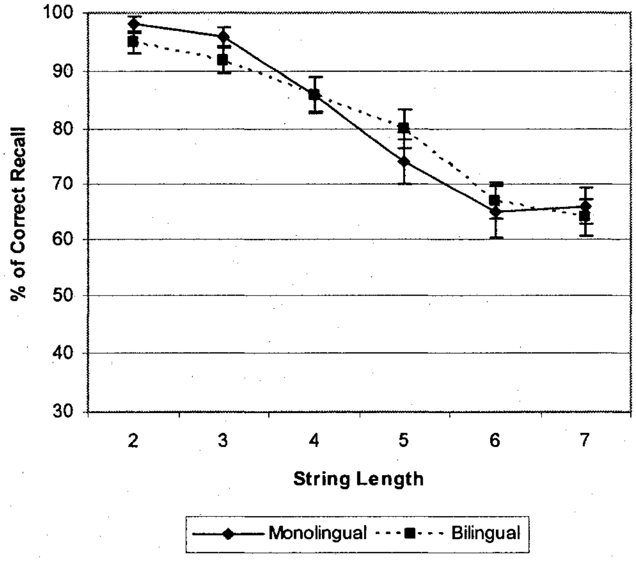
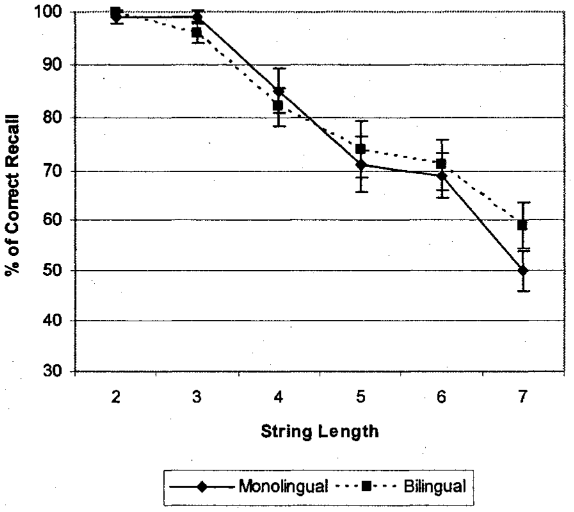
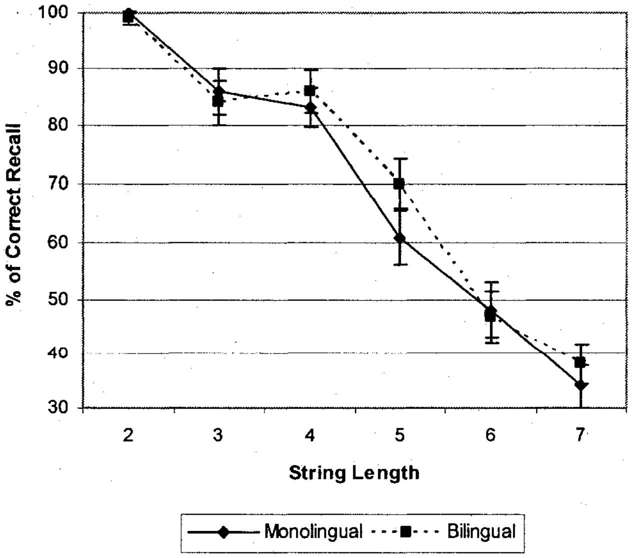


Figure 10. Percentage of correct recall for each string length in spatial tasks in Study 3 by language group: a) complex forward I; b) complex forward II; c) complex sequencing I; and d) complex sequencing II.

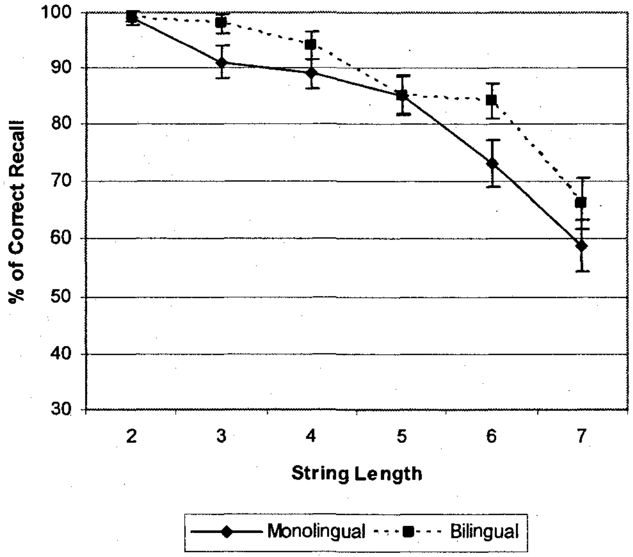
a) Complex forward spatial task I



b) Complex forward spatial task II



c) Complex sequencing spatial task I



d) Complex sequencing spatial task II

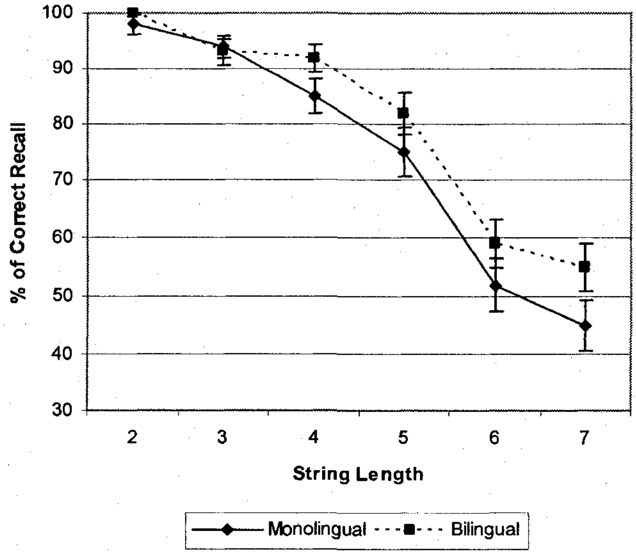
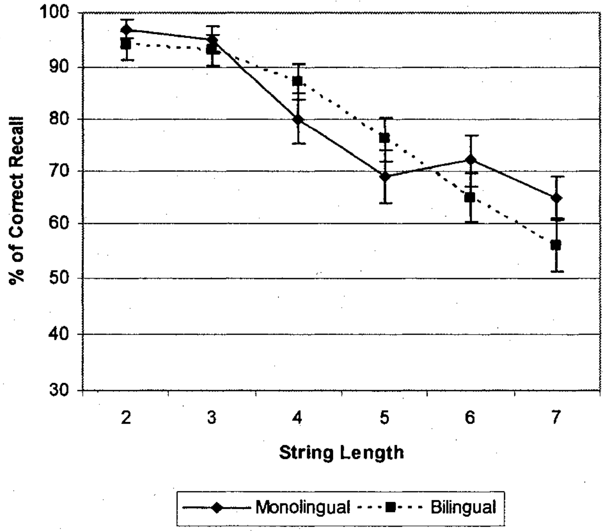
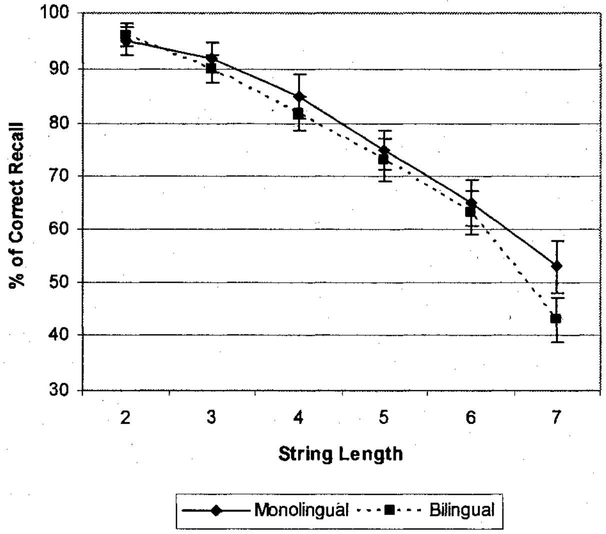


Figure 11. Percentage of correct recall for each string length in digit tasks in Study 3 by language group: a) complex forward I; b) complex forward II; c) complex sequencing I; and d) complex sequencing II.

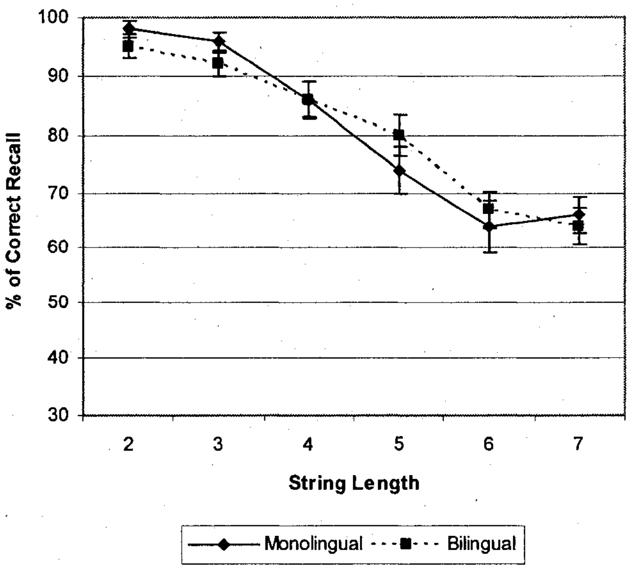
a) Complex forward digit task I



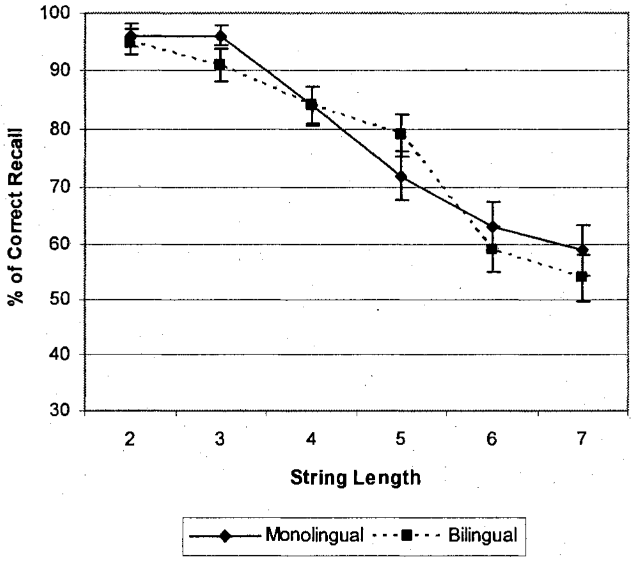
b) Complex forward digit task II



c) Complex sequencing digit task I



d) Complex sequencing digit task II



Principal Component Analysis

Principal component analysis makes no assumption about an underlying causal model. The objective of this type of analysis is to assess the proportion of the variance accounted for by the first few components in the data and can be used to summarize the data with little loss of information. Therefore, a principal component analysis was conducted to reduce the number of variables to be used in the final regression model to determine the factors that affected WM performance, including attentional control (7 variables: randomness indices in the Random Number Generation task including RNG, TPI, Adjacency, Runs, Redundancy, Coupon, and RG), processing speed (9 variables: RTs of 1-choice condition, 4 conditions in both 2- and 4-choice condition), and attentional scope (1 variable: running memory span). To obtain reliable results, the minimum number of participants providing usable data for the analysis should be at least five times the number of variables being analyzed (O'Rourke et al., 2005). In order to achieve better insight into the commonalities underlying the 8 WM measures and the 17 measures of factors possibly affecting WM performance, principal component analyses were performed on all the 114 participants tested, regardless of the language group assignment. The inclusion of the 20 unclassified participants was justified because language experience is not important in the identification of the construct of WM or the identification of the factors affecting WM.

First, total scores for all eight WM tasks were subjected to a principal component analysis to investigate the structure of WM. Table 8 displays the component loadings after applying a varimax (orthogonal) rotation. Three components were extracted on the basis of substantial eigenvalues (greater than 1: component 1 = 3.55; component 2 = 1.41; component 3 = 1.02), which together accounted for 75% of the total variance. In interpreting the rotated factor pattern, a measure was said to load onto a given component if the factor loading was .45 or greater for that component and less than .45 for the others (O'Rourke et al., 2005). Using these criteria, the first component attracted high loadings on the variables from all spatial WM measures, representing the spatial WM component. The scores from the digit span tasks, in contrast, loaded onto two component scores, with the complex digit tasks loading onto the second component and those from the simple digit tasks loading onto the third component. Therefore the results indicate that spatial and digit WM tasks measure different WM abilities and that WM is not one unitary construct. This is consistent with claims by Oberauer et al. (2000) that WM may have a differentiated pattern of correlations with factors of content abilities, such as numerical and spatial.

Table 8. *Component Loadings From Principal Component Analysis of all WM Test Scores in Study 3 With Varimax Rotation*

Memory Measures	Component 1	Component 2	Component 3	h^2
Simple Forward Spatial task	**.83**	.14	.15	.73
Simple Sequencing Spatial task	**.83**	.22	.15	.76
Complex Forward Spatial task	**.76**	.11	.11	.61
Complex Sequencing Spatial task	**.88**	.02	.15	.80
Simple Forward Digit task	.24	.09	**.79**	.69
Simple Sequencing Digit task	.10	.15	**.84**	.73
Complex Forward Digit task	.14	**.90**	.13	.84
Complex Sequencing Digit task	.15	**.89**	.12	.83

Note: n = 114. Communality estimates appear in column headed h^2.

Second, a principal component analysis was performed on all 17 measures of factors affecting WM: including 9 variables of speed (RTs of 1-choice condition, 4 conditions in both 2- and 4-choice condition), 7 indices for randomness in the RNG task (RNG, TPI, Adjacency, Runs, Redundancy, Coupon, and RG) and running memory span. Table 9 displays the component loadings after applying a varimax (orthogonal) rotation. Principal component analysis extracted four components on the basis of substantial eigenvalues (greater than 1: component 1 = 4.01; component 2 = 2.40; component 3 = 1.76; component 4 = 1.30), which together accounted for 68% of the total variance. An initial analysis showed that RTs in the compatible and arbitrary S-R mapping conditions in the 2-choice RT task loaded on both components 1 and 2 while the RTs in the incompatible S-R mapping condition in the 2-choice RT task loaded onto none of the components. To eliminate this problem, RTs in these 3 conditions were deleted from the final analysis.

In interpreting the rotated factor pattern, a measure was said to load on a given component if the factor loading was .45 or greater for that component, and was less than .45 for the others. Therefore, the first component attracted high loadings on the variables from simple RT in the 1-, 2-, and 4-choice conditions and it represented mainly the simple RT component of information processing speed. The third component showed high loadings of RTs in compatible, arbitrary and incompatible S-R mapping conditions in 4-choice condition and running memory span, representing the complex RT component of information processing speed. Consistent with the previous research, four measures (TPI, Adjacency, Runs and RNG) were found to load onto the second component of "response-distractor inhibition", and three measures (Redundancy, Coupon and RG) loaded on the fourth component of "WM updating" (Friedman & Miyake, 2004; Miyake et al., 2000).

Table 9. *Component Loadings from Principal Component Analysis of all 17 Variables of Factors Affecting WM Performance in Study 3 with Varimax Rotation*

	Component				
Measures	1	2	3	4	h^2
1-choice RT	**.82**	.04	.04	.09	.68
2-choice simple RT	**.88**	.04	.18	-.08	.82
2-choice compatible S-R mapping RT	-	-	-	-	-
2-choice arbitrary S-R mapping RT	-	-	-	-	-
2-choice incompatible S-R mapping RT	-	-	-	-	-
4-choice simple RT	**.88**	.08	.22	-.11	.83
4-choice compatible S-R mapping RT	.44	.23	**.71**	-.05	.76
4-choice arbitrary S-R mapping RT	.35	.10	**.77**	.03	.73
4-choice incompatible S-R mapping RT	.29	.13	**.72**	18	.66
Random Number Generation	-.07	**.78**	.06	.13	.63
Turning Point Index	-.14	**-.83**	-.03	-.10	.72
Adjacency	.04	**.82**	.07	-.06	.68
Runs	.09	**.76**	.18	.04	.62
Redundancy	.02	.06	-.08	**.79**	.62
Coupon	-.12	.15	.19	**.70**	.57
Repetition Gap	-.01	.04	-.01	**-.82**	.67
Running Memory Span	.17	-.01	**-.67**	.02	.48

Note: n = 114. Communality estimates appear in column headed h^2.

Multiple Regressions

The final step is to determine the structure of the relationships among all factors affecting WM performance for the whole sample first, and then for monolingual and bilingual groups separately in order to explore the relative importance of each of the measurements as determinants of the language group-WM relation. In order to investigate these questions, multiple regression analyses were performed. Previous results of principal component analysis indicated how the various potential factors that affect WM performance, information processing speed, executive control and attentional scope, related to one another. The first multiple regression was to demonstrate how these measures relate to overall WM performance for the whole sample. Since principal component analysis showed that WM measures represent three separate constructs of WM, spatial WM, simple digit WM, and complex digit WM, regression procedure was also conducted on the WM score, for spatial WM, simple digit WM and complex digit WM separately.

Using the multiple regression procedure, an aggregate measure of overall WM performance (average of total scores for eight WM task conditions) was regressed on the linear combination of the four factor scores (simple RT, complex RT, distractor inhibition and updating) obtained in the previous principal component analysis. Table 10 presents the beta weights and uniqueness indices for the main factors. The four factors together accounted for 41% of the variance in WM performance ($F(4, 100) = 17.09, p < .0001$, adjusted $R^2 = .28$). Beta weights (standardized multiple regression coefficients) and uniqueness indices were then reviewed to assess the relative importance of the four variables in the prediction of WM performance. The uniqueness index for a given predictor is the percentage of variance in the criterion accounted for by that predictor, beyond the variance accounted for by the other predictor variables. The results showed that complex RT displayed significant beta weights at .60 ($p < .0001$) and the beta weights for distractor inhibition was .21 ($p < .01$). The findings regarding uniqueness indices matched those for beta weights, in that only complex RT and distractor inhibition displayed significant indices. Complex RT accounted for approximately 36% of the variance in WM, $F(1, 100) = 59.94, p < .0001$, beyond the variance accounted for by all other factors. In contrast, distractor inhibition accounted for only 5% of the unique variance in WM, $F(1, 100) = 7.16, p < .01$. The composite performance of RTs in complex S-R mapping conditions and the running memory span appears to be the best indicator of WM performance for this young adult sample.

Table 10. *Beta Weights and Uniqueness Indices Obtained in Multiple Regression Analyses Predicting Overall WM for the Whole Sample in Study 3*

	Beta Weights		Uniqueness Indices	
Predictor	β	t	Uniqueness Index	F
Simple RT (Component 1)	-.07	-0.96	.01	0.92
Distractor Inhibition (Component 2)	-.21	-2.68**	.05	7.16*
Complex RT (Component 3)	-.60	-7.74**	.36	59.94**
Updating (Component 4)	-.11	-1.41	.01	1.99

* $p < .05$, ** $p < .001$

Note. $n = 114$. Adjusted $R^2 = .28$, $F(4, 100) = 17.09$, $p < .0001$, for predictor variables.

Based on the results of the multiple regression above, two factors were subjected to multiple regression for monolingual and bilingual groups separately: the composite overall WM score was regressed on the average z-scores of the four variables of distractor inhibition measure and the average of z-scores the four variables of complex RT measure. Tables 11a and 11b present the beta weights and uniqueness indices for the main factors for monolingual and bilingual group separately.

In the monolingual group, the results showed that complex RT and distractor inhibition together accounted for 36% of the variance in WM, $F(2, 41) = 11.33, p < .0002$ (adjusted $R^2 = .32$). The results showed that both complex RT and distractor inhibition displayed significant beta weights. Distractor inhibition demonstrated the larger beta weights at -.41($p < .01$), whereas the beta weight for complex RT was -.32 ($p < .05$). The finding regarding uniqueness indices matched those for beta weights, in that distractor inhibition accounted for approximately 15% of the variance in WM, $F(1, 41) = 9.42, p < .01$, beyond the variance accounted for by the complex RT factor, and complex RT accounted for 9% of the unique variance in WM, $F(1, 41) = 5.68, p < .02$. In the bilingual group, complex RT and distractor inhibition accounted for 10% of the variance in WM, $F(2, 40) = 2.22, p = .12$ (adjusted $R^2 = .06$). The results showed that only complex RT displayed significant beta weights at .31, $p < .05$, and significant uniqueness index, $F(1, 40) = 4.24, p < .05$, accounting for approximately 10% of the variance, beyond the variance accounted for by distractor inhibition. The results suggest that for both monolingual and bilingual young adults, complex RT accounted for variance in WM performance; however for monolinguals, distractor inhibition is a more important predictor, whereas for bilinguals distractor inhibition is not a significant factor in WM performance.

Table 11. *Beta Weights and Uniqueness Indices Obtained in Multiple Regression Analyses Predicting Overall WM for a) Monolingual Participants; and b) Bilingual Participants in Study 3*

a)

	Beta Weights		Uniqueness Indices	
Predictor	β	t	Uniqueness Index	F
Complex RT	-.32	-2.38*	.09	5.68*
Distractor Inhibition	-.41	-3.07*	.15	9.42**

* $p < .05$, ** $p < .001$

Note. n = 49. Adjusted R^2 =.32, F (2, 41) = 11.33, $p < .0002$, for predictor variables.

b)

	Beta Weights		Uniqueness Indices	
Predictor	β	t	Uniqueness Index	F
Complex RT	-.31	-2.06*	.10	4.24*
Distractor Inhibition	-.11	0.74	.01	0.54

* $p < .05$, ** $p < .001$

Note. n = 45. Adjusted R^2 =.05, F (2, 40) = 2.22, p = .12, for predictor variables.

Previous principal component analysis showed that three components were extracted from all eight WM measures, therefore, the aggregate measures of spatial WM, simple digit WM, and complex digit WM (average of total scores for WM variables of each component) were also regressed on the linear combination of the four component scores (simple RT, complex RT, distractor inhibition, and updating). Table 12 presents the beta weights and uniqueness indices for the main factors.

For the spatial WM measures (all four spatial WM tasks), the four factors together accounted for 28% of the variance in WM performance ($F(4, 102) = 10.15, p < .0001$, adjusted $R^2 = .26$). The results showed that complex RT and simple RT displayed significant beta weights at .48 ($p < .0001$) and .17 ($p < .05$), respectively. The findings regarding uniqueness indices matched those for beta weights, in that complex RT accounted for approximately 23% of the variance in spatial WM, $F(1, 102) = 33.21, p < .0001$, beyond the variance accounted for by all other factors; simple RT accounted for only 3% of the unique variance in spatial WM, $F(1, 102) = 4.28, p < .05$. The composite performance of RTs in complex S-R mapping conditions and the running memory span appear to be the best indicator of spatial WM performance for this young adult sample.

For the simple digit WM measures, the four factors together accounted for 19% of the variance in WM performance ($F(4, 104) = 6.19, p < .0002$, adjusted $R^2 = .16$). The results showed that complex RT and distractor inhibition displayed significant beta weights at .37 ($p < .0001$) and .19 ($p < .05$), respectively. The findings regarding uniqueness indices matched those for beta weights, in that complex RT accounted for approximately 13% of the variance in spatial WM, $F(1, 104) = 17.27, p < .0001$, beyond the variance accounted for by all other factors; distractor inhibition accounted for only 4% of the unique variance in spatial WM, $F(1, 104) = 4.80, p < .05$. For the complex digit WM measures, the four factors together accounted for 19% of the variance in WM performance ($F(4, 102) = 5.80, p < .0003$, adjusted $R^2 = .15$). The results showed that only complex RT displayed significant beta weights at .41 and it accounted for approximately 17% of the variance in spatial WM, $F(1, 104) = 20.86, p < .0001$, beyond the variance accounted for by all other factors. In sum, complex RT appears to be a stable predictor of WM performance. Other predictors are weaker and vary with the criterion task.

Table 12. *Beta Weights and Uniqueness Indices Obtained in Multiple Regression Analyses for the Whole Sample in Study 3, Predicting a) Spatial WM; b) Simple Digit WM; and c) Complex Digit WM*

a) Spatial WM

	Beta Weights		Uniqueness Indices	
Predictor	β	t	Uniqueness Index	F
Simple RT (Component 1)	-.17	-2.07*	.03	4.28*
Distractor Inhibition (Component 2)	-.14	-1.68	.02	2.82
Complex RT (Component 3)	-.48	-5.76**	.23	33.21**
Updating (Component 4)	-.03	-0.39	.01	0.14

b) Simple Digit WM

	Beta Weights		Uniqueness Indices	
Predictor	β	t	Uniqueness Index	F
Simple RT (Component 1)	-.01	-0.05	.01	0.01
Distractor Inhibition (Component 2)	-.19	-2.19*	.04	4.80*
Complex RT (Component 3)	-.37	-4.16**	.13	17.27**
Updating (Component 4)	-.14	-1.64	.02	2.68

c) Complex Digit WM

	Beta Weights		Uniqueness Indices	
Predictor	β	t	Uniqueness Index	F
Simple RT (Component 1)	.10	-1.07	.01	1.15
Distractor Inhibition (Component 2)	-.10	-1.11	.01	1.22
Complex RT (Component 3)	-.41	-4.57**	.17	20.86**
Updating (Component 4)	-.08	-0.87	.01	0.75

* *p* < .05, ** *p* < .001

Based on the results of multiple regressions above, only significant factors were subjected to multiple regressions for monolingual and bilingual groups separately: the composite spatial WM scores were regressed on the aggregate scores of simple RT and complex RT; the composite simple digit WM scores were regressed on the aggregate scores of complex RT and distractor inhibition (see Appendix E for full analyses). Monolinguals and bilinguals showed similar results. For the spatial WM measures, neither simple RT nor complex RT showed significant beta weights. For the simple digit WM measures, only for monolinguals, distractor inhibition displayed a significant beta weight at .33, and it accounted for approximately 9% of the unique variance in simple digit WM, $F(1, 43) = 4.85, p < .05$. For the complex digit WM measures, because only complex RT was a significant predictor, only correlational analysis was conducted on complex RT score and complex digit WM score. The complex digit WM score was correlated only with complex RT measure for monolinguals ($r = -.53, p < .0002$), but not for bilinguals($r = .01, p = .94$). In sum, for both the overall WM construct and the three subcomponents, predictor variables accounted for more variance in WM performance in monolinguals than in bilinguals.

However, because only very basic analysis methods were used in this investigation, the resulting model is rather simple. In addition, the results of the two language groups were not directly comparable. It is, thus, difficult to say how different factors account for the variance in WM performance for the two groups, other than at the descriptive level. Further questions remain as to whether speed and distractor inhibition would affect WM if other tasks were used; and whether the pattern of contributions of speed and distractor inhibition to overall WM will hold for other age groups.

Discussion

Study 3 replicates and extends the evidence for bilingual advantages in WM found in Study 2. Results from 49 bilinguals and 45 monolingual university students showed that the two groups performed similarly on measures of general intelligence, processing speed, attentional control, attentional scope, and the digit WM tasks, but not on the vocabulary test and the spatial WM tasks. Consistent with previous research (e.g., Bialystok & Feng, in press), monolingual young adults scored higher in the standardized test of receptive vocabulary. There was no difference between the two groups on any of the tasks used to measure the factors affecting WM, including attentional control, in which the bilingual advantage has been shown sometimes in young adults group (e.g., Costa et al., 2008). However, this result may be explained by the limited sample size ($N = 94$), the cognitive demand of the task used in this study (incompatible S-R mapping condition of the choice RT tasks), and the sensitivity of the measures to distinguish group difference (randomness indices).

Although bilingual and monolingual young adults did not show group difference in any of the digit WM tasks, however, bilinguals scored significantly higher than monolinguals on the spatial WM tasks with higher information processing load (simple forward task). This pattern replicates results with monolingual and bilingual children. In a study with visuospatial memory tasks differing in information processing load (Bialystok, Diamond, & Feng, in preparation), there were no group differences in visual spatial memory tasks for 7-year-old children. However, bilingual children obtained higher scores than the monolinguals in the forward spatial tasks but not in the sequencing spatial tasks, which provided evidence for the influence of bilingualism on executive functions for manipulation of information in WM in young children.

The complex sequencing tasks required participants to recall both the spatial and the color dimensions of the target information, such that successful performance not only depended on the correct recall of locations, but also on monitoring the two sets of locations corresponding to the different colors. Bilinguals obtained higher scores on this complex task, consistent with previous research findings of the influences of bilingualism on executive functions, especially in conditions involving more conflict. In the complex spatial WM task, the recall of locations from two color sets created conflict because participants had to pay attention to both dimensions (location and color) of the target information and maintain that information actively in mind so that they would be prepared to recall locations of either set first, when the target color of locations recalled was unpredictable.

The manipulation of both information processing levels (simple forward task) and attentional control demands (complex sequencing) in WM tasks was successful in showing bilingual advantages in spatial WM tasks. However, in the simple tasks, the bilingual advantage was evident in the forward task but not in the sequencing task; whereas in the complex tasks, the advantage was in the sequencing task but not in the forward task. It was hypothesized that sequencing tasks should involve higher information processing demands, however the results showed that performance in sequencing tasks was better than in forward tasks. In the forward version participants had to recall the locations in exactly the same order as presented. In contrast, in the sequencing version, when asked to indicate the cell locations in a fixed order (from left to right, top to bottom), there was no longer pressure to recall the position of each location in serial order, in a sense making the sequencing task a recognition memory task. Recall requires more processing resources than recognition (Craik & McDowd, 1987). It is likely that participants simply recalled the locations presented in the sequencing version regardless of the presentation order, making the information processing demands lower in the sequencing version than in the forward version, contrary to the hypotheses. Therefore bilinguals did score higher in the simple task with higher levels of information processing level, but it was the forward version of the task instead of the hypothesized sequencing version.

If the sequencing version of the tasks did reduce the information processing level, bilingual WM advantage was actually evident in the simple task with higher information processing demand and in the complex task with lower information processing demand. This could point to the interaction between the information processing and attentional control demand in the WM tasks. When the attentional control demand was lower (simple task), lower information processing level (sequencing version) washed out the group difference, because it was not effortful enough and therefore not sensitive enough to detect the impact of different language experience. However when the attentional demand was higher (complex task), higher information processing level (forward version) again washed out the group difference. But this time it was probably because it was too effortful even for the young adult population, which was indicated with the worst performance in this condition of the task. Therefore, the more sensitive measure of bilingual WM advantage with low attentional control demand was tasks with high levels of information processing (simple forward version), whereas the more sensitive measure with high attentional control demand was tasks with lower levels of information processing (complex sequencing task).

The finding that bilingualism only affects WM tasks with appropriate levels of attentional control and information processing load is also confirmed by similar performance on all digit WM tasks by participants in both language groups. In these digit WM tasks, the choice of single-unit digits of 1-9 makes the possible items to be recalled fewer than in the spatial WM tasks, in which there are 25 possible cell locations. This lower information processing load in digit WM tasks might be one of the reasons monolinguals and bilinguals showed comparable performance. When the information processing load is not challenging enough for young adults, manipulation of the attentional control demands or the information processing levels of the tasks will not elicit different performance because there are sufficient mental resources to perform the task regardless of the manipulations.

The eight WM measures used in Study 3 constituted three sets of WM measures, namely, spatial WM tasks (component 1), complex digit tasks (component 2) and simple digit tasks (component 3). The findings of principal component analysis highlighted the differences between the tests of different content (digit, spatial) as well as the interaction between the information processing demand and manipulation of the attentional control demand of the task (simple, complex).

Distractor inhibition (attentional control) and complex RT (processing speed) were extracted as factors that significantly predicted overall WM performance. Most of the current models of WM concentrate on one particular resource for individual differences or developmental changes, but other resources should be incorporated to achieve better understanding of WM. Novel to the literature is different patterns of regression models in the monolingual and bilingual groups. Results from monolinguals emphasized the importance of individuals' score in distractor inhibition indices as well as the composite score in both the complex RT tasks and attentional scope, which together account for a considerable amount of variance in WM performance. For bilinguals, only performance in complex RT tasks and attentional scope significantly predicted WM performance to a very limited extend. This different pattern needs to be interpreted with caution, as it is based only on the data from this one study, which had a modest sample size.

"Complex RT" appears to be the most important predictor of WM performance for the sample in Study 3. This composite measure includes performance in the complex conditions of the processing speed task and performance in the running memory task. One issue that needs to be addressed is why running memory span had a high loading on in the "complex RT" component, together with the RTs in the three complex conditions of the 4-choice processing speed task. This is an unexpected pattern because running memory span was used to measure attentional scope but not processing speed. The 4-

choice RT task was an adaptation from the classical RT task paradigm of Hick (1952), and followed the rationale of the RT tasks by Wilhelm and Oberauer (2006). It was proposed that the arbitrary and incompatible S-R rule mapping conditions of the choice RT tasks are not pure measures of processing speed, instead, they are conditions of RT tasks also tapping WM capacities (arbitrary condition) and executive functions (incompatible condition) in a speeded situation.

The running memory task was believed to be a measure of attentional scope. The fast presentation and unpredicted long-list of presentation should prevent the processing, such as rehearsal and chunking, which can take place in an ordinary memory span task (e.g., digit span task). Therefore participants have to draw items from sensory memory representation of the end of the list into WM. However, based on the result of pilot testing, the presentation rate in the running memory task was 800ms per digit instead of the rate of 250ms per digit used in the literature (e.g., Bunting & Cohen, 2005). This change of presentation rate did not seem to affect the overall performance in the task, because the average span of 3 in the current study is consistent with previous findings of this task. The slower presentation of the items,however, might have allowed time for more processing and therefore made the running memory task in Study 3 tap the ability of holding as many items in WM as possible while rapidly updating these items as the presentation goes on. Therefore it is possible that the running memory task was tapping a situation similar to the complex RT task conditions so that the "complex RT" component in fact represents the ability of "rapid processing of information in WM". If this true, then it explains why the "complex RT" component accounted for a significant amount variance in the overall WM performance, because it represent performance in the situation most like the situations in the WM tasks.

Finally, correlational analyses were conducted on WM measures and intelligence score (the number of correctly completed items in the 12-item version of the Raven test). The overall WM measures (average across all eight WM tasks) were correlated with the intelligence measure ($r = .32, p < .0007$). For both monolinguals and bilinguals, the overall WM score was moderately correlated with intelligence (monolingual: $r = .31, p < .05$; bilingual: $r = .27, p = .08$), although for bilinguals this correlation was marginally significant. Based on the results of the principal component analysis conducted on all the eight WM tasks, scores were also calculated for each component: spatial WM, simple digit WM and complex WM. The digit WM scores were correlated with each other ($r = .31, p < .002$) and both were correlated with the spatial WM score (simple digit WM: $r = .36, p < .0001$; complex digit WM: $r = .31, p < .002$); however, neither of the digit WM scores was correlated with intelligence. The spatial WM score was significantly correlated with intelligence score, $r = .40, p < .0001$. The correlation of the three WM measures and Raven score are presented in Table 13a and 13b and show different patterns for the two groups. For monolinguals, the three WM measures were correlated with each other although only spatial WM was significantly correlated with intelligence. For bilinguals, among the three WM measures, only spatial WM was correlated with simple digit WM. Although bilingual's overall WM performance was not correlated with intelligence, their spatial WM score did show a significant correlation with intelligence. These results are consistent with previous research, WM measures in the current study, especially the spatial WM measures, correlated with the intelligence measure.

Table 13. *Correlation Matrix for WM scores and Intelligence Measure in Study 3 for a) Monolingual Participants (n = 49); and b) Bilingual Participants (n=45)*

a)

Variables	Spatial WM	Complex Digit WM	Simple Digit WM	Intelligence
Spatial WM	-			
Complex Digit WM	.68***	-		
Simple Digit WM	.47**	.53***	-	
Intelligence	.30*	.25	.22	-

b)

Variables	Spatial WM	Complex Digit WM	Simple Digit WM	Intelligence
Spatial WM	-			
Complex Digit WM	.04	-		
Simple Digit WM	.32*	.02	-	
Intelligence	.48**	-.13	-.06	-

* $p < .05$; ** $p < .01$; *** $p < .001$.

GENERAL DISCUSSION

This dissertation examined the WM performance of young adult bilinguals and monolinguals and the relationship between WM task performance and measures of attentional control, processing speed and attentional scope. The primary goal was to investigate whether there would be a bilingual advantage in WM tasks. The second goal was to examine how three factors affecting WM performance contribute to potential differences in WM performance by monolinguals and bilinguals. The study yielded clear results with respect to both of these goals. Certain bilingual advantages in WM tasks were found in the young adult sample. The ability to inhibit distractors and processing speed in complex RT tasks were associated with WM performance for monolinguals, but only performance in complex RT tasks was associated with WM performance for bilinguals.

Bilingualism and WM

Bilingual Advantages in WM

Results from the current dissertation are the first to show a clear positive effect of bilingualism on spatial WM, representing bilinguals' more advanced ability to process information in the WM task conditions placing higher demands on attentional control. Previous research has shown that the bilingual advantages are evident in inhibitory control and set switching components of executive functions. The dissertation presents the new finding that there is another positive influence of bilingualism on cognition, in that bilingual experience also enhances the ability to process information more efficiently in the WM systems.

A seemingly conflicting result from Study 2 and Study 3 needs to be addressed first. The Matrix span task was used in Study 2 as a spatial WM measure and showed a bilingual advantage at the longer string length (> 4). However, in Study 3, the sequencing version of the simple spatial task (very similar in design to the Matrix span task) did not show any group difference even in the longer string length (6-8). Instead, bilinguals scored higher in the simple forward task, a task measuring short-term storage of spatial information. One of the reasons might be that in Study 2, the matrix span task was presented on the computer screen but participants were asked to transform the sequence of spatial locations onto another blank matrix on the answer sheet. In Study 3, however participants did not have to re-configure the presentation of the spatial locations on the computer screen since they indicated the locations on the same matrix where they saw the presentation. This change in the way of recording responses might have simplified the task in Study 3 by decreasing the processing load involved. This conjecture is supported by the fact that the Matrix span task in Study 1 and 2 resulted in an average span of 4 – the maximum number of locations that could be held in mind in the correct order – whereas in Study 3, the span for the sequencing task was 6 and many participants actually obtained a span of 8 (maximum string length).

Similarly, in Study 3 the sequencing version of the simple spatial WM task elicited better performance than the forward version of the task. As discussed in the discussion of Study 3, the simple sequencing task was in a way a recognition task instead of a pure recall test. In the forward version participants had to recall the locations in the exact order as they were presented. In the sequencing version they simply remembered the locations presented and recalled them in the order of left to right, and top to bottom. The particular order of recall might not have increased the level of control needed in the retrieval process but instead might have taken off the pressure of recalling the serial order of presentation, making this condition easier than the forward version. So although on the surface it seems like the results for the simple sequencing spatial WM task in Study 3 do not replicate those from the Matrix task in Study 2, both results show that in spatial WM tasks, increasing the information processing demand, either by requiring effortful reconfiguration of the spatial locations (Study 2), or by requiring recall of long series of spatial locations (Study 3) leads to a bilingual advantage when the cognitive processing requires higher levels of attentional control. This explanation is consistent with the argument that executive processing is required in any simple or complex WM tasks as long as information is stored longer than a passive trace is retained, and the level of executive control required is dependent on the task demands for different WM tasks (Reuter-Lorenz & Jonides, 2007).

The bilingual advantage in WM is an important finding because studies with young adults have been less likely to distinguish between the executive function abilities of monolinguals and bilinguals (e.g., Bialystok, 2006) than studies with children (Carlson & Meltzoff, 2008) or older adults (Bialystok et al., 2004). The bilingual advantage in the simple forward spatial memory task in Study 3 is consistent with findings of a bilingual advantage in spatial memory tasks in children of school age (Bialystok, Diamond, &

Feng, in preparation). In that study, bilingual children outperformed monolinguals on a spatial memory task but both groups showed similar performance on a spatial WM task involving the transformation of spatial locations during recall (Matrix span task and sequencing simple spatial task). The authors interpreted these results as showing that the simple spatial memory task was effortful for young children and therefore placed high processing demand on them. The complex WM measure in the study, the transformational spatial WM task, was very challenging for children for both language groups, and therefore eliminated the possibility of differentiating bilinguals from monolinguals through ceiling effects, even though it required even higher executive control of processing. The results of Study 2 and 3 extend the positive influence of bilingualism on spatial WM previously found for children to a young adult population. As in the research with children, the existence and magnitude of group difference depends on the level of executive control involved in the task, with largest group differences found for moderate levels of control.

Construct of WM

Although a bilingual advantage in WM was supported by data from some of the spatial WM tasks, it should be noted that bilinguals did not show better performance in all WM tasks in Study 3. In Study 2, bilinguals and monolinguals obtained the same score on the alpha span task and forward Corsi block test; in Study 3, digit WM tasks showed no group differences. The bilingual advantage in WM is specific to spatial WM measures, specifically, the Matrix span task (Study 2) and simple forward and complex sequencing spatial WM tasks (Study 3). Bilinguals did not have better general abilities to store and process information in WM and they were only better at WM tasks that involved higher levels of attention control. These results from WM tasks with different content information are consistent with the Baddeley WM model, where phonological loop (digit) and visuospatial sketchpad (locations in a matrix) represent independent WM components. The bilingual advantage appears to be limited to the spatial WM tasks and is not found in the verbal domain (alpha span and digit WM tasks).

Verbal WM tasks using actual words as stimuli were purposely avoided in Study 3 because of known bilingual disadvantages in rapid verbal retrieval. This choice of task was validated because the bilingual group in Study 3 did have lower scores on standardized receptive vocabulary test than monolinguals, consistent with findings for young adult bilinguals. In Study 2, however, bilinguals and monolinguals performed similarly in alpha span tasks although it was a WM measure using actual words stimuli. This could be explained by the equivalent vocabulary scores for both monolingual and bilingual groups. Understanding WM tasks is difficult in part because performance depends on both specific skills that differ by domain and general skills that cross domains. Several studies examining individual differences in adults have suggested that there may be a general component of ability that is common across different WM tasks, as well as unique components of specific tasks (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski et al., 1999; Shah & Miyake, 1996). In this sense, spatial WM tasks could be regarded as a more pure measure WM performance for the bilingual group.

Nonetheless, regardless of the language group factor, the analyses of the WM tasks (principle component analyses) in Study 1 and Study 3 supported the idea that WM is not a unitary construct but in fact includes at least two facets with respect to the content information: non-spatial (digit and verbal) and spatial (Oberauer et al., 2000). In Study 1 both sequencing span and alpha span loaded onto the same component whereas the Matrix span task loaded onto a different component together with the traditional and computerized Corsi block tests. In Study 3, all spatial WM tasks loaded onto one component, complex digit WM tasks loaded on the second component, and simple digit WM tasks loaded onto the third component. The result that simple and complex digit WM tasks loaded onto different component might point to the possibility that the levels of attentional control in WM tasks might interact with the content information of WM tasks to determine the constructs of WM. In the digit WM tasks of Study 3, simple and complex tasks represented different WM construct because they required different levels of attentional control.

Therefore, the choice of WM tasks is an important aspects of the research, and probably multiple measures of WM are necessary in the construction of WM models. In most WM studies, only one complex span task is used (usually reading span or operation span). This could cause problems for claims about WM based on the evaluation of a single measurement. The conclusion based on reading span task (verbal WM) might not apply to spatial WM tasks. For this reason, Miyake et al (2001) has argued for the importance of studying both verbal and visuospatial domains of WM. In addition, in the current dissertation verbal WM tasks were not correlated with IQ in either Study 1 or

Study 3, but spatial WM measures did correlate with IQ scores. If correlation with IQ is regarded as a characteristic of WM tasks (Ackerman et al., 2005), the spatial WM tasks might be more representative of WM measures. This result further point to the importance of including WM tasks of different content information in WM research.

Bilingual Advantages Only in Spatial WM?

Bilinguals did not perform better than monolinguals in all the spatial WM tasks; there were no group differences in the simple sequencing task and the complex forward task of Study 3. Therefore, the results might not be fully explained by the domain-specific view of WM, since the bilingual advantage was not evident in all WM tasks of specific content domain. Why did the bilingual advantage in WM only become evident in some of the spatial WM tasks? Why did bilinguals only show advanced performance on tasks involving relatively higher levels of information processing and attentional control demands in both the simple and the complex tasks? Probably the current results could be partially explained from the analyses of WM from the functional dimension (e.g., Corniodi & Vecchi, 2003; Oberauer et al., 2000): the WM constructs could be differentiated along different demands of executive control.

One perspective from which to consider whether the bilingual advantage is limited to spatial WM is to examine the different levels of executive function involvement in the spatial and digit WM tasks. It is possible that the bilingual advantage in spatial WM tasks is another example of their advanced attentional control abilities. The multicomponent WM model proposed by Baddeley (1986) assumes that spatial tasks require higher involvement of the central executive than verbal tasks. It has been suggested that there is a much stronger tie between the visuospatial sketchpad and the central executive than between the phonological loop and the central executive in the WM system (Baddeley, 1986). This difference in central executive involvement reflects the differences in the extent to which the short-term maintenance of verbal materials and visuospatial materials are practiced and automatized. It is likely that uses of mental imagery are less automatic than phonological coding and consequently place heavier demands on the central executive. Baddeley (1996) believes that it is plausible that memorizing spatial patterns or a sequence of spatial locations is not as practiced as maintaining information in the verbal domain, and, hence, has to draw more heavily on executive control mechanisms.

Miyake et al. (2001) also point out that although there is a well-practiced rehearsal mechanism for verbal materials, no such rehearsal mechanism seems to exist for visuospatial materials. The capacity for visuospatial storage is severely limited, so it is unlikely that performance on a complex visuospatial task could proceed without the involvement of executive functions. The capacity restriction may explain why the involvement of central executive is necessary or essential in the maintenance of visuospatial information. Miyake and colleagues (2001) showed that spatial STM and spatial WM tasks were related to executive function tasks equally strongly and cannot be differentiated. In contrast, in the verbal domain, WM is more related to executive function than STM.

In the research of visuospatial WM, the studies by Cornoldi, Vecchi and colleagues (reviewed in Cornoldi & Vecchi, 2003) suggest that each visual-spatial WM task can be defined by a certain processing demand which can be identified through appropriate task analysis. They provided examples of visual-spatial WM operations at different levels of activity: storage and basic maintenance of information (very low level), basic maintenance/rehearsal mechanisms (low level), generation of simple images (medium level), transformation of visual traces or mental images (high level), and organization/reinterpretation of mental images (very high level).

Similarly, Miyake et al. (2001) showed that the executive function involvement in spatial visualization (mental encoding and complex manipulation) was higher than spatial rotation tasks (manipulation in one step) and spatial rotation was higher than visual-spatial perceptual tasks. Therefore, according to these authors, even within the visuospatial WM systems, different tasks tapping different spatial abilities could differ in the degree of executive function involvement. The kind of executive function in spatial WM tasks entailed the controlled activation, maintenance, and transformation of visual-spatial information together with the inhibition of inappropriate automated routines (Duncan, Emslie, Williams, Johnson, & Freer, 1996; Kane, Bleckley, Conway, & Engle, 2001). Many of these executive function processes are believed to be responsible for the individual differences in spatial WM tasks, which always involve spatial visualization and transformation.

Therefore, it may be that bilinguals and monolinguals performed similarly in all four versions of the digit WM tasks because the executive function involvement in these tasks was not challenging enough for participants of this age group and therefore could not differentiate the different participants of language group. Even though digit and spatial WM tasks only vary in the content-domain, the crucial factor that differentiates the tasks could be the levels of executive control involvement. The complex tasks required higher levels of attentional control than the simple tasks because the successful recall depended on both the identity and the color of the target items. In the the simple tasks, the forward version might involve higher executive function processing than the sequencing version. The sequencing version involves less executive control because as in recognition task, less controlled processing was involved in the retrieval. For the same reason, in the complex tasks, the executive function involvement in the forward version might have exceeded the limit for the participants and therefore only in the tasks with appropriate levels of executive function involvement (complex sequencing task), was a bilingual advantage evident.

This explanation is consistent with the proposal that while Baddeley and colleagues assumed a general WM system and independent subsystems in their classical model, the WM systems and its subsystems can also be viewed as representatives of processes along continuous dimensions rather than as discrete entities (Cornoldi & Vecchi, 2003). The authors believe that one of the dimensions in this continuity is the level of control required by the WM processes. This dimension is specifically suited to locating imagery processes within the WM system. The nature of each process is defined by the characteristics of the information being used, and at the same time, by the characteristics of the task to be performed. It is believed that the degree of control required by each task could be the variable that allows the better analysis of WM processes and WM structure. The current studies provide supporting evidence for this continuity view of WM, at least in the visuospatial domain.

Bilingual Advantage in both Executive Functions and WM?

The present results showed that the bilingual advantage in WM is sensitive to manipulations in the WM tasks, both in the content domain and the levels of attentional control. Therefore, the positive influence of bilingualism on WM cannot be generalized to an advantage in all contents or functions of WM. This is similar to the claims that bilingualism only affects certain components of executive functions, for example, conflict resolution and task switching. Both of these selective advantages could have benefited from the bilingual language experience. Previous research has shown that bilingual experience enables the resolution of conflict and control over switching back and forth between tasks. The current results provide evidence that bilingual experience also changes the way that individuals process information in the limited capacity human mind. However, there remains the question as to what is the mechanism underlying the bilingual advantage in both executive functions and WM. Does one serve as the cause and the other serve as the result? Or, is one simply an addition to the other? Also, why are the two ideas so closely related and together shown as areas of bilingual advantage in cognitive functioning?

One tentative possibility is that executive functions and WM are two terms used interchangeably by researchers to refer to the same or overlapping theoretical concept. In the literature, there appears to be some confusion about the differentiation between executive functions and WM. For example, both Baddeley's WM model and Miyake's executive function model have a deep connection with the executive attention view proposed by Norman and Shallice (1986), in which a central attention system is thought to regulate various subprocesses. Baddeley's (1986) conceptualization of the central executive parallels, and in fact, adopted the framework of the supervisory attentional system (SAS) model by Norman and Shallice (1986). Baddeley (1996, 2007) pointed out that the central executive processes included the capacity to focus attention, to divide attention between two concurrent tasks, to switch attention from one task to another, and the capacity to integrate WM and LTM.

Miyake et al. (2000) argued that since the central executive component of the Baddeley's (1986) WM model is responsible for the control and regulation of cognitive processes, it is equivalent to what they referred to as executive functions. The authors also adopted the executive function model of Norman and Shallice (1986), and have argued for a common executive function mechanism, similar to their executive attention (Norman & Shallice, 1986) as well as partially dissociable executive function components, including updating, inhibition and set shifting. In the Miyake executive function model, it is claimed that the "updating" component of executive function is highly related to WM performance. In the original study of Miyake's executive function model, tasks used to measure "updating", namely, keeping-track and letter memory, are very similar paradigm to running memory task. Furthermore, one of the complex executive tasks used to measure 'central executive' was the operation span task, one of the most widely used WM task.

In a recent review of the executive function literature during the preschool period using an integrative framework, Garon, Bryson, and Smith (2008) adopted Miyake's executive function model and focused on three executive function components, namely, WM, response inhibition, and shifting. Their interpretation of WM followed Baddeley's WM theory rather than the updating function originally proposed by Miyake. In the Miyake model, the updating function is not equivalent to WM but is highly related to it. Updating requires monitoring and coding incoming information for relevance to the task at hand and then appropriately revising the items held in WM by replacing old, no longer relevant information with newer, more relevant information (Morris & Jones, 1990). Importantly, this updating function goes beyond the simple maintenance of task-relevant information in its requirement to dynamically manipulate the contents of WM (Lehto, 1996; Morris & Jones, 1990). That is, the essence of updating lies in the requirement to actively manipulate relevant information in WM, rather than passively store information.

So it is no surprise that bilinguals show advantages in both executive functions and WM, because both executive functions and WM have come from the same theoretical base and represent very similar aspects of human cognitive functioning. Following Miyake's executive function model, previous research has shown a bilingual advantage in inhibition and switching; the current dissertation showed bilinguals' better performance in complex WM tasks, which, according to the model, represents better general executive functions. Following Baddleley's model, because bilingual advantages have been shown in some components of executive functions, and central executive serves as the connecting point for all other subsystems of WM, then a bilingual advantage in WM is expected and is confirmed in the current study. It remains possible that indeed executive functions and WM represent theoretical concepts deeply connected, that is, different terms are used to capture one important function of human cognition – the capacity to control over different processes in the limited human mental resource.

However, some researchers still believe that WM is one component of executive functions (e.g., Davidson, Amso, Anderson, & Diamond, 2006). In this case, executive functions and WM represent concepts not much overlap but WM is only one of abilities of the multiple-component concept of executive functions. But as discussed earlier, WM and executive functions are highly correlated, especially in spatial WM. So in any case the bilingual's better performance on the spatial WM tasks is consistent with previous findings of bilingual advantages in certain executive functions and furthermore supports the literature showing the close relationship between WM and executive functions. Although depending on the different theoretical views of executive functions and WM, the explanation of the mechanism underlying the bilingual advantage of both WM and some executive functions will be different.

Why Bilingualism-WM Association?

Various theories have been proposed to explain the bilingualism-executive functions association. Some researchers believe that bilinguals' better control mechanism is generalized from their abilities in inhibiting or ignoring the non-target language in the language domain (Abutalebi & Green, 2007; Green, 1998). Similarly, based on the research findings that WM performance is positively correlated with language proficiency, especially L2 proficiency, the following section provides a tentative explanation of the bilingualism-WM association.

Several researchers have suggested that L2 acquisition is facilitated by good phonological and general WM resources (Service & Kohonen, 1995). Miyake and Friedman (1998) have proposed that individual differences in L2 proficiency may be related to WM as a general language measure. They found that a learner's WM capacity was positively correlated with the ability to acquire native-like skills in a L2. It was also found that complex WM measure, reading span task, can help predict differences in L2 proficiency for young adults (Harrington & Sawyer, 1992) and children (Masoura & Gathercole, 1999; Service, 1992). Moreover, Ransdell et al. (2006) showed that for university students, reading span correlated with reading comprehension for both bilinguals and monolinguals, indicating the relative importance of this WM measure for concurrent reading performance.

However, it has also been proposed that the reverse should be considered. That is, L2 training and experience may actually provide a kind of expert knowledge that can be used to improve performance in general WM tasks (Ransdell, Arecco, & Levy, 2001). This is in line with the research that is beginning to look at the influence of L2 expertise in general cognitive processing (Kroll, Michael, Tokowicz, & Dufour, 2002; Miyake & Friedman, 1998; Tokowicz, Michael, & Kroll, 2004). Sasaki (1996) found L2 proficiency to be distinct from, but correlated with, a general factor of cognitive ability in college students. Students with higher L2 proficiency revealed better strategy use than students with lower L2 proficiency, but not better IQ. It was also found that in a writing task, dual-task interference effects were limited in the bilingual group compared with monolinguals (Ransdell et al., 2001). The authors argued that the skill required to inhibit the demands of concurrent memory loads during transient storage may be akin to that of inhibiting the nontarget language of input in expert performance.

Tokowicz, Michael, and Kroll (2004) pointed out that study-abroad experience encourages the use of approximate translations to communicate, but only higher WM capacity (measured in operational span) learners can do so because this strategy requires multiple items to be manipulated in memory simultaneously. It was demonstrated that individuals with higher WM capacity have the available WM (or can allocate resources appropriately) to take advantage of a particular communicative success in the study-abroad context. In another study, Kroll et al. (2002) compared the performance of early stage learners of a L2 to the performance of fluent bilinguals on an adapted reading span task in L1. The results showed that bilingual young adults had higher reading span than early L2 learners. The authors argued that the span advantage may reflect a self-selection factor based on verbal and/or cognitive abilities. That is, only individuals with relatively high cognitive abilities may succeed in L2 learning and go on to become fluent bilinguals. Nonetheless they acknowledged that "alternatively, the bilingual span advantage may be a positive cognitive consequence of bilingualism (p.160)". On the basis of the data reported, it is impossible to determine which of these alternatives is correct or even whether they are mutually exclusive.

Interestingly, Christoffels, de Groot, and Kroll (2006) tested young adult interpreters, unbalanced, and balanced bilinguals with equivalent proficiency in both languages on reading span, speaking span (study a list of words and then produce a grammatically correct sentence for each of the words in the set of recall), and word span (recall the presented words in the same order of presentation). The main result was that interpreters had better memory performance than bilinguals. Whereas the interpreters' WM and STM capacity was not influenced by language of testing, the capacity for the other two groups was better in L1 than in L2. The fact that balanced bilinguals were distinguished from the unbalanced bilinguals on the lexical retrieval tasks but not on the WM/memory tasks suggests that language proficiency might not be the crucial factor in determining WM performance, although it is related to lexical retrieval performance. These results showed that interpreters developed greater efficiency in language processing capacity in the L2 than ordinary bilinguals, and that WM is an important subskill for simultaneous interpreting. In all, a particular kind of bilingual expertise, simultaneous interpreting, is selectively associated with enhanced memory capacity in both L1 and L2. Yet, it is still important to learn whether this enhanced memory is a prerequisite for or a consequence of simultaneous interpreting experience.

The above review points to the close relationship between language proficiency (both L1 and L2) and WM performance. On the one hand, better WM capacity might be the cause of better language proficiency; on the other hand, language proficiency and WM performance might share the same underlying cognitive mechanism. However, the data from the present dissertation do not help resolve the issue of the direction of the association between L2 language proficiency and WM. Partly this is because the proficiency assessment was only based on receptive English vocabulary. Because some bilinguals claimed English to be the dominant language (L1), but others claimed English to be non-dominant language (L2), it is not clear whether the single index of language proficiency indicated the language proficiency of L1 or L2 for the bilingual participants. Also in the present study, bilingual participants were defined only as those who had balanced usage of both languages. Therefore consistent with previous research (Christoffels et al., 2006), the current data provide evidence that the balanced usage of L1 and L2 on a daily basis is related to WM performance.

Although the dissertation did not help clarify the relationship between language proficiency (L1 and L2) and WM performance, the correlational analyses showed that English proficiency is associated with performance on some WM tasks. In Study 1, data from monolingual participants showed that PPVT scores were only correlated with the scores of the alpha span task ($r = .27, p < .05$) but not with the Corsi block or Matrix span tasks. In Study 2, there was no correlation between PPVT and any WM measures (alpha span, Corsi block and Matrix span scores) in the monolingual group, but for bilinguals, PPVT correlated with alpha span task (span: $r = .48, p < .03$; score: $r = .45, p < .04$). In Study 3 monolinguals' PPVT score was correlated with the spatial WM ($r = .47, p < .0008$), and complex digit WM ($r = .43, p < .004$), but not with simple digit WM. However for bilinguals, PPVT score was only correlated with spatial WM ($r = .29, p < .05$), but not with either simple or complex digit WM. Taken together, PPVT score only showed very few correlations with WM tasks.

It is not surprising that for bilinguals, vocabulary score was correlated with verbal WM task (alpha span) in Study 2. For monolinguals, this correlation was only evident when the sample size was bigger (*n* = 62 in Study 1 and *n* = 22 in Study 2), possibly because this WM task was not tapping the language proficiency in the monolingual group as much as it did in the bilingual group. It was suspicious to find that in study 3, PPVT was correlated with spatial WM for both monolingual and bilinguals, and PPVT score was even correlated with complex digit WM for monolinguals. Both bilinguals and monolinguals show the relationship between their English vocabulary and WM performance, and monolinguals' vocabulary seemed to be more correlated with their WM performance, even in the spatial WM tasks. However, it should be noted that in Study 2, vocabulary was not related to any spatial WM tasks. Therefore, no clear conclusions about the association between language proficiency and WM performance can be draw based on the results of the current dissertation. Thus, the relation between language proficiency and WM for bilinguals still needs to be clarified with future research, and preferably in the context of research on language proficiency and WM for monolinguals.

Revisiting the Sources Underlying Different WM Performance

One of the aims of WM research has been to determine which aspects of WM better account for developmental and individual differences and in the past two decades, many models of WM have thus been proposed (for reviews, see Conway et al., 2007; Miyake & Shah, 1999). For example, individual differences in WM have been conceptualized in terms of the ability to monitor attentional resources (Engle, Kane et al., 1999). Cowan suggested that a meaningful measure of WM depends on an emphasis on the focus of attention (Cowan et al., 2005), a capacity-limited attention component. On another view, researchers have argued that the causes of differences in WM are differences in information processing speed.

Study 3 investigated these three potential sources of individual differences in WM performance – attentional control, processing speed and attentional scope. The results showed different patterns in the regression model for bilingual and monolingual young adults in predicting WM performance. Only for the monolinguals did performance in complex RT tasks and abilities in distractor inhibition account for some of the variance in the overall WM performance. These results were suggestive but in no way conclusive. Before future studies are conducted to construct theoretical models of WM, the current results simply showed that for monolingual young adults, both the attentional control and processing speed factors contribute to the individual differences in WM performance, as accepted in the literature. However, the pattern of the regression model for bilinguals was not identified. This does not mean that distractor inhibition and processing speed do not affect bilinguals' WM performance, instead it suggests that there could be other factors determining the WM performance for bilinguals, although they have not yet been identified in the present study. One such example could be the updating component of executive functions, the ability to continuously update and monitor incoming information, which has been suggested to be primarily involved in the operation span task (Miyake et al., 2000).

Similarly, the conclusion about equivalent performance on executive functions, speed, and attentional span needs to be reconsidered. The measure of executive functions, the Random Number Generation task, although always used as an index of general executive function (e.g., Miyake et al., 2001), might not be sensitive enough for group comparisons. Both Towse (e.g., 1998) and Vandierendonck (e.g., 2000) agree that the random generation tasks, either number generation or interval generation, is best used as a secondary task in the dual-task paradigm in the Baddeley WM model. Very few studies have used this task as an independent measure, although Miyake and colleagues (e.g., Miyake et al., 2000) have been using it in constructing their models of executive functions or WM. However, the fact that a bilingual advantage in executive functions was not evident in this type of task could mean that there is no bilingual advantage in executive task tapping the general "complex executive" (Miyake et al., 2001), but bilinguals' better executive functioning is evident in conditions involving conflict resolution or set switching.

The processing speed tasks used in the study did not show different performance between the groups. Bilingual and monolingual young adults performed the same in the simple RT tasks (simple RT and compatible S-R mapping condition), indicating their equivalent basic information processing speed. Although it was hypothesized that bilinguals could show better performance in the RT conditions involving WM and conflict resolution (arbitrary S-R mapping and incompatible S-R mapping condition), bilinguals and monolinguals again performed the same. Considering the age of the group, the tasks chosen might not be challenging enough (2- or 4- choice RT task). Since processing speed performance fits a linear function (Deary, Der, & Ford, 2001), it could be speculated 9- or more- choice versions of the task might yield the expected difference. Also it has been proposed that processing speed tasks could perhaps account for a larger part of the variance in the case of age differences than in the case of individual differences. Wilhelm and Oberauer (2006) argued that when it comes to predicting individual differences in intelligence in young adults, measures of WM capacity have been more successful than speed variables. Nonetheless, the current data showed no difference between monolingual and bilingual young adults in either simple or complex RT task conditions. Yet still the performance of the complex RT task conditions accounted for some of the variance in the WM tasks for monolinguals but not for bilinguals.

Only one measure of attentional scope, the running memory task, was used in the current study. In this task, unpredictable long series of digits were presented and participants were required to recall the digits starting from the very last one in a backward order. Constant attention is therefore needed to be paid to each digit so that successful recall can be obtained once the last digit disappears from the screen. Cowan (e.g., 2005) used this task to show that WM capacity is limited to 3 or 4 chunks of information. The results in the present study confirmed that finding and showed no group difference between monolingual and bilingual participants. Therefore, together with the results in measures of processing speed and attentional control, the bilinguals and monolingual young adults in Study 3 performed the same on all three measures of factors affecting WM, but they differed in certain WM measures. However, the results of the regression model of overall WM performance differed between monolingual and bilingual group, suggesting that for these two groups of young adults, different factors could affect their WM performance in different ways.

WM, Bilingualism, and General Intelligence

Evidence centred on the relationship between WM capacity and general cognitive performance has steadily accumulated in the last two decades (for review, see Ackerman, et al., 2005; de Ribaupierre & Lecerf, 2006). Kyllonen and Christal (1990) first demonstrated substantial overlap between measures of WM and reasoning abilities, leading to a claim that "reasoning ability is (little more than) WM capacity" (p. 389). Claims of overlap between WM and intelligence have since resulted in the strong assertion that WM is the same as *g* or general fluid intelligence (Conway et al., 2002; Fry & Hale, 1996; Salthouse, 1992a, 1992b; Salthouse, Babcock, Mitchell, Palmon, & Skovronek, 1990). Given that WM and intelligence research have interesting parallels (e.g., Miyake & Shah, 1999), a better understanding of bilingual WM is likely to help illuminate the nature of bilingual intelligence.

With the major developments of the claim that the construct of complex WM is distinct from simple span memory, some researchers have argued that the larger correlation for complex span tasks reflects the fact that they better capture the storage and processing dynamics of the WM system than do simple spans (Daneman & Carpenter, 1980). Other researchers suggest that the larger correlation is due to the fact that both complex spans and tasks of higher-order cognition require the ability to control attention (Engle, Kane et al., 1999). According to Unsworth and Engle (2006), the extent to which a span task will correlate with higher-order cognition is based in part on the extent to which retrieval from secondary memory is required (although see Conway & Engle, 1994). The authors argued that complex spans correlate with measures of higher-order cognition because they require greater retrieval from secondary memory than simple spans. However, Ackerman, Beier, and Boyle (2005) conducted a meta-analysis examining the relationship between WM and *g*, as well as between STM and *g*. The results suggested that STM and WM were equally related to *g*, and WM is not distinctive from *g*. Oberauer, Schulze, Wilhelm, and Su¨ß (2005; see also Wilhelm & Oberauer, 2006) explained that the close relationship between simple and complex WM with general intelligence as that the WM construct originates in theories of cognition, in which the concept of a very limited processing capacity plays a central role, and therefore it can help to understand complex performance such as studied in fluid intelligence tasks.

Regardless of the debate about the exact relationship between WM and intelligence, the literature has agreed on a close relationship between WM and general intelligence. The Matrix span task used in Study 1 was significantly correlated with intelligence (monolingual participants only). In Study 3, for both monolingual and bilinguals, the spatial WM performance was significantly correlated with intelligence scores, but performance for neither simple nor complex digit tasks correlated with intelligence. The results for the correlation between digit WM tasks and short-form Raven (Study 3) did not support the association between WM task and intelligence, but they were consistent with the findings in Study 1 that verbal WM tasks (alpha span and sequencing span) were not correlated with Cattell scores. Both the Matrix span (Study 1) and spatial WM tasks (Study 3) correlated with intelligence measures for monolinguals and bilinguals. Therefore it is possible that for young adult participants, spatial WM tasks better capture the similarities between WM and fluid intelligence.

Bilinguals and monolinguals showed the same patterns of correlation between WM and intelligence. More importantly, bilingual and monolingual young adults performed comparably on the intelligence tests. Although bilingualism may influence some aspects of executive functions and WM, bilingual experience does not seem to affect performance in general intelligence measures (non-verbal reasoning). Both WM and intelligence could rely on the processing of information in limited cognitive resources, and it is possible to distinguish between specific resources conceded to each position of the system and the global quantity of resources available to the overall cognitive system (Cornildi & Vecchi, 2003). Therefore, individual differences in WM or intelligence could be due to either a low degree of available local resources at one or more points in the WM system or to a lower degree of available overall resources. Bilingualism only influenced the controlled processing in WM, and bilingualism does not increase the overall cognitive resource in human mind or increase the non-verbal reasoning abilities in general.

Limitations and Future Research

However promising, it may be that the results from the current dissertation apply only to balanced bilinguals who use both languages on a daily basis. Most of the participants in the group started the active use of two languages in childhood (6-12 years). However, only the proficiency of English receptive vocabulary was confirmed by standardized test, with no other assessments of language proficiency. Bilinguals' proficiency of the other language remained unclear. Most of the participants were educated in English and claimed that they feel more comfortable using English, even though they were exposed to their other language earlier than to English. Many bilinguals did not know how to read and write in the other language. In the literature "balanced bilingual" usually refers to bilinguals with balanced proficiency in both languages, but the present study defined balance more in terms of use than proficiency. Recent research by Luk (2008) has shown that functional usage and formal proficiency in fact affect bilinguals' performance in different ways. Therefore, future research should include more detailed assessments of the language profiles of the bilingual participants or include different kinds of bilingual participants based on the proficiency of their languages instead of the functional usage of the languages.

Future research is also needed to confirm the effects of bilingualism on WM in other age groups. Results from children's studies have shown some similar results, but more research is needed to support the claims. Research on elderly population is also needed to confirm the pattern and see if it will hold with aging.

The current studies avoided using verbal materials like words or sentences in the WM tasks, except for the alpha span task in Study 1 and 2. However, widely used WM tasks such as operational span and reading span, are based on the recall of words. But as discussed before, verbal tasks might not be used as a pure measure of WM or executive function for bilinguals. For example, the verbal proactive interference task did not show bilingual advantage in the proportional proactive interference effect in young adults, but it is not necessarily true to conclude that there was no bilingual advantage in resolving proactive interference (Bialystok & Feng, in press). For example, bilingual children did have fewer intrusions in the proactive interference task. Therefore the results for adults in the verbal proactive interference task might be confounded with their disadvantage in vocabulary. Similarly, in the verbal fluency task, controlling for the vocabulary scores, bilinguals did show better performance in letter fluency and the same performance in category fluency (Bialystok et al., 2008), although it has been consistently reported that bilinguals are poorer in the fluency tasks (e.g., Gollan et al., 2002). Thus, future research should include verbal WM tasks in the investigation of bilinguals WM, but careful attention should be paid to the verbal materials used in the tasks.

Finally, the models of WM performance need to be interpreted with caution. First, the sample size is modest, although it meets the criterion for the regression analysis (Tabachnick & Fidell, 2007). However, the sample size limited the possibility of conducting other types of analysis such as step-wise regression or structural equation modeling. Furthermore, language group was not entered into the regression model as an independent variable to predict WM performance. Therefore the results of the two groups only showed different regression model for WM performance at the descriptive level, no direct comparison was made between the regressions models for monolingual and bilingual group based on the current data.

Conclusions

Bilingual young adults outperformed their monolingual peers on WM tasks involving high levels of attentional control but showed no difference in the amount of information that they can hold in mind or on tasks for which the attentional control demand was not challenging enough or too challenging for this age group. These results add to the evidence for a cognitive advantage from lifelong experience of speaking more than one language every day. After 7-12 years of using two languages actively on a daily basis, bilingual young adults showed better performance in WM tasks with higher levels of attentional control, but they scored lower on the standard receptive vocabulary test of English. Although WM has been consistently related to intelligence, being a bilingual does not lead to higher IQ scores either.

The most important finding in this dissertation is that bilingualism affects the performance of WM tasks that involve high levels of central executive control. A bilingual advantage has previously been shown on certain aspects of executive functioning, namely, conflict resolution and task switching. Since performance in executive functions and WM are always closely related in the literature, this bilingual advantage leads to the hypothesis of a bilingual advantage in WM. In fact, executive functions and WM may represent similar or overlapping theoretical concepts, and the present results confirm that in WM tasks the manipulation of levels of executive control can differentiate bilingual from monolingual young adults. At any given moment, bilinguals' both languages are activated. This particular language experience has been argued to generalize to other cognitive domain and affect the specific executive functions of resolving conflict and switching between task sets. The current data show that the particular language experience might have a more general cognitive result and affect how bilinguals process information in the limited human mental resource: in the way that bilinguals are more proficient in processing information in face of higher levels of attentional control.

Recent genetic and twin studies (Friedman, Miyake, Young, DeFries, Corley, & Hewitt, 2008; Kremen et al., 2007) have shown the heredity foundations for WM and executive functions. Although it is not clear whether executive functions include WM or executive function is part of the WM systems, this new genetic research point to the genetic foundations of these important functions of human cognitive processes. Meanwhile, the present dissertation shows that life experience also helps to shape the performance of executive functions and WM. As the world becomes increasingly more bilingual, it is imperative that the cognitive advantages of bilingualism be brought to the forefront of investigation.

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Appendix A. Language Background Questionnaire

Sex: M F Today's date (DD/MM/YY):________________

Subject ID:__________________ Date of birth (DD/MM/YY):________________

Country of birth:_______________

* If not born in Canada, when did you move to Canada? (date) ____________________

If you have any of the following health conditions, please check the appropriate box:

( ) **Hearing Problems:** If so, do you wear a hearing aid? Yes No

( ) **Vision Problems:** If so, do you wear glasses? Yes No

Is your vision corrected to 20/20 with glasses? Yes No

Are you colour blind? Yes No If so, what type? _____________________

Are you right or left handed? Right Left

How many years have you been registered at the university? ____________________

Have you earned any other degree or diploma prior to the current degree? Yes No

*If yes, what is the degree/diploma and how long did it take to complete it? ___________

How often do you use a computer? Daily Weekly Monthly Occasionally Never

How do you rate your computer skills? Poor Fair Good Very good Excellent

Global Self-assessment: Overall, how would you describe your levels of bilingualism?

Not Bilingual		Non-fluent Bilingual		Fluent Bilingual
1	2	3	4	5

Do you speak any languages fluently in addition to English? (If yes, please specify what language and how old you were when you began to speak it fluently.) ____________
(Continue only if answer is yes)

What is your First language? ______ **What is your Second language?** ________
About Your English Where did you learn English?

Home School Community Work Other

At what age did you first start learning English informally at home? ________________

At what age did you first start learning English formally at school? ________________

At what age did you first start using English actively? ________________

How often do you use English now? Daily Weekly Monthly Occasionally

Where do you use English now? Home School Work Community Other

How do you rate your understanding of English? Poor Fair Good Very good Excellent

How do you rate your speaking ability in English? Poor Fair Good Very good Excellent

About Your Other Language(s) ________________

Do you speak/read/write in another language (not English) at work/school? Yes No

Have you ever lived in a place where this language is the dominant language? Yes No

* If yes, for how long?____________ And where had you stayed? ________________

Where did you learn this language? Home School Community Work Other

At what age did you first start learning this language informally at home? ________________

At what age did you first start learning this language formally at school? ________________

At what age did you first start using this language actively? ________________

How often do you use this other language now? Daily Weekly Monthly Occasionally

Where do you use this language? Home Work Community Other

How do you rate your understanding? Poor Fair Good Very good Excellent

How do you rate your speaking? Poor Fair Good Very good Excellent

Experimenter's Judgment of Participant's Level of Bilingualism: ________________

Appendix B. ANOVA on the Spatial Recall Score Data in Study 3:

2 (monolingual, bilingual) X 2 (simple, complex) X 2 (forward, sequencing)

	Strict Scores		Total Scores	
Language Effect	$F(1, 80) = 1.73$	$p = .19$	***F(1, 80) = 3.27***	***p < .07***
Complexity	$F(1, 80) = 83.64$	$p < .0001$	$F(1, 80) = 402.15$	$p < .0001$
Complexity X Language	$F(1, 80) = 1.88$	$p = .17$	$F(1, 80) < 1$	
Processing Level	$F(1, 80) = 22.32$	$p < .0001$	$F(1, 80) = 56.10$	$p < .0001$
Processing Level X Language	$F(1, 80) < 1$		$F(1, 80) < 1$	
Complexity X Processing Level	$F(1, 80) < 1$		$F(1, 80) < 1$	
Complexity X Processing Level X Language	**F(1, 80) = 5.19**	**p < .03**	$F(1, 80) = 1.05$	$p = .30$

Appendix C. ANOVA on the Digit Recall Score Data in Study 3:

2 (monolingual, bilingual) X 2 (simple, complex) X 2 (forward, sequencing)

	Strict Scores		Total Scores	
Language Effect	$F(1, 78) < 1$		$F(1, 78) < 1$	
Complexity	$F(1, 78) = 68.43$	$p < .0001$	$F(1, 78) = 260.88$	$p < .0001$
Complexity X Language	$F(1, 78) < 1$		$F(1, 78) < 1$	
Processing Level	$F(1, 78) = 35.04$	$p < .0001$	$F(1, 78) = 67.15$	$p < .0001$
Processing Level X Language	$F(1, 78) < 1$		$F(1, 78) < 1$	
Complexity X Processing Level	$F(1, 78) = 21.04$	$p < .0001$	$F(1, 78) = 19.37$	$p < .0001$
Complexity X Processing Level X Language	$F(1, 78) < 1$		$F(1, 78) < 1$	

Appendix D. ANOVA on the Percentage of Correct Recall Data in Study 3:

2 (monolingual, bilingual) X 7/8 (string length)

Simple Forward

	Spatial Tasks		Digit Tasks	
Language Group Effect	$F(1, 80) = 2.73$	$p = .10$	$F(1,80) < 1$	
String Length Effect	$F(6, 480) = 246.39$	$p < .0001$	$F(6, 480) = 113.04$	$p < .0001$
Language X String Length	$F(1, 80) = 1.80$	$p = .10$	$F(1, 80) = 1.28$	$p = .27$

Simple Sequencing

	Spatial Tasks		Digit Tasks	
Language Group Effect	$F(1, 80) = 1.73$	$p = .19$	$F(1,80) < 1$	
String Length Effect	$F(6, 480) = 147.97$	$p < .0001$	$F(6, 480) = 57.08$	$p < .0001$
Language X String Length	$F(1,80) < 1$		$F(1,80) < 1$	

Complex Forward

	Spatial Tasks		Digit Tasks	
Language Group Effect	$F(1,80) < 1$		$F(1,78) < 1$	
String Length Effect	$F(5, 400) = 104.47$	$p < .0001$	$F(5, 390) = 60.54$	$p < .0001$
Language X String Length	$F(1, 80) = 1.03$	$p = .40$	$F(1, 78) = 1.08$	$p = .37$

Complex Sequencing

	Spatial Tasks		Digit Tasks	
Language Group Effect	**$F(1, 80) = 5.00$**	**$p < .03$**	$F(1,80) < 1$	
String Length Effect	$F(5, 400) = 84.27$	$p < .0001$	$F(5, 400) = 48.34$	$p < .0001$
Language X String Length	$F(1,80) < 1$		$F(1,80) < 1$	

Appendix E

Beta Weights and Uniqueness Indices Obtained in Multiple Regression Analyses in Study 3, predicting Spatial WM for monolinguals a) and bilinguals b); and predicting Simple Digit WM for monolinguals c) and bilinguals d)

a)

	Beta Weights		Uniqueness Indices	
Predictor	β	t	Uniqueness Index	F
Simple RT	-.25	-1.69	.05	2.85
Complex RT	-.26	-1.73	.06	2.98

Note. n = 49. Adjusted R^2 =.14, *F* (2, 43) = 4.56, *p* < .02, for predictor variables.

b)

	Beta Weights		Uniqueness Indices	
Predictor	β	t	Uniqueness Index	F
Simple RT	-.12	-0.68	.01	0.46
Complex RT	-.31	-1.71	.06	2.91

Note. n = 45. Adjusted R^2 =.11, *F* (2, 40) = 3.67, *p* < .04, for predictor variables.

c)

	Beta Weights		Uniqueness Indices	
Predictor	β	t	Uniqueness Index	F
Distractor Inhibition	-.33	-2.20*	.09	4.85*
Complex RT	-.14	-0.95	.02	0.90

Note. n = 49. Adjusted R^2 =.12, *F* (2, 43) = 4.20, *p* < .03, for predictor variables.

d)

	Beta Weights		Uniqueness Indices	
Predictor	β	t	Uniqueness Index	F
Distractor Inhibition	.14	0.87	.02	0.75
Complex RT	-.12	-0.73	.01	0.54

Note. n = 45. Adjusted R^2 =.02, *F* (2, 40) = 0.57, *n.s*, for predictor variables.

**p* < .05, ** *p* < .001