INVESTIGATING INDIVIDUAL DIFFERENCES IN SPATIAL ABILITY AND

MATHEMATICS ACHIEVEMENT: AN INFORMATION PROCESSING APPROACH

by

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(Under the Direction of Martha Carr)

ABSTRACT

The main objective of this dissertation is two-fold: to propose a theoretical model that explains how gender differences in performance on spatial ability tasks may be understood as a function of the relative strength of two working memory components, visuospatial working memory and verbal working memory, and strategy use; to empirically test the relationships among all working memory components (visuospatial working memory, verbal working memory, and executive functioning), mental rotation spatial ability, and mathematics achievement. This objective was accomplished in the two papers included in this dissertation. The first paper is a theoretical paper that culminated in a proposed model that illustrated the psychological mechanism underlying gender differences in performance on spatial ability tasks. The second paper reported an empirical study that utilized structural equation modeling to explore the connection between mental rotation spatial ability and mathematics achievement through the lens of information processing theory.

INDEX WORDS: spatial ability, working memory, strategy use, mathematics achievement

AN INFORMATION PROCESSING APPROACH TO STUDY INDIVIDUAL DIFFERENCES

IN SPATIAL ABILITY AND MATHEMATICS ACHIEVEMENT

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DEDICATION

To my mother, who instilled in me an intellectual curiosity and who was my first teacher of mathematics, writing, music, and Chinese calligraphy, and many other domains of knowledge and the arts. I am especially indebted to her devotion to my early education, despite all the challenges she faced as a single parent. I also thank her for her continued support throughout my undergraduate and graduate education.

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Chapter 3 presents an empirical study that applies information processing theory to explain variables that jointly influence psychometric spatial ability (mental rotation) and mathematics achievement in university students. The relationships among VSWM, VWM, executive functioning, mental rotation, and mathematics achievement are investigated. The primary objective of this study is to understand the relative importance of each working memory component in explaining individual differences in mental rotation and mathematics achievement. The second objective of the study is to explore the relationship between mental rotation and mathematics achievement through the lens of information processing theory. Structural equation

modeling is used to test an implicit model and a few alternative models that derive from the implicit model. The results of the analyses show VSWM and mental rotation are close to identical constructs. Among all predictor variables of mathematics achievement included in the models (VSWM, VWM, executive functioning, and mental rotation), mathematics achievement is best explained by either VSWM or mental rotation but not when both variables serve as the predictor variables. The significance of this study is that it investigates the relationships among all relevant variables suggested by the literature in a single study.

CHAPTER 2

SPATIAL ABILITY IS PREDICTED BY WORKING MEMORY AND STRATEGY USE[1]

Abstract

In this review, a new model that is grounded on information processing theory is proposed to account for gender differences in spatial ability. The proposed model assumes that the relative strength of working memory, as expressed by the ratio of visuospatial working memory to verbal working memory, influences the type of strategies used on spatial ability tasks. Strategy use, in turn, influences performance on spatial ability tasks. Gender differences in spatial ability can be explained by gender differences in strategy use and as a function of the relative strength of visuospatial working memory to verbal working memory.

Keywords: spatial ability, gender differences, working memory, strategy use

Introduction

A meaningful interpretation of gender differences in spatial ability needs to be grounded in a thorough understanding of the cognitive processes underlying task performance (Botella, Peña Contreras, Shih, & Santacreu, 2009; Kyllonen, Lohman, & Snow, 1984; Mohler, 2008; Zimmer, Munzer, & Umla-Runge, 2010). Gender differences in spatial ability have been linked to gender differences in visuospatial working memory (Coluccia & Louse, 2004; Kaufman, 2007) and differences in strategy use (Glück & Fitting, 2003). However, this does not fully explain the pattern of gender difference findings in which gender differences appear to be a function of the type of spatial ability measure used. Furthermore, existing models are incomplete in that they either do not consider verbal working memory or do not consider working memory in combination with strategies as the explanation for gender differences in spatial ability. In this review, we propose a model that suggests gender differences in spatial ability are best understood as predicted by the relative strength of visuospatial working memory (VSWM) to verbal working memory (VWM) and strategy use.

An overview of prior models of gender differences in spatial ability is presented first, followed by the exposition of the proposed model. A review of the research literature based on Baddeley's (1986) multi-componential theory of working memory follows. The research on gender differences in VSWM and VWM is reviewed first. The research on gender differences in strategy use is reviewed next. Finally, we evaluate the proposed model against existing evidence and discuss limitations and future extensions of the proposed model.

Prior Models of Gender Differences in Spatial Ability

Although ample evidence shows young adult males outperform young adult females on mental rotation tests and in navigation studies (Coluccia & Louse, 2004; Linn & Peterson, 1985; Voyer, Voyer, & Bryden, 1995), those differences are not best explained by gender differences in working memory or strategy use alone. Prior models of gender differences in spatial ability focused either on working memory or strategy use. Only a few considered both factors.

Working memory as a mediator. In a systematic review of the research literature examining the relationship between VSWM and spatial orientation, Coluccia and Louse (2004) suggested gender differences in spatial orientation emerge as a function of the cognitive demands of the spatial ability tasks on VSWM. Coluccia and Louse (2004) cited research that indicating that males have higher VSWM than females and concluded that this difference is why males do better on spatial orientation tasks. Kaufman (2007) proposed and tested a model that assumes gender differences in spatial ability to be due to gender differences in VSWM. Kaufman assessed the impact of gender, spatial short-term memory (Simple Block Span), VSWM (Rotation-block Span and Verification-block Span), and VWM (Verbal Working Memory Test) on spatial ability (Mental Rotation Test and Differential Aptitude Test–Space Relations). His data indicated that VSWM completely mediated the relationship between gender and the spatial ability. However, gender differences in VSWM emerged only when a processing demand was added. No gender differences were found for the Simple Block Span, a spatial short-term memory task, but when a processing demand was added to the task, either verbal (deciding whether a sentence makes sense) or spatial (deciding whether letters are correct or inverted), gender differences emerged. Thus, both Kaufman (2007) and Coluccia and Louse (2004) emphasized the role of processing demands in the emergence of gender differences in VSWM (see also Vecchi & Girelli, 1998).

What was missing from Kaufman's work is an evaluation of the mental processes that are involved in block span tasks both with and without processing demands. There may have been a shift in strategies as a function of the processing demand or the strategies used for the Simple Block Span task may have become inefficient when the processing demand was added. If gender differences in strategy use are differentially affected by the processing demand of the tasks, that may explain gender differences in VSWM, but less so in visuospatial short-term memory.

Strategy use as a mediator. In reviewing literature on gender differences in spatial navigation, Saucier, Green, Leason, MacFadden, Bell, and Elias (2002) attributed males' advantage in task performance to males' preference for Euclidean strategies (also known as holistic strategies) and females' preference for landmarks strategies (also known as analytic strategies) during navigation (see also Lawton, 1994; Sandstrom, Kaufman, & Huettel, 1998). This model was based on findings of gender differences in strategy use in real-world navigation (Study 1, Saucier et al., 2002), as well as on a paper-and-pencil adapted task (Study 2, Saucier et al., 2002). Similarly, in a critical review of the relationship between spatial ability and strategy use, Glück and Fitting (2003) emphasized the importance of assessing strategy use in future research on gender differences in spatial ability.

While these models highlight the importance of strategy assessment, and there is some empirical evidence for gender differences in strategy use and spatial ability, gender differences in strategy use are not always accompanied by gender differences in performance within the same study. For instance, on Cube Comparison Task, which involves determining whether two cubes are identical based on the patterns on their three visible faces, Glück (1999) found gender differences in strategy use, with more males using holistic strategies and more females using analytic strategies, even in the absence of gender differences in performance.

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Furthermore, the "strategy use as a mediator" model does not explain what produces gender-specific preferences in strategy use in the first place. The results of Bowers and LaBarba (1988), as cited by Glück and Fitting (2003), indicate gender differences in spatial ability reflect more than gender differences in strategy use, or at least, are not directly determined by strategy use. Using a dual-task paradigm, Bowers and LaBarba (1988) found a verbal interference task disrupted only high spatial ability females and low spatial ability males' spatial visualization performance. Based on these results, the researchers inferred that these two groups relied on analytic strategies when solving the task. Thus, it appears in addition to gender and strategy use, there may be other factors that more directly influence gender differences in spatial ability. Working memory is a likely candidate in that strategy use takes place in working memory and, presumably, underlies performance on spatial ability tasks. The interaction between working memory and strategy use may be needed to explain findings like those of Bowers and LaBarba.

The Proposed Model

The proposed model specifies the logical sequence and the chain of effects among gender, working memory, and strategy use. Most importantly, the proposed model can explain why analytic strategies are associated with good spatial task performance in some females, but with poor spatial task performance in males. Specifically, the proposed model assumes that working memory, as expressed by a ratio score of VSWM to VWM, influences strategy use. Individuals whose VSWM is better than their VWM will be more likely to acquire holistic strategies and individuals whose VWM is better than their VSWM will be more likely to acquire analytic strategies. Because on average, males have a better VSWM than females, but have similar VWM, males are expected to have a higher VSWM to VWM ratio than females and will be more likely to acquire and use holistic strategies. Because females are stronger in VWM in

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contrast to VSWM their VSWM to VWM ratio is expected to be lower than males. This pattern is assumed to support the acquisition and use of analytic strategies when solving spatial tasks. Gender differences in spatial ability emerge when holistic strategies produce superior outcomes. Holistic strategies are hypothesized to be more efficient than analytic strategies for complex spatial tasks. In contrast, performance on spatial tasks results in fewer gender differences when analytic strategies are as effective as holistic strategies.

In a nutshell, the novel aspect of the proposed model is the specification of a ratio score of VSWM to VWM as the cognitive mechanism that produces gender differences strategy use, which in turn produces gender differences in performance on spatial ability tasks. The proposed model offers a relatively parsimonious and empirically testable explanation of gender differences in spatial ability.

Components of Working Memory

Working memory plays a critical role in complex cognitive activities (Miyake & Shah, 1999). Although many models of working memory have been proposed, most can be distinguished in one critical respect: having a unitary or a multi-componential structure. Proponents of a unitary view of working memory (e.g., Anderson, Reder, & Lebiere, 1996; Engle, Cantor, Carullo, 1992; Engle, Tuholski, Laughlin, & Conway, 1999) emphasized the attentional control function of working memory (Kane, Bleckley, Conway, & Engle, 2001) and its connection with long-term memory (Cowan, 2005), as well as its connection with the "g" factor in psychometric literature (Colom, Rebolloa, Palacios, Juan-Espinosa, & Kyllonen, 2004; Conway, Kane, & Engle, 2003). Proponents of a multi-componential view of working memory (e.g., Daneman & Tardif, 1987; Shah & Miyake, 1996), on the other hand, emphasized the

domain-specificity of the temporary storage function of working memory and its connection with achievements in specific cognitive domains.

Theorists and applied researchers endorsing a multi-componential view of working memory may be further divided into three camps: 1) those concerned primarily with distinguishing between maintenance (passive storage) and manipulation (active processing) functions (e.g., Duff & Logie, 2001; Pickering, Gathercole, Hall, & Lloyd, 2001; Vecchi & Girelli, 1998; Vecchi & Cornoldi, 1999); 2) those concerned primarily with distinguishing between different formats of mental representation stored (e.g., Lycke, Specht, Ersland, & Hugdahl, 2008; Shah & Miyake, 1996); 3) and those concerned both with the formats of mental representation and activity levels (e.g., Baddeley, 1986; Logie, 1995; Mammarella, Pazzaglia, & Cornoldi, 2008).

This review used Baddeley's (1986) multi-componential theory of working memory as a conceptual framework to investigate individual and gender differences in strategy use and spatial ability. This is because prior research suggested that Baddeley's (1986) theory was useful in explaining academic achievement in specific content domains (e.g., Kaufman, 2007; Shah & Miyake, 1996). However, it should be acknowledged that no consensus has been reached regarding whether working memory is best regarded as unitary or multi-dimensional (see Miyake & Shah, 1999 for a comprehensive review on this topic).

Baddeley's (1986) working memory model assumes that working memory is comprised of a phonological loop, a visuospatial sketchpad, and a central executive. According to this model, the central executive controls the two domain-specific slave systems. The two slave systems may be compared with what other researchers refer to as verbal short-term memory and visuospatial short-term memory. However, it is unclear whether the phonological loop and the

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visuospatial sketchpad are pure passive storage systems, or whether each possesses a domain-specific active processor. In other words, whether the domain-general central executive fulfills the dual-function of image manipulation and sub-vocal rehearsal, or whether there exists separate, domain-specific active processors within the sketchpad (i.e., inner-scribe, see Logie, 1995) and verbal information (i.e., sub-vocal rehearsal mechanism, see Daneman & Carpenter, 1980), respectively, is open to question.

In this article, the phonological loop is equated to verbal short-term memory and the visuospatial sketchpad is equated to visuospatial short-term memory. For theoretical parsimony, it is assumed that verbal working memory (VWM) and visuospatial working memory (VSWM) are products of the interactions between central executive and verbal short-term memory, central executive and visuospatial short-term memory. The central executive (executive functioning) refers to a constellation of cognitive functions that facilitate problem solving, planning, attention allocation, and switching (Taylor, Barker, Heavey, & McHale, 2012). To be consistent with contemporary research on this topic, in this article, in lieu of central executive, the term executive functioning is used throughout.

Gender Differences in Visuospatial Short-Term and Working Memory

Studies that looked at gender differences in spatial short-term memory often used tasks similar to forward Corsi Block-tapping (Milner, 1971; also known as Spatial Span in the Wechsler Memory Scale, 1997). There is less evidence of gender differences in visuospatial short-term memory than evidence of gender differences in VSWM. In the ensuing paragraphs, findings from studies using forward Corsi Block-tapping to assess spatial short-term memory are presented first. This is followed by the presentation of findings from studies using backward Corsi Block-tapping, n-back, and complex span tasks to assess VSWM.

Gender differences in visuospatial short-term memory. Forward and backward Corsi Block-tapping tasks are considered to be the gold standard in the neuropsychological assessment of visuospatial short-term memory and VSWM (see Milner, 1971; Kessels, van Zandvoort, Postma, Kappelle, & de Haan, 2000; Kaufman, 2007; Fischer, 2001; Bosco, Longoni, & Vecchi, 2004). On forward Corsi Block-tapping, participants are required to reproduce the spatial locations of the tapped blocks (or flashed squares on a screen, if the task is computer-adapted) based on the original order of their presentation. Forward Corsi Block-tapping is typically considered to be measuring spatial short-term memory, because the task involves little active processing.

Studies using similar tasks to forward Corsi Block-tapping either show a marginal male advantage in task performance (Capitani, Laiacona, & Ciceri, 1991; Grossi, Matarese, & Orsini, 1980; Orsini, Chiacchio, Cinque, Cocchiaro, Schiappa, & Grossi, 1986) or no gender differences (Kaufman, 2007; Postma, Jager, Kessels, Koppeschaar, & van Honk, 2004; Vecchi & Girelli, 1998). In Capitani et al. (1999) study, although gender differences were statistically significant, the absolute differences in block span between males and females on forward Corsi Block-tapping was a mere .27 blocks.

In Grossi et al. (1980) study, forward Corsi block-tapping was administered to 300 medical school students (150 males). A statistically significant male advantage was found. However, the effect size was not provided, making it impossible to evaluate the magnitude of the gender differences. In Orsini et al. (1986) study, the forward Corsi Block-tapping was administered to 1,354 adults, age ranged from 20 to 99 years. Gender differences favoring males were found, but the effect size cannot be determined from the data provided. Also, Orsini et al.

(1986) did not look at gender by age interaction, making it difficult to infer whether gender differences vary at different levels of age.

Overall, findings on gender differences in spatial short-term memory using various types of simple span tasks (i.e., tasks with only a storage demand but no processing demand) are mixed, with three studies showing a marginal male advantage and three studies showing no gender differences (see Table 2.1). The studies that showed gender differences have a large sample size whereas the studies that showed no gender differences have a small sample size, which might have resulted in insufficient statistical power to detect these differences. Thus, at best, it can be concluded that there is some empirical evidence for gender differences in spatial short-term memory favoring males when the sample size is large, but these differences are marginal when they appear.

Gender differences in visuospatial working memory. There are a number of ways to assess VSWM. Backward Corsi Block-tapping is considered a classic instrument of VSWM. On backward Corsi Block-tapping, participants are required to recall spatial locations in the reverse order of their presentation. Backward Corsi Block-tapping has an active processing demand in addition to the storage demand of forward Corsi Block-tapping. Unfortunately, few studies have looked at gender differences in VSWM using backward Corsi Block-tapping task. In two experiments conducted by Ruggiero, Sergi, and Iachini (2008), gender differences in block span for backward Corsi Block-tapping were not statistically significant in Experiment 1 that included only young participants, and barely reached statistical significance in Experiment 2 that included both young (in their 20s) and elderly (in their 60s) participants.

The n-back task is another instrument of VSWM that is frequently used in brain imaging research. It has also been used in some behavioral studies, where accuracy and reaction time are

of interest. Spatial n-back requires participants to determine the spatial locations of the presented stimulus they saw "n-back" as each new stimulus is shown (Lejback, Crossley, & Vrbancic, 2011). Using a high load spatial n-back (2-back) on 36 undergraduate psychology students (18 males), Lejback, Crossley, and Vrbancic (2011) found gender to be a statistically significant predictor of performance on spatial 2-back, with males outperforming females ($d = 1.09$). Thus, despite a relatively small sample size, gender differences in VSWM emerged in this behavioral spatial 2-back study.

Complex span tasks have also been used to assess VSWM. Complex span tasks typically have both a primary storage demand and a secondary processing demand. In Vecchi and Girelli (1998) study, in addition to the previously discussed spatial short-term memory tasks, the researchers also administered two complex span VSWM tasks. In addition to recalling the spatial locations of the previously shown matrix of half-filled blocks, participants were also required to identify the final destination of a moving path (described in a series of verbal statements that are pre-recorded on a tape) in a blank matrix. Even with a relatively small sample size ($N = 36$, 18 males), males were shown to outperform females at a statistically significant level. The effect size of the gender differences was $d = .50$ for the 2D VSWM task and $d = .60$ for the 3D VSWM task.

Similarly, in Cattaneo, Postma, and Vecchi (2006) study, participants were shown either words or cartoon object icons in different locations and were instructed to relocate them in either the same format (no need of transformation) or in a different format (object icons transformed into words and vice versa). Males outperformed females for complex processing when only some of the object icons and words were presented together in the encoding phase and both had to be transformed in the recall phase. Males also outperformed females on the primary spatial

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locations recall task when demanding interference tasks (e.g., articulatory suppression where participants needed to repeat back the alphabets; spatial-tapping condition where participants needed to tap the corner of the printing paper) were simultaneously administered. Again, a male advantage in task performance was present despite a relatively small sample size ($N = 40$ undergraduate students, 20 males).

In Kaufman (2007) study, in addition to a spatial short-term memory task (simple span), two VSWM tasks (complex span) were also administered. On the two VSWM tasks, participants were to recall the locations of a series of blocks in the order they were presented, while doing either a verification task (tapping verbal processing) or a rotation task (tapping spatial processing). Males' advantage on the two VSWM tasks were both statistically significant, with an effect size of $d = .58$ for the Verification-Block Span and an effect size of $d = .65$ for the Rotation-Block Span. The fact that gender differences in favor of males emerged, whether the complex span tasks entailed verbal processing or visuospatial processing, points to the need to examine the strategies being used both on the storage and the processing aspects of working memory tasks. It is possible that gender differences in the recall of blocks emerged for complex span tasks that involve either a verbal or a spatial processing are due to gender differences in strategy use in retaining the blocks, but that possibility needs to be tested.

Finally, in Duff and Hampson (2001) study, the complex span task they used to assess VSWM required participants to uncover the locations of several pairs of colored dots concealed under arrays of flaps. To successfully perform the task, participants needed to suppress mental representations of the already discovered matched and unmatched pairs in order to avoid searching in the same locations during ongoing searches (Duff & Hampson, 2001). Interestingly, females outperformed males on this VSWM task in all three experiments, making this one of the

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few studies where females exhibited better VSWM than males. This task differed from other VSWM tasks in that a substantial demand of the task was remembering previously identified pairs so there was less processing involved. Furthermore, the VSWM task used in Duff and Hampson (2001) study seems to be testing inhibition as much as spatial processing. This may explain why a male advantage in task performance did not emerge.

In sum, the studies reviewed utilized a variety of tasks that included backward Corsi Block-tapping, n-back, and complex span VSWM tasks. Five studies indicated gender differences favoring males, one study indicated gender differences favoring females, and one study found no gender differences (see Table 2.1). The effect sizes reported in the five studies that showed a male advantage in VSWM were moderate. The stronger gender differences in VSWM in comparison to visuospatial short-term memory may reflect the role of strategy use in active processing. One possible interpretation of these results is that the additional processing demand entailed in VSWM tasks impacts the effectiveness of the strategies being used to solve the tasks. When strategies are more efficient, they will be less affected by the increased processing demand of the working memory task. Examining the strategies that are used on these tasks is necessary to understand performance differences.

Visuospatial Working Memory and Spatial Ability

In an influential meta-analysis, Linn and Peterson (1985; see also Voyer, Voyer, & Bryden, 1995) divided spatial ability into three categories based on task demands on VSWM. The researchers labeled these spatial abilities as spatial perception, mental rotation, and spatial visualization. Spatial perception refers to the ability to perceive spatial relations among objects in the face of distracting information (Linn & Peterson, 1985). Spatial perception is typically measured by Embedded Figures (Witkin, 1971), Rod-and-Frame (Oltman, 1968), and Water

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Level Task (Piaget & Inhelder, 1956). Mental rotation refers to the ability to mentally represent and manipulate 2D or 3D visuospatial images (Linn & Peterson, 1985). Mental rotation is typically measured by the Vandenberg and Kuse Mental Rotation Test (Vandenberg & Kuse, 1978), the Primary Mental Abilities—Spatial Relations test (Thurstone, 1958), the Matching Parts and Figures test (Levy & Levy, 1999), or the Cube Rotations Test (Ekstrom, French, Harman, & Dermen, 1976). Spatial visualization refers to the ability to apprehend, encode spatial forms (Carroll, 1993), to recognize if parts of an object are displaced from their original positions (Mohler, 2008), and to perform multistep mental folding or rotation (Linn & Peterson, 1985). Spatial visualization is typically measured by Paper Folding Test (Ekstrom, French, Harman, & Dermen, 1976).

Among the three types of spatial ability described by Linn and Peterson (1985), mental rotation is where gender differences in performance are most pronounced. Although spatial visualization is similar to mental rotation in cognitive demand (Harris, Hirsh-Pasek, & Newcombe, 2013), among the three categories of spatial abilities meta-analyzed by Linn and Peterson (1985), gender differences in performance on spatial visualization were less evident.

Another way of categorizing spatial tasks is by considering the distinction between spatial tasks where mental transformation involves an egocentric or an allocentric frame of reference (Allen, 1999; Malinowski, 2001). The distinction has also been known as the "small-scale" (object-based) and "large-scale" (environment-based) spatial ability distinction (see also Casey, 2013; Jansen, 2009; Quaiser-Pohl, Lehmann, & Eid, 2004). In a systematic review, Hegarty and Waller (2004) found small-scale and large-scale spatial ability to be partially dissociated. Tasks measuring small-scale spatial ability typically require participants to adopt an allocentric frame of reference. An allocentric frame of reference refers to the central axis of an

object (see also Kozhevnikov & Hegarty, 2001). During allocentric spatial transformation, an object would revolve around its own central axis (several central axes may be identified for a given object). Because psychometric spatial abilities (e.g., spatial perception, mental rotation, and spatial visualization) typically require spatial transformations along the allocentric frame of reference), these types of spatial ability would logically subsume under the small-scale spatial ability category. Tasks measuring large-scale spatial ability typically require participants to adopt an egocentric frame of reference (Hegarty & Waller, 2004). The egocentric frame of reference refers to the body axis of the participants. During egocentric spatial transformation, one's perspective changes with respect to the larger environment, but the spatial relationships among individual objects within that environment do not change.

What little research that has been done examining the interactions among gender, VSWM, and performance on small-scale and large-scale spatial ability tasks suggests that gender differences in VSWM may contribute to the male advantage in spatial ability (Coluccia & Louse, 2005; Lawton & Hatcher, 2005). Kaufman (2007) found that gender predicted performance on two mental rotation tests, the Differential Aptitude Tests—Space Relations (Bennett, Seashore, & Wesman, 1990) and the Mental Rotation Test (Vandenberg & Kuse, 1978), through VSWM. Specifically, the results of the mediation analysis showed that VSWM, as measured by a complex span task, completely mediated the relationship between gender and spatial ability.

A number of studies have examined the relationship between VSWM and small-scale spatial ability. These studies showed that small-scale spatial ability performance is linked to VSWM. Miyake et al. (2001) investigated the relationships among visuospatial short-term memory, VSWM, executive functioning, and three psychometric spatial abilities (spatial perception, mental rotation, and spatial visualization) using structural equation modeling. These

researchers found that the zero-order latent correlation between VSWM (what they call "visuospatial STM-WM" factor) and the three psychometric spatial abilities ranged from .54 to .69. Using both a correlational design and a dual-task paradigm, Shah and Miyake (1996) demonstrated that VSWM and spatial ability are closely related. The VSWM task used in the study had both a storage demand and a processing demand. Specifically, participants needed to indicate whether a given letter on the computer screen was correct or inversed, while keeping track of the orientation of the letter. Spatial ability was measured using Paper Form Board, Space Relations, Clocks, and Identical Pictures tasks. In Study 1, the correlation between spatial span performance and a composite spatial ability score of the four spatial ability tasks was .66. In Study 2, a concurrent visuospatial processing task (mental rotation) or verbal processing task (sentence verification) were administered along with the primary task of spatial span. It was found that the concurrent visuospatial processing task disrupted spatial span performance more than a concurrent verbal processing task. Thus, both Miyake et al. (2001) and Shah and Miyake (1996) studies suggest VSWM and spatial ability are closely related.

There are also a few studies that directly investigated the interactions among gender, VSWM, and performance on large-scale spatial ability tasks. A study by Bosco, Longoni, and Vecchi (2004) offered some insights on the complex interactions among these three variables. Bosco et al. (2004) explored the extent to which spatial orientation task performance could be explained by VSWM involvement and whether gender differences in VSWM contributed to gender differences in spatial orientation task performance. In that study, the Jigsaw Puzzle Span Task (Richardson & Vecchi, 2002), which assesses the ability to allocate displaced fragments of a picture without moving the pieces, the Mental Pathway Task (Vecchi & Cornoldi, 1999), which requires participants to follow pathways based on directional statements in matrices of different

sizes, the Visual Pattern Test (Della Sala , Gray, Baddeley, & Wilson, 1999), which requires participants to memorize the configurations of black squares on matrices of various sizes, and the aforementioned Corsi Block-tapping (Milner, 1971) were used to measure VSWM. Landmark knowledge, survey knowledge, and route knowledge tasks based on a simplified map of an archaeological site, Roman Palatino, were used to measure spatial orientation. Significant gender differences in spatial orientation task performance were found. A stronger relationship between VSWM and large-scale spatial ability was found for males than for females, which the researchers interpreted as reflecting males relying more heavily on VSWM when performing spatial orientation tasks. Although strategy use was not directly assessed in that study, Bosco et al. (2004) hinted at the role of strategy use in spatial orientation task performance when they stated, "these results highlighted that cognitive strategies may both modulate cognitive abilities and help interpret gender differences" (Bosco et al., 2004, p. 530).

A number of studies examined the relationship between VSWM and large-scale spatial ability. These studies suggested that large-scale spatial ability performance involves VSWM. In Baldwin and Reagan (2009), participants were classified into good and poor spatial ability groups based on their self-reported sense of direction. Both ability groups learned novel routes while performing a secondary interference task involving either verbal processing (articulatory suppression) or spatial processing (sequential spatial-tapping). The results showed despite equivalent interference task performance between the good and poor spatial ability groups, the spatial-tapping task interfered more with route learning for the good spatial ability group, whereas the articulatory suppression task interfered more with route learning for the poor spatial ability group. The researchers inferred from these findings that high spatial ability individuals

relied more heavily on VSWM when learning routes than low spatial ability individuals. Low spatial ability individuals, instead, relied more heavily on VWM when learning routes.

In two other studies of similar nature, Brunyé and Taylor (2008) and Pazzaglia, Meneghetti, De Beni, and Gyselinck (2010) used a dual-task paradigm to study VWM and VSWM's involvement in spatial text processing. In Brunyé and Taylor (2008) study, spatial-tapping was administered as a concurrent task as research participants recall from memory spatial texts conveyed in route and survey descriptions. It was found that spatial-tapping impaired memory performance of spatial texts. In Pazzaglia, Meneghetti, De Beni, and Gyselinck (2010), two concurrent VSWM interference tasks that used identical visual stimuli (black dots on a white background) but different presentation modes (sequential vs. simultaneous) were administered as participants recalled spatial and non-spatial texts. It was found that both (sequential and simultaneous) VSWM interference tasks impaired spatial text recall. Assuming success in recalling spatial text depends on constructing good mental models of spatial layouts in VSWM, it made sense that the two concurrent VSWM interference tasks would impair spatial text recall (see Table 2.2 for additional references supporting the association between VSWM and large-scale spatial ability).

Overall, large-scale spatial ability studies showed that individuals with better VSWM tend to also excel in large-scale spatial tasks including tasks that require orienting oneself in large-scale space (Palermo, Iaria, & Guariglia, 2008), in real world way-finding (Malinowski, 2001; Nori, Grandicelli, & Giusberti, 2009), in navigating in virtual environment (Moffat, Zonderman, & Resnick, 2001), in schematic map drawing (Coluccia, Bosco, & Brandimonte, 2007; Coluccia, 2008; Quaiser-Pohl, Lehmann, & Eid, 2004), in inferring spatial distances (Ruggiero, Sergi, & Iachini, 2008), and in encoding and decoding route descriptions conveying

spatial configurations and metric information (De Beni, Pazzaglia, Gyselinck, & Meneghetti, 2005; Gyselinck, Meneghetti, De Beni, & Pazzaglia, 2009; Gyselinck, De Beni, Pazzaglia, Meneghetti, & Mondoloni, 2007; Pazzaglia, De Beni, & Meneghetti, 2007). There is some evidence that on average, males and high spatial ability individuals utilize VSWM to a greater extent than females and low spatial ability individuals. The latter tend to rely on VWM to a greater extent. More research that directly assesses the interactions among gender, working memory, and large-spatial ability is needed to ascertain whether gender differences in large-scale spatial ability are primarily due to gender differences in the relative strength of VSWM to VWM.

Gender Differences in Verbal Short-Term and Working Memory

Studies of gender differences in verbal short-term memory typically use simple span tasks similar to Forward Digit Span (Wechsler, 1981; 1997). Results from these studies generally do not show any gender differences (see Table 2.3). Studies examining gender differences in VWM utilize a variety of tasks. The findings are mixed, but most do not show any gender differences. In the ensuing paragraphs, we first review studies using various adaptations of the Forward Digit Span to assess verbal short-term memory. We then review studies using Backward Digit Span (Wechsler, 1997), n-back, and complex span tasks to measure VWM. The section concludes with an interpretation of why gender differences in VWM are not as clear-cut as gender differences in verbal ability that are often reported in the psychometric literature.

Forward Digit Span (Wechsler, 1981; 1997) is a commonly used neuropsychological instrument of verbal short-term memory. Forward Digit Span requires primarily the ability to store simple verbal information (e.g., digit sequence) with few active processing demands. On Forward Digit Span, participants are required to recall the digits they hear in the original order of the digits' presentation. Two of the three studies that used Forward Digit Span (Duff & Hampson,

2001; Orsini, Chacchio, Cinque, & Cocchiaro, 1986) to measure verbal short-term memory did not find significant gender differences. One study by Grossi, Matarese, and Orsini (1980) found a female advantage. A study using a word recall task to measure verbal short-term memory also found significant gender differences favoring females (Herlitz, Nilsson, & Backman, 1997).

Backward Digit Span is typically considered to be a VWM task because it has an active processing demand in addition to the passive storage demand of the forward digit span. To our knowledge, only one study that used backward digit span to measure VWM also compared gender differences. Duff and Hampson (2001) found no gender differences when Backward Digit Span was administered to 92 (46 males) undergraduate students.

The verbal n-back task requires participants to determine the identity of the letters presented n trials back as each new letter is shown (Lejback, Crossley, & Vrbancic, 2011). In Lejback et al. (2011), a medium-high load verbal n-back (2-back) was administered to 36 undergraduate psychology students (18 males). The researchers did not find gender to be a statistically significant predictor of verbal 2-back task performance. The null finding is consistent with the results of Goldstein et al. (2005) and Nagel, Ohannissien, and Cummins (2007) studies, which used similar n-back tasks to assess VWM.

However, findings on gender differences in brain activation patterns during n-back task performance are less clear-cut. In one study, Goldstein et al. (2005) found females show more activation in regions that are responsible for maintaining and processing verbal information. A study by Speck, Ernst, Braun, Koch, Miller, and Chang (2000) found both behavioral and brain activation differences between the genders ($N = 17$, 9 males, mean age = 35.6 years for males, mean age = 31.6 years for females). Using verbal 1-back, 1-increment, 2-increment, and 2-back tasks, Speck et al. (2000) found females outperform males in response accuracy. In addition, the

researchers found gender differences in brain activation with females predominately activating the left hemisphere and males showing either symmetrical activation or right brain dominance. In contrast, when a verbal n-back task was administered to 50 subjects (25 males) age ranged from 18 to 58 years, Schmidt, Jogia, Fast, Christodoulou, Haldane, Kumari, Frangou (2009) found no gender differences in brain activation patterns when subjects were matched for age, level of education, and ethnicity. Nor did they find gender differences in accuracy or reaction time.

Complex span tasks have also been used to measure VWM. Studies using complex span VWM tasks typically show a female advantage in task performance. Verbal complex span tasks have a storage and a processing demand that are both verbal in nature. In Study 3 of Duff and Hampson (2001) study, the Digit Ordering Task[1] was given to 88 undergraduate students (44 male) to measure their VWM. The task requires participants to randomly say aloud numbers 1 to 10 without repetition or omission (Duff & Hampson, 2001). Performance was evaluated based on the number of errors (repetitions and omissions) made. Results showed that females made significantly more errors than males. The effect size of these gender differences was $d = .59$. In the Robert and Savoie (2006) study, one verbal short-term memory task (Forward Digit Span) and three complex span VWM tasks (French versions of the Reading-span, Verbal-span, and Speaking-span) were given to 100 young adults (50 males) age ranged from 19 and 25 years. No gender differences were found for the composite score of VWM, which was comprised of scores of the three complex span measures. Finally, in Harness, Jacot, Scherf, White, and Warnick (2008) study, Word List Recall task (Ward & Tan, 2004) was used to measure VWM. One-hundred-forty-four undergraduate students (72 males) were given the test under a standard

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[1] Digit Ordering Task is also known as random digit generation task (Petrides, Alivisatos, Meyer, & Evans, 1993).

condition (no distraction) and a distraction condition, where a secondary verbal interference task was simultaneously administered alongside the primary word list recall task. In the no distraction condition, no gender differences in word-recall were found, whereas in the distraction condition, females recalled fewer words than males.

Of the four studies that examined gender differences in verbal short-term memory, two studies found gender differences whereas the other two found no gender differences. Of the seven studies reviewed that investigated gender differences in VWM, five behavioral (among which four used an n-back task and one used a composite score of Forward Digit Span and complex span tasks) found no gender differences; two studies yielded mixed findings in that on some tasks, males outperformed females and in other tasks no gender differences were found. Typically, gender differences were found for more complex tasks (e.g., in Duff & Hampson, 2001, when Digit Ordering Task was used to measure VWM and in Harness et al., 2008, when Word List Recall task was used in the distraction condition), whereas no differences were found for simpler tasks (e.g., in Harness et al., 2008, when Word List Recall task was used in the no distraction condition and in Duff and Hampson, 2001, when Backward Digit Span was used to measure VWM).

In light of females' better performance on psychometric verbal ability tests (Stumpf, 1995; Andreou, Vlachos, & Andreou, 2005), mixed findings of gender differences in VWM and some findings favoring males seem to be counterintuitive. One explanation is that the tasks can be completed using verbal or visuospatial processing. There is evidence that serial order retrieval of verbal information involves spatial processing (Dijck, Abrahamse, Majerus and Fias, 2013). Visuospatial processing may be a more efficient means of completing the more complex verbal

working memory tasks. Research examining the strategies used to complete verbal working memory tasks of varying levels of complexity needs to be done.

Strategy Use Contributes to Gender Differences in Spatial Ability

Performance on spatial ability tasks has been proposed to be a function of strategy use (Baldwin & Reagan, 2009; Botella, Peña, Contreras, Shih, & Santacreu, 2009; Glück & Fitting, 2003). Strategies are "behavioral routines" an individual employs to accomplish complex cognitive tasks (Reichle, Carpenter, & Just, 2000). The dominant theory is that the male advantage in spatial task performance is, in part, due to males' preference for holistic strategies (Glück & Fitting, 2003). In this section, we review research that examined gender differences in strategy use on small-scale and large-scale spatial ability tasks (see Table 2.4). We then discuss how gender differences in working memory influence strategy use and how strategy use, in turn, influences performance on spatial ability tasks.

Strategies used to solve spatial ability tasks can be broadly categorized as holistic and analytic strategies (Janssen & Geiser, 2012; Li & O'Boyle, 2011). Holistic strategies involve processing spatial relationships via mental rotation and visualization. Analytic strategies involve processing spatial relationships verbally and sequentially (Peña et al., 2008). Some strategies include aspects of both holistic and analytic strategies. Terms such as "piecemeal" and "weak holistic" have been used to describe these strategies (see Barratt, 1953; Geiser, Lehmann, Eid, 2006; Heil & Jansen-Osmann, 2008; Just & Carpenter, 1985; Peña et al., 2008; Quaiser-Pohl, Rohe, & Amberger, 2010). For these strategies, segments (parts) of an image, rather than the whole image, are rotated sequentially during mental comparisons (Kyllonen, Lohman, & Snow, 1984). Holistic strategies are typically associated with better performance on spatial ability tasks, especially in males (see Table 2.4 for a list of studies examining the relationship between

strategy use and spatial ability). However, while analytic strategies are typically associated with poorer performance in males, analytic strategies are sometimes associated with good performance in females and on some spatial ability tasks (see Fitting, 2002).

Gender Differences in Large-Scale Spatial Ability

Males generally outperform females when navigating in real-world and virtual environments (see Coluccia & Louse, 2004; Lawton, 1994; Malinowski & Gillespie, 2001). On average, males more heavily rely on Euclidean information, spatial configurations formed by landmarks, whereas females more heavily rely on the locations and appearances of individual landmarks when navigating in large-scale space (Choi & Silverman, 2003; Coluccia & Louse, 2004; Lawton, 1994; Picucci, Caffo, & Bosco, 2011). These two approaches to solving large-scale spatial tasks are known as holistic and analytic strategies, respectively (see Glück & Fitting, 2003).

There is evidence that strategy use influences performance on large-scale spatial ability tasks. An individual relying on analytic strategies may find it challenging to identify a shortcut on a map, or when traveling in the reverse direction from the itinerary. An individual relying on holistic strategies, on the other hand, can more flexibly use landmarks to find shortcuts, or to travel in the reverse direction from the itinerary (Lawton, 1994). Thus, holistic strategies are considered to be more advantageous than analytic strategies, at least when large-scale spatial navigation is concerned.

Spatial navigation studies showed that on average, males prefer to use holistic strategies and females prefer to use analytic strategies. These gender differences were found in studies using the self-report method to assess strategy use (Lawton, 1994) and in studies using

participants' response patterns to infer strategy use (Brown, Lahar, & Mosley, 1998; Dabbs, Chang, Strong, & Milun, 1998; Miller & Santoni, 1986).

Unlike spatial navigation, there are fewer gender differences in route learning (see Castelli, Corazzini, & Geminiani, 2008; Pazzaglia, Cornoldi, & De Beni, 2000, but see also Galea & Kimura, 1993, for an exception) and sometimes even a female advantage on tasks that involve memorizing landmarks (see Lejbak, Vrbancic, & Crossley, 2009; Voyer, Postma, Brake, & Imperato-McGinley, 2007). This is not surprising because analytic strategies can be equally helpful when the only objective of a task is to identify a learned route from a static map that is filled with landmarks. With the aid of landmarks, during a learning phase, females can memorize routes by verbally labeling the key landmarks at the turning points of those routes (Malinowski, 2001). Verbal processing via analytic strategies, in this case, allows females with a weak VSWM to accomplish the task. Location memory appears to be females' forte (see Voyer et al., 2007). Thus, it makes sense that some females may do well on tasks where their superior memory of landmarks may compensate for their relatively weak VSWM. Unfortunately, a pitfall of these studies is that they did not directly assess strategy use, making it difficult to infer whether gender differences in spatial navigation and route learning, when there are any, are due to males' preference for holistic strategies and females' preference for analytic strategies.

In sum, gender differences in performance on large-scale spatial tasks are associated with gender differences in strategy use. Of the behavioral large-scale spatial studies reviewed, five studies showed that on average, males prefer holistic strategies whereas females prefer analytic strategies. Males tend to outperform females on large-scale spatial ability tasks involving navigating in real world or virtual space. Two behavioral studies showed few or no gender

differences in route learning task performance, which can likely be accomplished using either analytic or holistic strategies.

Gender Differences in Small-Scale Spatial Ability

Mental rotation is a form of small-scale spatial ability where gender differences in task performance are most pronounced with males tending to outperform females (Linn & Peterson, 1985; Voyer et al., 1995). These gender differences persist in the absence of time pressure (Voyer et al., 2004), when the presentation mode changes from simultaneous presentation to sequential presentation (Titze, Heil, & Jansen, 2008; Titze, Heil, & Jansen, 2010), and when tactile stimuli are used in lieu of the printed materials (Robert & Chevrier, 2003). Because processing speed alone cannot completely explain males' better task performance on mental rotation tests (Voyer et al., 2004), it is likely that there may be some gender differences in strategy use.

Regarding research on gender differences in strategy use, on mental rotation tests, Geiser et al. (2006) and Janssen and Geiser (2010; 2012) showed that males are more likely to rely on visuospatial representations and holistic processing whereas females are more likely to rely on verbal labels and sequential processing. These differences have been found in studies using different versions of the classic Mental Rotation Test (e.g., Peters, Laeng, Latham, & Jackson,1995; Vandenberg & Kuse, 1978), Cube Comparison Test (Janssen & Geiser, 2010), Picture Rotation Test (Quaiser-Pohl, Rohe, & Amberger, 2010), as well as tests using 2D irregular-shaped line drawings (polygons) as task stimuli (Heil & Jansen-Osmann, 2008; Raabe, Hoger, & Delius, 2006).

One study by Glück (1999) used the self-report method to study strategy use in 800 secondary school students (387 males) on a mental rotation test (Cube Comparison Test). The

researcher found that more male students used holistic strategies and more female students used analytic strategies to perform the task. However, in that study, the researchers did not find actual performance differences between the genders.

Another study by Janssen and Geiser (2012) examined gender differences in strategy use using Peters et al.'s (1995) redrawn Mental Rotation Test and Amthauer, Brocke, Liepmann, and Beauducel's (2001) Cube Comparison Test. The researchers explored whether gender differences in self-reported strategy use were present in the German and Cambodia samples. The Cambodia sample was comprised of 310 university students (55.2% males) and the German sample was comprised of 278 secondary school students and 68 university students (38.7% males). On both tasks, males in both samples reported more holistic strategy use, whereas females in both samples reported more analytic strategy use. On the Mental Rotation Test, significant gender differences in performance favoring males were evident in both the German ($d = .87$) and the Cambodian ($d = .37$) samples. On the Cube Comparison Test, significant gender differences favoring males were present only for the German sample ($d = .43$).

Brain imaging research also provides some evidence for gender differences in strategy use. Using stimuli taken from the redrawn Mental Rotation Test (Peters et al., 1995), Butler, Imperato-McGinley, Pan, Voyer, Cordero, Zhu, and Silbersweig's (2006) examined the neural basis of gender differences in strategy use using fMRI. The study showed that the brain activation patterns between men and women differ when participants make the "same-different" judgment on whether the image next to the target item is identical or different from the target item. Men activated the primary sensory cortices, basal ganglia, and precuneus. These researchers interpreted the activation patterns as suggesting "automatic," "bottom-up," and "effortless processing." Women, on the other hand, activated dorsal-medial prefrontal and other

higher-order multimodal cortical association regions. These researchers interpreted the activation patterns as suggesting "top-down" and "effortful processing."

Jordan, Wüstenberg, Heinze, Peters, and Jancke (2002) used the fMRI technique to investigate gender differences in brain activation patterns as participants decide whether the two stimuli on display, which include rotated letters, rotated irregular 2D shapes, and rotated 3D cubes taken from the Mental Rotation Test (Vandenberg & Kuse, 1978), are identical. These researchers found gender differences in cerebral activation patterns even when gender differences in task performance were controlled. However, the precise activation patterns reported in this study do not completely overlap those reported in Butler et al. (2006) study. In short, a convergence of evidence from different behavioral and brain studies suggests that there are gender differences in strategy use when solving mental rotation problems.

Strategy use on mental rotation tasks has also been assessed through the analysis of response accuracy and response latency. Consistent with studies using the self-report method to assess strategy use, studies using statistical analyses to assess strategy use suggest that males tend to use holistic strategies and females tend to use analytic strategies to solve mental rotation problems. However, some of these studies showed that the types of strategies used on spatial tasks do not fit neatly into the holistic versus analytic dichotomy. Geiser, Lehmann, and Eid (2006), for instance, assessed the response latency and accuracy of 1,693 (843 males) elementary school and undergraduate students using Peters et al.'s (1995) redrawn Mental Rotation Test and identified five strategy categories based on an analysis of the participants' response patterns. Strategy use was inferred from the results of the latent class analysis (LCA)—a statistical method that can be used to classify test takers into different subgroups, in this case, strategy classes, based on participants' response patterns.

The researchers identified five latent classes overall and inferred that participants who were in what they labeled as the "non-rotator" class (Class 2) were verbal-analytic strategy users. This subgroup of test-takers had high solution probabilities for test items with configurationally different distracter choices, which can be successfully solved using either holistic or analytic strategies (Geiser et al., 2006; Voyer & Hou, 2006). The "non-rotator" solution class had poorer performance on test items with mirror-image distracter choices, which could only be solved using holistic strategies. Female participants were somewhat overrepresented in the "non-rotator" class. Thus, it was inferred that more female than male participants were analytic strategy users. Male participants were overrepresented in what the researchers labeled as the "fast rotator" class (Class 5), which is characterized by a high response accuracy for both types of items just mentioned and a low response latency (or a fast reaction time).

Besides the "fast rotator" class, two other classes (Class 3 and Class 4) could be distinguished by the speediness of response. Reaction time data suggests test-takers from these two classes may have engaged in spatial processing during task performance, but did so with different levels of proficiency. Class 3 was labeled as a "medium rotator" class. Participants in this class were highly likely to correctly solve the first eight items, but few reached the last four items by the time limit. Gender differences in Class 3 were rather pronounced, with a greater percentage of males being classified into Class 3. Class 4 was labeled as a "slow rotator" class, because of the significant drop in response accuracy that occurred as early as item four. A greater percentage of females were represented in this class. Still another class was labeled as the "poor performance" class (Class 1). Test-takers in this class had poor performance overall. The researchers suggested that this subgroup either did not use any strategies or were using either type of strategy inefficiently. Again, a greater percentage of females were found in this solution

class. The findings that females were overrepresented in Class 1, Class 2, and Class 4 suggest that they may have used strategies that were less efficient and that did not involve holistic processing.

Using a similar research method and the redrawn mental rotation test (Peters et al., 1995), Janssen and Geiser (2010) studied 346 (134 males) secondary and undergraduate students' response patterns. Similar to Geiser et al. (2006) study, analyses of the response patterns suggested that more males than females used holistic strategies, whereas more females than males used analytic strategies. Janssen and Geiser (2010) performed a latent class analysis on two mental rotation tests (i.e., the redrawn Mental Rotation Test, by Peters et al., 1995; German Cube Comparison Test, by Amthauer et al., 2001). The researchers did not find that females preferred analytic strategies on the German Cube Comparison Test, although they found males preferred holistic strategies on the same test by analyzing the response patterns. The class assignment in Janssen and Geiser (2010) study replicated Geiser et al. (2006) study in that males were overrepresented in classes that are indicative of holistic strategy use and females were overrepresented in classes that are indicative of analytic strategy use.

In sum, gender differences in performance on mental rotation (small-scale) spatial tasks are associated with gender differences in strategy use. Of the studies reviewed, six behavioral studies showed that on average, on tests of mental rotation, males prefer holistic strategies whereas females prefer analytic strategies. One behavioral study showed males prefer holistic strategy on both the Mental Rotation Test and the German Cube Comparison Test, whereas females prefer analytic strategies only on the Mental Rotation Test. Two brain imaging studies revealed gender differences in brain activation patterns that suggested differences in strategy use, but did not collect behavioral data of strategy use. Four studies showed that holistic strategies are

associated with better spatial task performance (see Table 2.4), but the research on analytic strategies is less clear. Specifically, one study (see Lawton, 1994) showed no gender differences in performance, three studies showed that analytic strategies are linked to poorer performance on spatial tasks comparing to holistic strategies and one study showed that analytic strategies are associated with good performance in females (see an empirical study cited in Glück & Fitting, 2003).

Evaluation of the Proposed Model

The tendency to play to strength is not unique to strategy use. Webb, Lubinski, and Benbow (2002), for instance, found that the relative strength of verbal to mathematical ability resulted in the pursuit of different academic goals. Males, who have stronger mathematical ability relative to verbal ability, tend to pursue math and science related academic goals, whereas females tend to pursue academic goals that take advantage of their stronger verbal ability. As with Webb et al. (2002), the crux of our claim is the relative strength of VSWM to VWM is responsible for gender differences in strategy use. Gender differences in spatial task performance emerge when holistic strategies are more effective than analytic strategie .

The proposed model is consistent with Halpern and Collaer's (2005) and Casey's (2013) conclusions about gender differences in spatial ability. According to Halpern and Collaer (2005), females tend to use verbal labels (analytic strategies) to encode object features when solving spatial tasks. This may be due to females' strength in verbal processing. Males tend to use Euclidean information (holistic strategies) when solving spatial tasks. This may be due to males' strength in representing spatial relationships (except for location memory, which seems to be females' forte, see Voyer et al., 2007). Casey (2013) went beyond listing potential factors that could influence gender differences in spatial ability by proposing an interactive model that

integrate biological (genetic) and psychosocial (environmental) perspectives. Casey (2013) specifically suggested that working memory and strategy use are important mediators of gender differences in spatial ability. Both Halpern and Collaer's (2005) and Casey's (2013) proposals are consistent with the proposed model.

There are several recent empirical studies that support different aspects of the proposed model. The Kaufman (2007) study indicated a complex relationship among VSWM, VWM and spatial ability. On the one hand, VWM correlated with spatial ability for females, but not for males. On the other hand, in a model where VWM was considered together with VSWM, VWM did not predict spatial ability. VSWM mediated the relationship between gender and spatial ability. The results of Kaufman (2007) study suggest that VWM may play some role in at least females' performance on spatial tasks, albeit not directly. It may be that this role comes in the form of gender differences in strategy use.

Meneghetti, Gyselinck, Pazzaglia, De Beni (2009) examined individual differences in spatial text processing and found that both VSWM and VWM were involved when processing spatial texts. The most noteworthy aspect of the study is that individuals with low spatial ability (mental rotation) utilized their VWM to a greater extent than their high spatial ability counterparts. In a latter study, Meneghetti, De Beni, Pazzaglia, and Gyselinck (2011) used a questionnaire to directly assess strategy use. That study used similar stimuli (spatial texts) and paradigm (dual-task interference) as Meneghetti et al. (2009). The results showed that the concurrent spatial interference task reduced the use of holistic strategies, as indicated by the participants' ratings on a Likert scale. The researchers also found that a concurrent articulatory suppression task, which disrupts VWM, reduced the use of analytic strategies (Meneghetti et al. (2011). These findings support the argument that individuals play to their strength and that

interference in spatial working memory affects holistic strategy use whereas interference in verbal working memory affects analytic strategy use. Unfortunately, the researchers did not compare gender differences so we do not know whether males and females used different strategies.

Similarly, Baldwin and Reagan (2009) assessed the relationship between self-reported spatial orientation ability (Sense of Direction, SOD) and strategy use when learning routes in a virtual environment. Using verbal articulatory suppression and spatial tapping as secondary interference tasks, the researchers found that individuals with good-SOD relied more on their VSWM than on their VWM when learning routes and vice versa for people with poor-SOD. The finding that good-SOD individuals' route recall performance was more influenced by a secondary VSWM interference task than a secondary VWM interference task, and vice versa for poor-SOD individuals, supports the proposed model. Similarly, the finding that good-SOD individuals preferred holistic (visuospatial) strategies and poor-SOD individuals preferred analytic (landmarks) strategies also supports the proposed model.

In short, while studies that directly assessed all variables of interest to the proposed model are lacking, a convergence of evidence from studies using a variety of experimental paradigms and task stimuli corroborated different aspects of the proposed model. Specifically, gender differences in spatial ability are linked to differences in strategy use and differences in the reliance on VWM and VSWM. The proposed model goes beyond prior research and models by specifying a precise mechanism (i.e., the ratio of VSWM to VWM) through which gender differences in spatial task performance can be explained.

Limitations and Future Directions

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We acknowledge that our review of gender differences in mental rotation focused primarily on studies using 3D measures, this is because most published studies that examined gender differences in mental rotation used 3D measures. Therefore, the conclusions of our review may not necessarily generalize to studies using 2D measures. However, it is reasonable to expect the patterns of findings that emerge from 2D studies are generally consistent with 3D studies. For instance, Heil and Jansen-Osmann (2008) used 2D polygons as task stimuli and found females' reaction time increased as a function of stimuli complexity, whereas males' reaction time did not. The researchers inferred that females may have rotated the polygons in an "analytic, piecemeal fashion" and males may have rotated the polygons as a whole. The finding that females' reaction time is a function of stimuli complexity, as opposed to rotation angle (see Cooper, 1976), which would imply holistic strategies being used, is consistent with what we have concluded based on the 3D studies reviewed in this article.

Regarding gender differences in mental rotation task performance, Neubauer, Bergner, and Schatz (2010) compared males and female' performance differences on both 3D and 2D presentations of the Sheperd-Metzler Task (1971) and found a male advantage on the 2D, but not the 3D presentation of the task. A possible explanation of the null gender differences findings on the 3D measure is that the 2D task is considered to be more challenging. To complete the 2D task, participants must take an extra step by constructing a 3D representation from a 2D representation. Processing 3D representations does not require this extra step. Thus, processing the 2D representations is more cognitively demanding. Although it is reasonable to expect similar gender differences in strategy use and performance on 3D and 2D mental rotation tests, the data from this study indicate that gender differences emerge for the more complex 2D mental

rotation task. Given that this was only one study, a solid conclusion cannot be drawn without more research.

Although gender, working memory, and strategy use are the main factors reviewed that could influence performance on spatial ability tasks, other factors may interact with strategy use to influence gender differences in spatial task performance. Indeed, there is some evidence that task features (e.g., regularity of spatial layouts, complexity, dimensionality, abstractness of task stimuli) may influence strategy use (see Folk & Luce, 1987; Glück & Fitting, 2003; Kyllonen, Lohman, & Snow, 1984; Picucci et al., 2011; Yuille & Steiger, 1982). Answers to what task features make holistic strategies more effective than analytic strategies and what task features are irrelevant to the use of either strategy will shed light on when gender differences in spatial task performance arise and when they do not. These factors need to be considered in future empirical research on gender differences in spatial ability and when designing instructional programs to improve spatial ability in all populations.

Casey (2013) raised similar points when she highlighted that the magnitude of gender differences in spatial task performance varies depending on whether a task can also be successfully solved using strategies other than holistic strategies. Casey (2013) reasoned that gender difference are most expressed on mental rotation tests because analytic strategies are not as effective as holistic strategies in most cases, whereas gender differences are not as expressed on other (small-scale) spatial ability tests such as spatial visualization tests, because those tests can also be reliably solved using "step-by-step feature analyses" (i.e., analytic strategies). The proposed model may be improved by incorporating a task demand by strategy use interaction to increase the precision of the model's predictions. However, at present, there is insufficient research that explores this interaction to justify its inclusion to the proposed model.

Implications to Education

Gender differences in spatial ability and strategy use may have both a biological (Casey & Brabeck, 1989) and an environmental basis (Baenninger & Newcombe, 1989; Coluccia & Louse, 2004). For instance, Casey, and Brabeck (1989) and Casey, Pezaris, and Nuttall (1992) found college women who excelled on the mental rotation test were those with a combination of genetic potentials and prior experiences (e.g., right-handed women with non-right-handed relatives and who have had extensive spatial experiences themselves). Other work suggests that cultural upbringing, schooling experience (see Janssen & Geiser, 2012; Li & O'Boyle, 2011), spatial anxiety (see Lawton, 1994), and self-confidence (see Picucci, Caffo, & Bosco, 2011) may also contribute to gender differences in performance on spatial ability tasks, either independently or by interacting with working memory and strategy use. The fact that cultural upbringing and schooling experience are relevant to spatial task performance indicates that spatial ability is malleable through training.

In a recent meta-analysis on the effects of spatial ability training, Uttal et al. (2013) collected all studies that included both the treatment and control groups and measured spatial ability before and after the intervention. Spatial training was found to improve spatial ability with a mean effect size of 0.40. A few studies have examined whether spatial ability can be improved in children and whether spatial ability training improves mathematics achievement (e.g., Ben Chaim, Lapan, & Houang, 1988; Cakmak, Isiksal, & Koc, 2014; Cheng & Mix, 2012). For example, Cheng and Mix (2012) found that a short intervention aimed at improving spatial ability improved early elementary school students' spatial ability as measured by mental rotation tests. The students in the experimental group were also better on a measure of mathematical skill, suggesting that spatial ability training may also improve mathematics achievement. Similar

research with young adults is encouraging in that improvements in spatial ability are linked to improvements in mathematics, but the bulk of these studies are not rigorous experimental studies (e.g., Baki, Kosa, & Guven, 2011; Sorby, Casey, Veurink, & Dulaney. 2013; Sorby & Baartmans, 2000). Of note, Sorby and Baartmans (2000) and Sorby et al. (2013) developed a semester-long course designed to improve college students' spatial ability. The course has resulted in a higher retention rate in the engineering program, suggesting that improving spatial ability can impact academic achievement in the STEM areas. More rigorous experimental studies need to be done, however, to determine the impact of spatial ability training on academic and professional outcomes.

Furthermore, while the evidence suggests training spatial ability results in positive outcomes, it is less clear how and whether we should intervene in VSWM and strategy use. One question is whether it would be wise to instruct students to use holistic strategies or to focus on improving VSWM before attempting to teach holistic strategies. If students do not have sufficient VSWM to use holistic strategies, efforts to instruct students to use holistic strategies may backfire. However, teaching holistic strategies may also enhance VSWM. Another question concerns the best approach to instruction. Specifically, are different methods of instruction equally effective in improving spatial ability in different gender, age, and ability groups? For instance, Höffler and Leutner (2011) showed that low spatial ability individuals' learning outcomes were impaired by spatial visualization training using static pictures but enhanced by dynamic visual displays. In contrast, Lee, Wong, & Fung, 2011, found high spatial ability individuals benefitted more from active learning experience and Kühl, Scheiter, Gerjets, and Gemballa (2011) found dynamic and static spatial visualization training to be equally effective in improving spatial ability. At present, as stated by Uttal, Meadow, Tipton, Hand, Alden, Warren,

and Newcombe (2013), "there is not a single answer to the question of what works best or what we should do to improve spatial skills" (p. 370).

There is some evidence that suggests VSWM may be improved through training. In a recent meta-analysis investigating the impact of working memory training, Melbe-Lervåg and Hulme (2013) reported a reliable but short-term improvement in verbal and non-verbal working memory (VSWM) after the training. Moderate training effects for VSWM were sustained five months after the training. Only a few studies examined the impact of VSWM training longer than five months so it is difficult to draw clear conclusions about their effectiveness.

There is also some evidence that suggests effective strategy use can be enhanced through training and that training effective strategy use, in turn, improves performance on spatial ability tasks. Sometimes, effective strategy use may merely be prompted by making certain spatial cues more salient. Wan, Newcombe, and Fitzhugh (2013), for instance, found adult males and females performed at a similar level when giving directions using a map that has four legends. Furthermore, Males and females also used similar strategies in that they both used Euclidean information equally in an experimental condition when they were provided with maps with four legends. However, males used Euclidean information more than females and performed better than females in an experimental condition where fewer legends were provided (i.e., 1-legend-map condition). Based on these findings, Wan et al. (2013) proposed that one way to improve females' spatial ability would be to make Euclidean information more salient to them, as in the 4-legend-map condition. A study by Miller and Halpern (2013) was one of a few studies that used a randomized control trial to investigate the impact of strategy training. Although the researchers did not directly assess participants' strategy use before and after the intervention, they found that

teaching holistic (spatial) strategies to solve spatial problems (e.g., using hand gestures to indicate rotational motions) improved participants' posttest spatial ability test scores.

Finally, a few studies have explored whether spatial ability training differentially influences males' and females' performance on spatial ability tasks. Of the studies that included gender as a variable, one study found that while both males' and females' performance on spatial ability tasks improved after the training, gender gaps in task performance persisted (see Miller & Halpern, 2013). One study found males had a faster initial growth rate whereas females showed a greater improvement later in training (see Newcombe & Frick, 2010). A third study found that gender gaps in posttest spatial task performance were eliminated as a result of the strategy training (see Stieff, Dixon, Ryu, Kumi, & Hegarty, 2013).

The results of the intervention studies designed to improve spatial ability show that spatial ability can be improved through training and that the improvement affects achievement in the STEM areas. Because of this, more efforts need to be made to improve spatial ability, and possibly through strategy instruction and working memory training. It should be emphasized that strategy use and learning styles should not be confounded. Thus, it cannot be concluded that gender differences in spatial ability are due to gender differences in learning styles and that teachers need to tailor their instruction to accommodate differences in learning styles between male and female students. Such behavior would only inhibit the progress of females with poor initial spatial ability.

Conclusions

The proposed model assumes individuals are inclined to select strategies that are consistent with their cognitive strength (see also Just & Carpenter, 1985; Kyllonen, Lohman, & Snow, 1984). In this case, strategy use is determined by the relative strength of VSWM to VWM.

A number of patterns in the data support the model. First, holistic strategies are generally associated with good spatial task performance in both genders, but especially in males. Second, analytic strategies are associated with the good performance of many females and some males with a high VWM to VSWM ratio, but only when the spatial tasks do not require holistic strategies. Third, gender differences favoring males are most pronounced on spatial tasks or test items that can only be solved by using holistic strategies.

The validity of the proposed model awaits empirical testing that more directly assesses the roles of VSWM, VWM, strategy use, and spatial ability in a single study. Nevertheless, a convergence of evidence from the literature that covers different facets of the proposed model is generally consistent with this model. Overall, the proposed model offers a useful conceptual framework to guide future research on gender differences in spatial ability.

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Appendix 1

Table 2.1

Studies Showing Gender Differences in Visuospatial Short-Term Memory and Visuospatial Working Memory Using Different Types of Tasks

Studies	Tasks	Differences in favor of		
Visuospatial Short-Term Memory				
		Females	Males	No Differences
Capitani, Laiacona, & Ciceri (1991)	Corsi block-tapping, forward		Yes Gender differences in block span were not significant ($p > .05$)	
Grossi, Matarese, & Orsini (1980)	Corsi block-tapping, forward		Yes ($t = 5.63$, $p < .001$)	
Kaufman (2007)	Simple block span			Yes ($t = 1.10$, $p > .05$, $d = .22$)

Orsini, Chiacchio, Cinque, Cocchiaro, Schiappa, & Grossi (1986)	Corsi block-tapping, forward	Yes	ANOVA showed gender effects were significant (F = 10.59, $p <$ .001)
Postma, Jager, Kessels, Koppeschaar, & van Honk (2004)	Corsi block-tapping, forward		Yes No t or F statistics were provided ($p >$ .05)
Vecchi & Girelli (1998)	2D and 3D matrices, passive		Yes ($F < 1$, $p >$ .05, $d =$ .19 for 2D task, $d =$ .12 for 3D task)

Visuospatial Working Memory		Female	Male	No Differences
Cattaneo, Postma, and Vecchi (2006), Experiment 2	Object relocation		Males outperformed females in the more active condition (F (1, 38) =11.72, $p <$ .001)	
Duff and Hampson (2001)	Colored dots task (complex span)	females made significantly fewer errors on Trial 1 (t (87) = 5 3.06, $p < .01$) a significant main effect of sex was found for time (F (1, 88) = 4.82, p = .031)		
Kaufman (2007)	Rotation-block span		Yes ($t = 3.40$, p <.001, $d =$ .65)	
	Verification-block span		Yes ($t = 3.19$, p <.001, $d =$ .58)	
Lejback, Crossley, & Vrbancic (2011)	Spatial 2-back		Yes ($p < .05$, $d =$ 1.09)	

Ruggiero, Sergi, & Iachini (2008), study 1	Corsi block-tapping, forward		Yes No *t* or *F* statistics was provided (*p* > .05)
Ruggiero, Sergi, & Iachini (2008), study 2	Corsi block-tapping, forward	Yes No *t* or *F* statistics was provided (*p* < .05)	
Vecchi & Girelli (1998)	2D and 3D matrices, active	Yes (F (1, 34) = 12.44, *p* <.005, d = .50 for 2D task, d = .60 for 3D task)	

Appendix 2

Table 2.2

Studies Examining the Influence of VSWM on Spatial Task Performance

References	Tasks	Samples	Results
Bosco et al., 2004	Jigsaw puzzle	Undergraduate	VSWM and large-
	Mental pathway	psychology students	scale spatial ability
	Visual Pattern	N, 107 (54 women)	are closely associated
	Corsi's Blocks	Age, 18-36	Percentage of
	Spatial orientation		explained variance of
	Landmark		large-scale spatial
	knowledge		ability predicted by
	Survey knowledge		VSWM is
			significantly higher
			for men than for
			women
Coluccia, 2008	Route Knowledge	N, 96 (48 males)	The spatial tapping
(Experiment 1)	Spatial-tapping	Age, 19-30	task significantly
	The Palatine map		interfered with some
	Landmark		aspects of map
	positioning		learning
	Pointing		Learning of the

	Route finding		absolute positions and route knowledge were impaired by the concurrent spatial tapping task, suggesting VSWM's involvement in map learning
			Spatial-tapping task disrupted route-learning task performance
Garden et al., 2002 (Experiment 1)	Spatial-tapping Route-learning task	Undergraduate psychology students N, 65 (13 males) Age, 19-29	Concurrent spatial-tapping task led to a decrease in route-learning performance, suggesting a link between VSWM and large-scale spatial

			ability

Garden et al., 2002 (Experiment 2)	Spatial-tapping Real-life route	First year undergraduate students N, 30 (7 males) Age, 19-31	Spatial text processing of high mental rotation group was not impaired by the concurrent spatial-tapping, whereas spatial text processing of low mental rotation group was
Meneghetti et al., 2009 (Experiment 1)	Spatial-tapping Mental Rotation Spatial text recall	Undergraduate psychology students N, 121 (111 females) Age, mean = 20.09	Mental rotation is related to spatial text recall VSWM is related to performance on mental rotation test and spatial text recall

Meneghetti et al., 2011 (Experiment 2)	Mental rotations The Corsi's Blocks Spatial text recall	Undergraduate psychology students N, 120 (26 males) Age, mean = 23.40 years	High VSWM individuals do better on way-finding tasks than low VSWM individuals (fewer errors, less pausing behaviors, and shorter response latency)
Nori et al., 2009	Mental Rotation Corsi's Block, forward version Copying Task Spatial Problem Way-finding	Undergraduate psychology students N, 40 (20 males) Age, 19-32	High VSWM group performed significantly better than the low VSWM group [t (20) = 2.12, p < .05]

Appendix 3

Table 2.3

Studies Showing Gender Differences in Verbal Short-Term Memory and Verbal Working Memory Using Different Types of Tasks

Studies	Tasks	Differences in favor of		
Verbal Short-Term Memory				
		Females	Males	No Differences
Duff and Hampson (2001)	Forward digit span,			Yes (t (90) = .26, p = .792)
Grossi, Matarese, & Orsini (1980)	Forward digit span,	Yes (t = 2.08, p < .05)		
Herlitz, Nilsson, & Backman (1997)	Word recall (free recall)	Yes MANOVA showed significant effects of gender (Wilks's λ = .919, F (15, 966) = 5.67)		
Orsini, Chiacchio, Cinque, Cocchiaro, Schiappa, & Grossi (1986)	Forward digit span			Yes Multiple regression showed the coefficient for gender to be not significant (t (1350) = .9, p > .05)
Verbal Working Memory				

		Female	Male	No Differences
Duff and Hampson (2001), Experiment 2	Backward digit span			Yes (t (90) = .39, p = .700)
Duff and Hampson (2001), Experiment 3	Digit ordering task	Yes Females made fewer total errors than males, t (86) = 2.75, p = .007		
Goldstein et al. (2005)	Auditory WMEM task (similar to n-back)			Yes No significant mean gender differences in performance on the behavioral testing of WMEM
Harness, Jacot, Scherf, White, and Warnick (2008)	Free-word recall, with distraction	Yes Gender differences without the distraction task ($p < .05$, d = .85)		
	Free-word recall, no distraction			Yes Gender differences without the distraction task ($p > .05$, d = -.35)

Lejback, Crossley, & Vrbancic (2011)	Verbal 2-back		Yes $(p > .05, d = .08)$
Nagel, Ohannissien, and Cummins (2007)	Verbal 2-back and 3-back		Yes Student t tests showed no significant gender differences $(p > .05)$
Robert and Savoie (2006)	Composite VWM (forward digit span, reading-span, verbal-span, and speaking span)		Yes $(p > .05)$
Schmidt, Jogia, Fast, Christodoulou, Haldane, Kumari, Frangou (2009)	Verbal n-back		Yes $(p > .05)$
Speck, Ernst, Braun, Koch, Miller, and Chang (2000)	Verbal n-back (1-back, 1-increment, 2-increment, 2-back)	Yes Accuracy is significantly higher in females $(F = 11.0, p = 0.01)$	

Appendix 4

Table 2.4

Studies Examining the Influence of Strategies on Spatial Task Performance

References	Tasks	Samples	Results
Burin, Delgado, and Prieto, 2000	Reduced version of the Spanish adaptation of the DAT-SR Reduced version of the Spanish adaptation of Mac Quarrie's Block Counting Spanish puzzle test CER (Solution Strategies Questionnaire) Adaptation of Schultz's SSQ	College psychology students N, 152 (75 women) Age, mean = 23.03 (SD = 4.24)	Choice of strategy is not related to spatial task performance
Fitting, 2002	A virtual reality environment Self-reported strategy use	Individuals who felt they had a very good or very bad sense of direction (SOD)	No differences between high and low-SOD participants in how

		N, 64 (32 men)	frequently analytic
		Age, mean = 46.1	strategies are used
		years (SD = 5.7)	High-SOD
			participants used
			holistic strategies
			significantly more
			often than low-SOD
			participants
Lawton, 1994	Vandenberg and	University students	The partial
	Kuse Mental	taking an introductory	correlation
	Rotations Test	psychology course	(controlling for
	Piagetian Water-	N, 426 (288	gender) between
	Level Task	females)	holistic strategies and
	Way-Finding	Age, mean = 24.30	water-level task
	Strategy Scale	(SD = 8.01)	performance was
			significant, r (416)
			= .17, p < .001
			No significant

			relationship between analytic strategies and water level task performance, $r(420) = .03$, $p > .20$
			No significant relationship between the MRT performance and either of the two strategies
Peña, Contreras, Shih, and Santacreu, 2008	Nebe's Circle Matching The Money Standardized Test of Direction Sense Vandenberg and Kuse Mental Rotations Test Spatial Strategy Questionnaire	Students from introductory psychology subject pool N, 243 (150 females) Age, 18 to 32 years (mean = 19.7)	Strategies significantly enhance the prediction of mental rotation and spatial orientation task performance Hierarchical regression and bivariate correlation analyses suggest strategies make a unique contribution to

the variations in

spatial task

performance above

and beyond gender,

and at a magnitude

similar to gender

CHAPTER 3

HOW ARE COMPONENTS OF WORKING MEMORY, SPATAL ABILITY, AND

MATHEMATICS ACHIEVEMENT RELATED [2]

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[2] Wang, L., Carr, M., Alagoz, C., and Schwanenflugel, P. To be submitted to *Learning and Individual Differences*.

Abstract

Spatial ability has been linked to mathematics achievement. However, we do not understand the cognitive mechanisms underlying that relationship. The literature suggests that there exists an implicit model that best describes the relationships among all components of working memory (visuospatial working memory, verbal working memory, and executive functioning), mental rotation, and mathematics achievement. While the connections between all components of working memory with spatial ability and with mathematics achievement are supported by the literature, the implicit model has never been explicitly tested. This study filled this gap by first testing three models that derive from the implicit model via structural equation modeling. Model 1 assumes executive functioning predicts verbal working memory (VWM) and visuospatial working memory (VSWM) and all three components of working memory predict mental rotation and mathematics achievement. Model 2 is identical with Model 1, with the exception that it assumes that the impact of executive functioning on mathematics achievement is completely mediated by mental rotation. Model 3 assumes the connection between mental rotation and mathematics achievement is due to a common third predictor variable, VSWM. The results of these analyses show that among all components of working memory, VSWM is the best predictor of mental rotation and mathematics achievement. This study also tests a fourth model (Model 4), an alternative model to Model 3, which retains the path from mental rotation to mathematics achievement but removes the path from VSWM to mathematics achievement. Models 3 and 4 fit similarly to the data. This suggests that VSWM and mental rotation are close to identical constructs. Mathematics achievement is best explained by either VSWM or mental rotation, but not when both serve as predictor variables.

Introduction

Prior research showed that individual differences in spatial ability can be explained by visuospatial working memory (VSWM) (Cornoldi & Vecchi, 2003). Verbal working memory (VWM), to some extent, has also been shown to contribute to individual differences in spatial ability (Kaufman, 2007). There is also ample evidence suggesting executive functioning's role in predicting general academic achievement and domain-specific achievement (e.g., performance on spatial ability tasks and mathematics achievement) (Bull, Espy, & Wiebe, 2008; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). However, it is not clear the relative importance of these predictor variables in explaining individual differences in spatial ability and mathematics achievement because, to our knowledge, no study included measures of all these variables in a single study. This study explored how all components of working memory (VSWM, VWM, and executive functioning), spatial ability (mental rotation), and mathematics achievement are related by testing a few structural equation models.

Three prior studies led to the present study. The first study used structural equation modeling to examine the relationships among three categories of spatial abilities (spatial perception, mental rotation, and spatial visualization), executive functioning, and VSWM in young adults (see Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). The Miyake et al. (2001) study found executive functioning statistically significantly predicted all three categories of spatial abilities, whereas VSWM only statistically predicted spatial perception.

The second study established relationships among mathematics achievement, executive functioning, VSWM, and VWM in elementary school children (Bull, Espy, & Wiebe, 2008) using a combination of correlational analyses, multiple regressions, and growth curve modeling. The Bull, Espy, and Wiebe (2008) study found VSWM (Forward and Backward Corsi Blocks,

Wechsler, 1997), VWM (Forward and Backward Digit Span, Wechsler, 1997), and executive functioning (Shape School, Espy, 1997) of 4.5-year-olds were all statistically significant predictors of the children's mathematics achievement when they reached the age of 7.

The third study established relationships among VSWM, VWM, and spatial ability in young adults (Kaufman, 2007), also using a structural equation modeling approach. The Kaufman (2007) study found individual differences in mental rotation spatial ability (DAT Space Relations Test, The Psychological Corporation, 1995; Mental Rotation Test, Vandenberg & Kuse, 1978) were statistically significantly predicted both by individual differences in VSWM (Verification-block Span and Rotation-block Span, Shah & Miyake, 1996) and by individual differences in VWM (Reading Span, Baddeley, Logie, Nimmo-Smith, & Brereton, 1985; Daneman and Carpenter, 1980).

Although the three studies just described applied information processing theory to explain individual differences in either psychometric spatial ability or in mathematics achievement, none of these studies included all relevant variables, i.e., executive functioning, VSWM, VWM, spatial ability (mental rotation), and mathematics achievement, in a single study and tested the relationships among these variables. This study tested an implicit model that assumes all three components of working memory contribute to individual differences in spatial ability and mathematics achievement, but to different degrees. Prior studies that failed to include all relevant variables in a model may distort the relationships among the variables included in the model. Therefore, it is important to conduct this study. Because the variables of interest are latent variables and that the objective of this study is to simultaneously estimate the relationships among all relevant variables, structural equation modeling is deemed most appropriate.

Working memory is at the core of information processing theory. In the next few sections, an influential working memory model proposed by Baddeley's (1986) is described, followed by definitions of three categories of psychometric spatial abilities. Next, research that supports each pair of the relevant variables included in this study is presented. Finally, three structural equation models that derive from the implicit model are described.

A Tripartite Working Memory Model

Working memory plays a critical role in complex cognitive activities (Miyake & Shah, 1999). Although many models of working memory have been proposed, most can be distinguished by one critical respect: having a unitary or a multi-componential structure. On the one hand, proponents of a unitary view of working memory (e.g., Anderson, Reder, & Lebiere, 1996; Engle, Cantor, Carullo, 1992; Engle, Tuholski, Laughlin, & Conway, 1999; Kane, Bleckley, Conway, & Engle, 2001) emphasize the attentional control function of working memory and its connection to the "g" factor. Proponents of a multi-componential view of working memory (e.g., Baddeley, 1986; Daneman & Tardif, 1987; Shah & Miyake, 1996) emphasize the domain-specificity of the temporary storage function of working memory and its connection to achievement in specific cognitive domains.

Theorists and applied researchers endorsing a multi-componential view of working memory may be further divided into three camps: 1) those concerned primarily with distinguishing between maintenance (passive storage) and manipulation (active processing) functions (e.g., Duff & Logie, 2001; Vecchi & Girelli, 1998; Vecchi & Cornoldi, 1999); 2) those concerned primarily with distinguishing between different formats of mental representations (e.g., Lycke, Specht, Ersland, & Hugdahl, 2008; Shah & Miyake, 1996); and 3) those concerned

both with the formats of the mental representations and with the activity levels (e.g., Baddeley, 1986; Logie, 1995; Mammarella, Pazzaglia, & Cornoldi, 2008).

This study used Baddeley's (1986) multi-componential working memory model, which fits the third camp, as a conceptual framework to investigate individual differences in spatial ability and mathematics achievement. This is because Baddeley's (1986) working memory model is particularly useful in explaining individual differences in achievement in specific domains. It accounts for differences in both the format and the activity levels of incoming information by including both storage and processing components. The model assumes different formats of mental representation and processing mode in the form of VWM and VSWM. There are also theories proposing other ways of fractionating working memory. Some working memory models, in addition to designating a verbal and a visuospatial components, also propose auditory and tactile-kinesthetic components (for a comprehensive review of different models of working memory, see Miyake & Shah, 1999). This study used Baddeley's (1986) model because it is relatively parsimonious but at the same time reflects the non-unitary nature of working memory, and it is supported by substantial empirical research.

Baddeley's (1986) working memory model assumes working memory is comprised of a phonological loop, a visuospatial sketchpad, and a central executive. According to this model, the central executive controls the two domain-specific subsystems. The two domain-specific subsystems may be compared to what other researchers refer to as verbal short-term memory and visuospatial short-term memory. However, it is unclear whether the phonological loop and the visuospatial sketchpad are pure passive storage systems, or whether they might each possess a domain-specific active processor. In other words, whether the domain-general central executive fulfills the dual-function of image manipulation (within the visuospatial domain) and sub-vocal

rehearsal (within the verbal domain) or whether there exist separate domain-specific active processors within the sketchpad and the loop, to process visuospatial (e.g., inner-scribe, Logie, 1995) and verbal information (e.g., sub-vocal rehearsal mechanism, Daneman & Carpenter, 1980), is open to question.

Contemporary working memory research is consistent with Baddeley's (1986) working memory model: two domain-specific subsystems (one responsible for storing visuospatial and the other for storing verbal information) and a central processor (responsible for processing information of all modalities) are assumed. In this article, the loop and the sketchpad were treated as synonymous with verbal short-term memory and visuospatial short-term memory, respectively. The central executive (executive functioning) refers to a constellation of cognitive functions that facilitate problem-solving, planning, attention allocation, and switching attention across tasks (Taylor, Barker, Heavey, & McHale, 2012). To be consistent with contemporary research, in this article, "executive functioning" was used throughout in lieu of "the central executive." For theoretical parsimony, no domain-specific processing component within the loop or the sketchpad was assumed. Verbal working memory and VSWM were considered to be products of the interaction between executive functioning (the central executive) and verbal short-term memory, and between executive functioning and visuospatial short-term memory.

Psychometric Spatial Ability

Prior research established a link between verbal ability and VWM (e.g., Daneman & Carpenter, 1980; Hunt, Lunneborg, & Lewis, 1975). In parallel, spatial ability literature also showed individual and gender differences in spatial ability can be explained in terms of differences in VSWM (e.g., Kaufman, 2007; Miyake et al., 2001). This section describes three

types of psychometric spatial skills commonly referred to in empirical studies and the assessment of those spatial skills.

Although there is no consensus on how spatial ability is best defined, the term generally refers to the ability to represent and manipulate 2-D or 3-D spatial relationships mentally. The terms "spatial ability" and "spatial skills" have both been used by spatial cognition researchers. In this paper, these terms were treated as interchangeably. In an influential meta-analysis, Linn and Peterson (1985; see also Voyer, Voyer, & Bryden, 1995) defined three types of spatial skills that they labeled spatial perception, mental rotation, and spatial visualization. Spatial perception refers to the ability to perceive spatial relations among objects in the face of distracting information (Linn & Peterson, 1985). Spatial perception is typically measured by Embedded Figures (Witkin, 1971), Rod-and-Frame (Oltman, 1968), and Water Level Task (Piaget & Inhelder, 1956). Mental rotation refers to the ability to represent and manipulate 2D or 3D visuospatial images mentally (Linn & Peterson, 1985). Mental rotation is typically measured by the Vandenberg and Kuse Mental Rotation Test (Vandenberg & Kuse, 1978), Thurstone's Primary Mental Ability Tests—Spatial Relations (Thurstone & Thurstone, 1949), Matching Parts and Figures (Levy & Levy, 1999), and the Cube Rotations Test (Ekstrom, French, Harman, & Dermen, 1976). Spatial visualization refers to the ability to apprehend and to encode spatial forms (Carroll, 1993), to recognize if parts of an object are displaced from their original positions (Mohler, 2008), and to perform multistep mental folding or rotation (Linn & Peterson, 1985). Hence, mental rotation and spatial visualization are closely related by task demand. Spatial visualization is typically measured by the Paper Folding Test (Ekstrom, French, Harman, & Dermen, 1976).

Applying factor analytic techniques, Carroll's (1993) work suggested the existence of five psychometric spatial ability factors: spatial visualization, spatial relations, closure speed, flexibility of closure, and perceptual speed. The flexibility of closure factor from Carroll's (1993) model is analogous to spatial perception (see Mohler, 2008) in Linn and Peterson's (1985) terminology. In the same vein, the spatial relations factor is comparable to mental rotation in Linn and Peterson's (1985) terminology. Miyake et al. (2001) suggested that distinctions among different types of psychometric spatial skills can be understood in terms of their demand on working memory and executive functioning (Miyake et al., 2001; see also Hegarty, Shah, & Miyake, 2000; Shan & Miyake, 1996).

As pointed out by Miyake et al. (2001), tests of spatial visualization, such as the Paper Folding Test (Ekstrom, French, Harman, & Derman, 1976) and the Space Relation Test (Bennet, Seashore, & Wesman, 1972), typically require multistep mental transformations. These mental transformations require active maintenance of an overarching goal and sub-goals and a mental representation of task stimuli in the face of visuospatial interference. Based on a task analysis of commonly used tests of spatial visualization, mental rotation, and spatial perception, it has been suggested that the more mental transformations that are required by a task, the more demanding the task is of executive functioning. The results of Miyake et al.'s (2001) study suggest that the rank order from the most demanding to the least demanding of these three spatial skills are: spatial visualization, mental rotation, and spatial perception.

Spatial Ability and Mathematics Achievement

Because solving certain types of mathematics problems involves representing and manipulating images in space (Hegarty & Kozhevnikov, 1999), spatial ability has been suggested to predict mathematics achievement. There is ample evidence supporting the link between spatial

ability and mathematics achievement (see Battista, 1990; Carr, Steiner, Kyser, & Biddlecomb, 2008; Casey, Nuttall, & Pezaris, 2001; Sherman, 1979). The first line of evidence comes from behavioral research on mathematically precocious children (Robinson, Abbott, Berninger, & Busse, 1996; Swanson, 2006). The second line of evidence comes from behavioral research on average-achieving children (Holmes, Adams, & Hamilton, 2008), adolescents (Reuhkala, 2001), and healthy young adults (Tolar, Lederberg & Fletcher, 2009). The third line of evidence comes from behavioral studies on children with mathematics learning disabilities (Geary, 1993; 2007) such as dyscalculia, a condition characterized by difficulties representing and manipulating numerical information despite an average or an above average cognitive profile in other cognitive domains (Rotzer, Loenneker, Kucian, Klaver, & Aster, 2009).

A fourth line of evidence supporting the link between spatial ability and mathematics achievement comes from behavioral intervention studies. For instance, Cheng and Mix (2012) found basic numerical skills were improved through instruction designed to improve spatial ability. A fifth line of evidence supporting the link between spatial ability and mathematics achievement comes from behavioral research on the Spatial Numerical Association of Response Codes (SNARC) effect (see Mix & Cheng, 2012 for a review). Studies of the SNARC effect demonstrated that people respond faster with their left hands to smaller numbers but respond faster with their right hands to larger numbers. Researchers who conducted these studies interpreted the SNARC effect as indicating the automatic association between spatial locations and numerical magnitude estimation, which is predictive of mathematics achievement. The SNARC effect demonstrates a shared cognitive pathway between numbers and space. In addition, brain imaging studies showed that similar neural substrates were activated as adult participants undertook spatial and numerical tasks (see Hubbard, Piazza, Pinel, & Dehaene,

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2005, and Umiltà, Priftis, & Zorzi, 2009 for reviews). The results of these studies suggest common neural mechanisms underlie numerical and spatial processing. Overall, behavioral studies that looked at populations with typical and atypical cognitive profiles, spatial ability intervention studies, the SNARC effect, and neuroimaging studies of spatial and numerical processing all support the link between spatial ability and mathematics achievement. In this study, the relationship between spatial ability and mathematics achievement was sought in the framework of information processing theory.

Executive Functioning

Although a formal definition of executive functioning is lacking, researchers typically agree that the following elements are pertinent to the term (for a review, see Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). The first element of executive functioning is to control attention, i.e., to hold task-relevant information and to inhibit task-irrelevant information (Bull et al., 2008; Bull & Scerif, 2001; Diamond, 2012; Engle et al., 1999). A related function of this element is to supervise the phonological loop and the visuospatial sketchpad (Swanson, 2006). The second element of executive functioning deals with shifting attention between the phonological loop and the visuospatial sketchpad (Swanson, 2006; St Clair-Thompson & Gathercole, 2006; Lehto, Juujarvi, Kooistra, & Pulkkinen, 2003). The third element of executive functioning is to "communicate" with long-term memory and to update information stored in the phonological loop and the visuospatial sketchpad (Miyake et al., 2000; St Clair-Thompson & Gathercole, 2006; see also Bull et al., 2008 and Bull & Scerif, 2001). Collectively, executive functioning ensures that thoughts and actions are directed by an individual's internal goals such as when an individual prioritizes various tasks or is driven by an individual's need to adapt to environmental demands (Kray & Ferdinand, 2013). Recent studies highlighted the importance of

executive functioning in complex cognitive activities that are involved in academic achievement (e.g., Engle, Tuholski, Laughlin, & Conway, 1999). In a nutshell, executive functioning refers to the basic self-regulatory skills including the ability to control attention by inhibiting distractions and by shifting attention across multiple tasks.

Executive Functioning and Mathematics Achievement

Executive functioning supports academic achievement in general (Bull, Espy, & Wiebe, 2008; St Clair-Thompson & Gathercole, 2006) and mathematics achievement in particular (Bull, Espy, Wiebe, Sheffield, & Nelson, 2011; Bull & Scerif, 2001; Clark, Pritchard, & Woodward, 2010; Clark, Sheffield, Wiebe, & Espy, 2012; Swanson, 2006). Swanson (2006) proposed a model that included verbal short-term memory (measured by Forward Digit Span, Word Span, and Pseudo Word Span), VSWM (measured by Mapping and Visual Matrix), executive functioning (measured by Digit/Sentence Span, Backward Digit Span, Listening/Sentence Span, and Updating), and age as predictors of the criterion variable mathematics achievement (measured by mathematics calculation). Swanson (2006) found executive functioning contributes to mathematics achievement above and beyond verbal short-term memory and VSWM. Similarly, St Clair-Thompson and Gathercole (2006) showed that when controlling for VWM (measured by Listening Recall and Backwards Digit Recall) and VSWM (measured by Odd-One-Out and Spatial Span), the association between executive functioning (measured by Stop Signal and Stroop) and academic achievement in English, mathematics, and science, respectively, are statistically significant. The results of these studies support a model with a direct link between measures of executive functioning and mathematics achievement.

Executive Functioning and Spatial Ability

Executive functioning is also associated with spatial ability (Libon, Glosser, Malamut, Kaplan, Goldberg, Swenson, & Sands, 1994; Miyake et al., 2001). Miyake et al., (2001) found a strong association between executive functioning and spatial ability (spatial visualization and mental rotation). The researchers reported that executive functioning was strongly and equally associated with both visuospatial short-term memory and VSWM.

A second study examined the association between executive functioning and spatial ability in elderly populations (Libon et. al, 1994). Libon et al. (1994) used two spatial ability tests that required mental transformation of spatial relationships (Blocks Design from Wechsler Adult Intelligence Scale-revised, Wechsler, 1981; Hooper Visual Organization, Hooper, 1966) and two tests that measured executive functioning (Stroop Word-Color Interference Task, Stroop, 1935; Wisconsin Card Sorting Test, Heaton, 1981). The researchers found executive functioning to be correlated with spatial ability in an elderly age group (average age $\geq$ 75 years). In addition, comparing this age group's performance with a younger age group on these tasks, a multivariate effect of age in the same direction was obtained for executive functioning and spatial ability (Libon et al., 1994).

The few studies that have examined the relationship between executive functioning and spatial ability indicate a close association. These findings are generally consistent with Baddeley's (1986) working memory model, which suggests executive functioning is important for the optimal processing in both VWM and VSWM. In other words, executive functioning (the central executive) supervises "the two slave systems" that include the phonological loop and the visuospatial sketchpad. In this study, it was hypothesized that executive functioning would predict VWM and VSWM, through which it also predicts individual differences in spatial ability.

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In addition, executive functioning may also directly impact individual differences in mathematics achievement.

Visuospatial Working Memory and Mathematics Achievement

Kyttälä et al. (2003) found VSWM (as measured by Matrix Pattern Test, Logie and Pearson, 1997 and Corsi Block Task, Milner, 1971) to be correlated with counting skills in 6-year-olds, even after controlling for general intelligence. Using growth curve modeling, Bull et al. (2008) found children's performance on VSWM (as measured by Forward and Backward Corsi Blocks) at the age of 4.5 years predicted those children's mathematics achievement (as measured by the PIPS assessment) at the age of seven. Holmes, Adams, and Hamilton (2008) found VSWM (as measured by the Visual Patterns Test, Della Sala et al., 1997 and the Block Recall Task, Pickering & Gathercole, 2001) predicted mathematics achievement (as measured by several standardized tests that covered the areas of Number and Algebra; Shape, Space, and Measures; Handling Data; and Mental Arithmetic) in 7- to 10-years-olds'. Finally, Reuhkala (2001) study found VSWM (as measured by Visual Matrix Patterns, Logie & Peterson, 1997 and Corsi Blocks Task, Milner, 1971) predicted mathematics achievement in ninth graders aged 15 – 16 years.

Visuospatial Working Memory and Spatial Ability

Cornoldi and Vecchi (2003) developed a conceptual framework that explained individual differences in spatial ability in terms of differences in both the ability to temporarily hold and the ability to process visuospatial information. VSWM is where visuospatial images are processed. These researchers suggest that low VSWM individuals lose track of the intermediate products of their mental transformations more easily than high spatial ability individuals when solving mental rotation problems. Thus, both image storage and image processing, which relate to the

functioning of VSWM, seem to contribute to individual differences in spatial ability. Spatial ability involves manipulating images in space. Therefore, it makes intuitive sense why VSWM would predict spatial ability, as revealed by both behavioral and neuroimaging research.

Prior research has demonstrated the association between verbal ability and VWM (e.g., Daneman & Carpenter, 1980; Hunt, Lunneborg, & Lewis, 1975). Similar to behavioral research in the verbal domain, spatial cognition researchers also found a strong association between VSWM and spatial ability (e.g., Kaufman, 2007; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; Reuhkala, 2001). In parallel, neuroimaging research showed similar brain activity patterns when participants took both VSWM and mental rotation tests (see Levin, 2005). This research demonstrated the association between VSWM and mental rotation at the neuronal level.

Verbal Working Memory and Mathematics Achievement

Research on the association between verbal short-term memory and mathematics achievement and between verbal working memory (VWM) and mathematics achievement show mixed findings. Swanson (2006) and Swanson and Sachse-Lee's (2001) works established the link between VWM and mathematics achievement in mathematically precocious children and in children with mathematics learning disabilities, respectively. There is also evidence for VWM's involvement in predicting individual differences in mathematics achievement in average-achieving individuals (Wilson & Swanson, 2001). Gathercole (1998) and Henry and Millar (1993) hypothesized that rapid naming might be linked to the effectiveness of sub-vocal rehearsal, which in turn supports mathematical problem-solving. Logie, Gilhooly, and Wynn (1994) found sub-vocal rehearsal contributed to the accuracy of mental arithmetic computations. Similarly, Geary, Brown, and Samaranayake (1991) found children exceling in mathematics outperformed their average-achieving counterparts on tests requiring temporary retention of

ordered numerical information. Temporary storage of numerical information in one's mind

involves VWM. These findings supported the link between VWM and mathematics

achievement. Two other studies that supported the link between VWM and mathematics

achievement were Bull, Espy, and Wiebe (2008) and Tolar, Lederberg, and Fletcher (2009).

Bull, Espy, and Wiebe (2008) used the retention span of Digit Span assessed at the initial time

point as an indicator of VWM and found a 2.01-point increase in performance on a mathematics

achievement test to be associated with a one-digit increase in the retention span of Digit Span

when they analyzed 7-year-olds' performances on several cognitive ability tests that included

tests of mathematical problem-solving using hierarchical linear modeling. Tolar et al. (2009)

study used Reading Span Task (Conway, Kane, Hambrick, Wilhelm, & Engle, 2005), Counting

Span Task (Conway et al., 2005), Backward Digit Span (Wechsler Adult Intelligence Scale,

Third Edition, Wechsler, 1997), and Letter-Number Sequencing (Wechsler, 1997) to measure

VWM. In a structural equation model that included these variables, as well as measures of

computational fluency, 3D spatial visualization, algebra education, and algebra achievement,

Tolar et al. (2009) analyzed 195 undergraduate students' performances on these measures and

found that the direct path from VWM to computational fluency was statistically significant. In

addition, the researchers found that the latent correlation between VWM and computational

fluency was statistically significant and was at a moderate magnitude. These statistics supported

VWM's role in predicting mathematical achievement. It should be acknowledged that the

mathematical tasks used in many studies differ considerably from one another and might not

necessarily be the best indicators of mathematics achievement.

However, while the aforementioned Swanson's (2006) study provided some evidence for

the role played by VWM in predicting individual differences in mathematics achievement, the

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partial correlation between verbal short-term memory (measured by Forward Digit Span, Word Span, and Pseudoword Span) and mathematical computation after controlling for age was considerably lower in magnitude ($r = 0.28$) than the correlations between visuospatial short-term memory (measured by Mapping and Visual Matrix) and mathematical computations ($r = 0.40$) and between, executive functioning (measured by Digit/Sentence Span, Backward Digit Span, Listening/Sentence Span, and Updating) and mathematical computations ($r = 0.50$). Two other studies also failed to support the link between VWM and mathematics achievement. Using Working Memory Span and Backwards Digit Recall (both taken from Working Memory Test Battery for Children, Pickering & Gathercole, 2001) to measure VWM, Saint Clair-Thompson and Gathercole (2006) did not find a statistically significant association between VWM and mathematics achievement in 11 and 12-year-old children. Using Word Span (e.g., Daneman & Carpenter, 1980) and Complex Span to measure VWM, in Study 2, Reuhkala (2001) also did not find VWM and mathematics achievement to be related at a statistically significant level.

Overall, there is some evidence for verbal short-term memory and VWM's involvement in mathematics achievement. However, when verbal short-term memory and VWM were found to contribute to mathematics achievement, their contributions appeared to be less substantial than executive functioning and VSWM. There were also two studies that did not find VWM's contribution to mathematics achievement at a statistically significant level. For this study, it was hypothesized that VWM predicts individual differences in spatial ability and mathematics achievement.

Verbal Working Memory and Spatial Ability

Verbal processing takes place in VWM. VWM has also been found to correlate with spatial ability, and this correlation may reflect strategy use. Two types of strategies are broadly

defined in the literature (Janssen & Geiser, 2012; Li & O'Boyle, 2011). The first type is referred to as holistic strategies (also known as Euclidean strategies), which involves visuospatial transformation of mental representations of spatial relationships. The second type is referred to as analytic strategies (also known as verbal or "piecemeal" strategies), which involves verbal processing or a sequential (as opposed to a simultaneous) approach to transform visuospatial information (Peña, Contreras, Shih, & Santacreu, 2008). Prior research showed people with poor spatial ability (the majority of which are females) rely on analytic strategies more heavily when solving spatial ability tasks (Halpern & Collaer, 2005; Meneghetti, Gyselinck, Pazzaglia, & De Beni, 2009). Analytic strategies utilize VWM resources (Glück and Fitting, 2003). Thus, VWM and spatial ability may be linked as a function of analytic strategy use. Although not many studies focused specifically on the relationship between VWM and spatial ability, in studies that measured VWM alongside VSWM, there is some evidence for VWM's involvement in spatial ability task performance (e.g., Kaufman, 2007). However, existing evidence suggests that compared with VSWM, VWM may play a lesser role in explaining individual and gender differences in spatial ability (Kaufman, 2007). In sum, of the studies that included measures of VWM, there is some evidence for the link between VWM and spatial ability, possibly mediated by strategy use. However, comparing to other working memory components, VWM may play a lesser role in predicting individual differences in spatial ability and mathematics achievement.

Proposed Model

In reviewing the relevant literature, it appears that there exists an implicit model that best organizes the literature on the relationships between different components of working memory (VSWM, VWM, and executive functioning) and spatial ability (mental rotation), between different components of working memory and mathematics achievement. While there is evidence

supporting the connection between all components of working memory and spatial ability (Kaufman, 2007; Meneghetti, Gyselinck, Pazzaglia, & De Beni, 2009; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001), and between all components of working memory with mathematics achievement (e.g., Bull, Espy, & Wiebe, 2008; Tolar, Lederberg, & Fletcher, 2009), a model that included all five variables has never been explicitly tested. The three most comprehensive studies on this topic (see Bull et al., 2009; Kaufman, 2007; Miyake et al., 2001) examined the relationships among different subsets of these five variables. To the author's knowledge, no study has included all relevant variables. This study filled this gap by testing a few models that derive from the implicit model, using a structural equation modeling approach. Without including all variables in the model, the correlated variables may produce hidden effects. These hidden effects may have unknown impacts on model outcomes. For example, without including VWM in the model, VSWM may exaggerate the correlation between mental rotation and mathematics achievement.

Model 1 (see Figure 3.1) assumes executive functioning predicts verbal working memory (VWM) and visuospatial working memory (VSWM), as suggested by Baddeley's (1986) working memory model. Model 1 tests the hypotheses that all three components of working memory predict mental rotation. Model 1 also tests the hypotheses that VSWM, mental rotation, and VWM predict mathematics achievement. In Model 1, it is assumed that executive functioning predicts mathematics achievement above and beyond its shared variance with mental rotation. Model 2 (see Figure 3.2) is otherwise identical with Model 1, with the exception that it assumes that the impact of executive functioning on mathematics achievement is completely mediated by mental rotation, thereby freeing the direct path from executive functioning to mathematics achievement. If this model is correct, then executive functioning's influence on

mathematics achievement is entirely through VWM and VSWM. Model 3 (see Figure 3.3)

assumes the connection between mental rotation and mathematics achievement is due to a

common third predictor variable, VSWM. Model 3 is otherwise identical with Model 2. If this

model is correct, it would suggest that the connection between spatial ability and mathematics

achievement commonly reported in empirical studies is due to the common influence of VSWM.
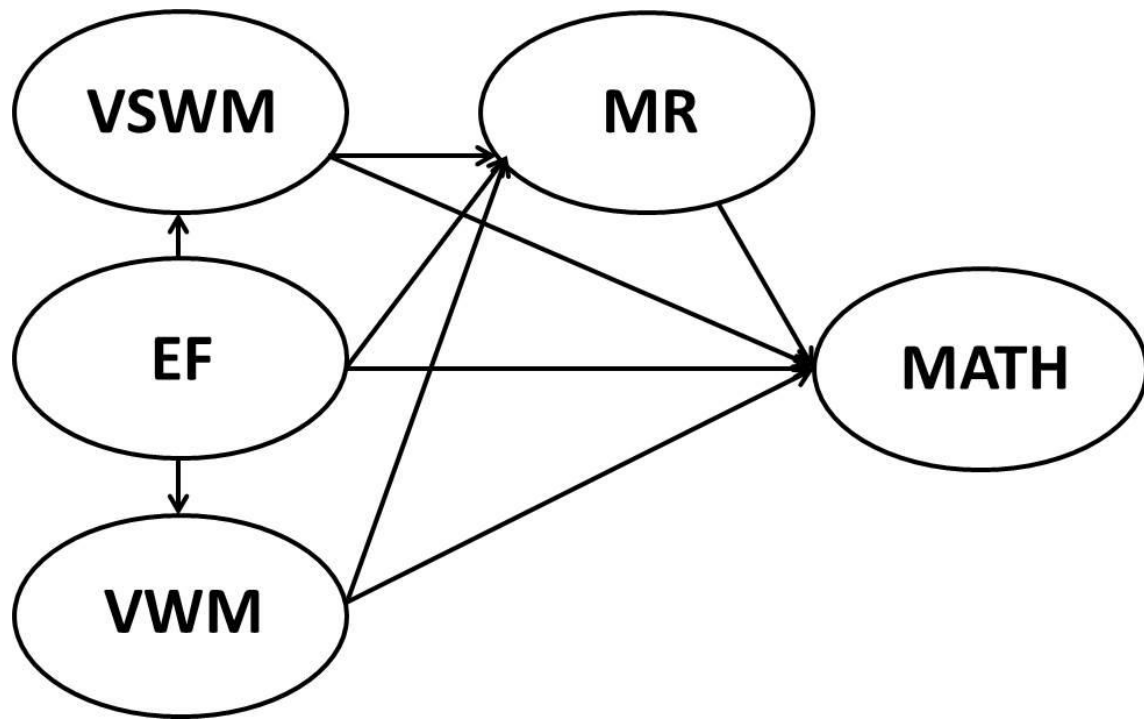
Figure 3.1. Model 1: Executive Functioning (EF) Predicts Mathematics Achievement (MATH) Both Directly and Indirectly through Mental Rotation (MR)
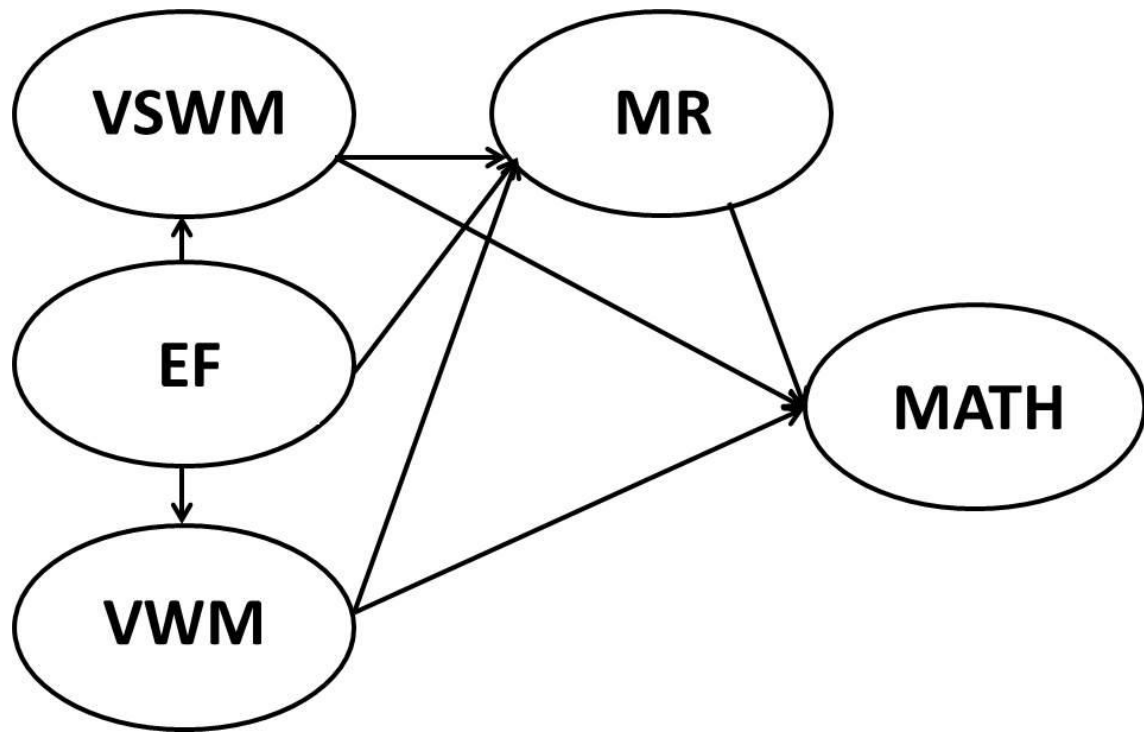
Figure 3.2. Model 2: The Connection between Executive Functioning (EF) and Mathematics Achievement (MATH) Is Completely Mediated by Mental Rotation (MR)
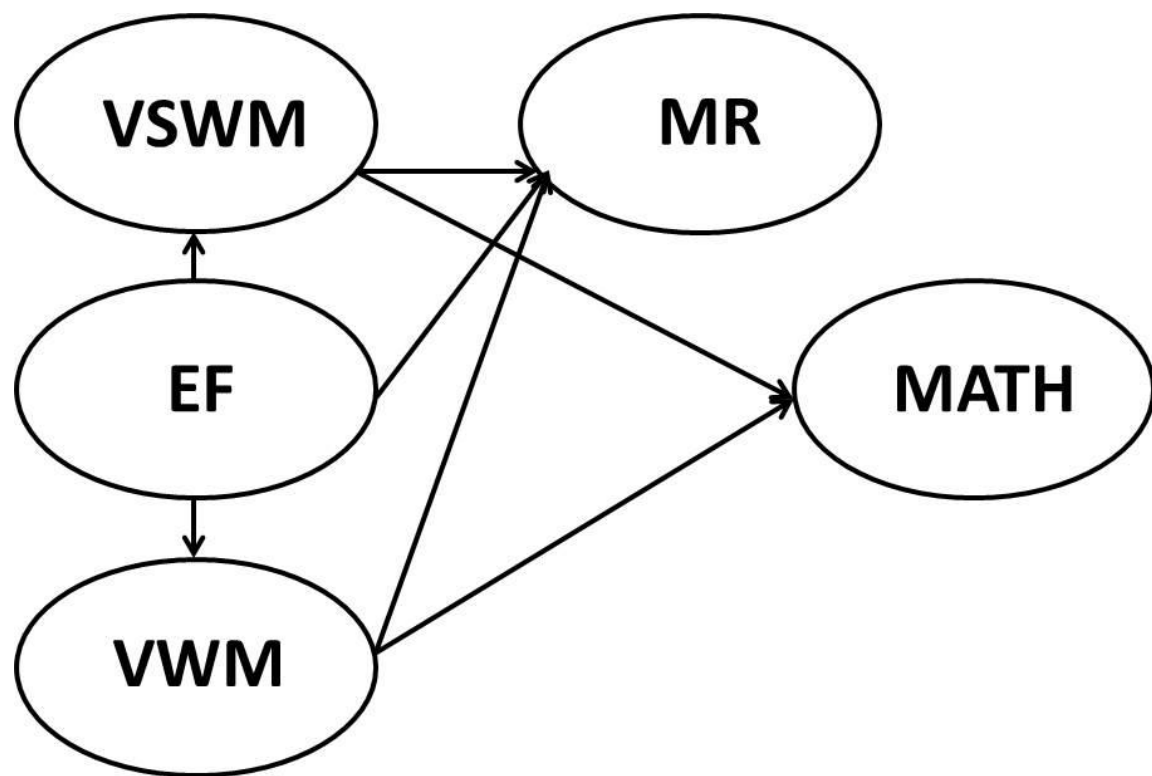
Figure 3.3. Model 3: The Connection between Mental Rotation (MR) and Mathematics Achievement (MATH) May Be Due to a Common Third Variable, VSWM

<center>**Methods**</center>

Participants

Participants were 144 (38 males) undergraduate and graduate students attending a medium-sized public research university in the Southeast region of the United States. The sample was comprised of 79.9 percent of European Americans, 6.3 percent of other, 5.6 percent of African Americans, 4.2 percent of Hispanic Americans, and 4.2 percent of Asian Americans. The mean age of the males in the sample was 25.13 years ($SD = 6.58$ years). The mean age of the females in the sample was 21.7 years ($SD = 4.98$ years). The research participants' college majors encompassed the fields of natural sciences, social sciences, and humanities. Specifically, 73.6 percent of the sample majored in the social sciences, 13.9 percent of the sample majored in the natural sciences, and 12.5 percent of the sample majored in the humanities. The participants were recruited either by flyers (see Appendix A) that were put up campus-wide or through third-parties (e.g., instructors of introductory educational psychology and calculus classes). The study was approved by the Institutional Review Board (IRB) at the University of Georgia. Participants took part in the study on a voluntary basis and signed a consent form (see Appendix B) prior to participating. All participants were automatically entered into a small prize drawing that would be performed at the conclusion of the study. The prize was to entice participants who volunteered to take part in this study.

Procedures and Materials

Participants were individually tested in a quiet conference room. A battery of tests, including Forward and Backward Digit Span (Wechsler, 1997), Forward and Backward Spatial Span (Wechsler, 1997), Color-Interference Test (Delis, Kaplan, & Kramer, 2001), Tower Test (Delis, Kaplan, & Kramer, 2001), Mental Rotation Test (Vandenberg & Kuse, 1978), and Solid

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Figure Turning (Levy & Levy, 1999) were given with the order of the tests counterbalanced. The average time to administer all tests to each participant was approximately an hour. A follow-up demographic survey was administered at the end of the testing session so that we could better characterize our sample of participants.

Forward and backward digit span (Appendix C). Forward and Backward Digit Span tasks measure VWM. Task stimuli are numerical strings (from 1 to 9). There are eight items on the Forward Digit Span test and seven items on the Backward Digit Span test. Each item has two trials that are at the same span. The difficulty of the test items increase incrementally as the numerical strings increase in length from one item to the next. For the study, numerical strings were read by the researcher at the rate of one digit per second. Correctly reproducing the numerical sequence heard in both trials of the same item earns one point. The raw total score of Forward Digit Span ranged from 0 to 16 and the raw total score of Backward Digit Span ranged from 0 to 14. The task stimuli and administration procedures of Backward Digit Span was similar to Forward Digit Span, except, instead of reciting the numerical strings in the same order as originally presented, participants were instructed to repeat the digits in the reverse order of what they heard on Backward Digit Span. The test manual reports the Cronbach's α for the Backward Digit Span task to be 0.84.

Forward and backward spatial span (Appendix D). Forward and Backward Spatial Span tasks measure VSWM. The task stimuli and basic administration procedures of Forward and Backward Spatial Span are similar to the Corsi Block-tapping (Milner, 1971). Nine blocks are attached to a base. The researcher tapped the blocks at the rate of one block per second. The participants were instructed to tap the blocks in the same order as the researcher (digits are printed on one side of the blocks that were kept invisible to the participants). There are eight

items on the Forward Spatial Span test and seven items on the Backward Spatial Span test. Each item has two trials that are at the same span. The item difficulty increases incrementally as a function of the increased length of the block sequence tapped. Correctly tapping the block sequence on both trials of an item earns one point. The raw total score ranged from 0 to 16 for the Forward Spatial Span test. The raw total score ranged from 0 to 14 for the Backward Spatial Span test. The task stimuli and administration procedures of Backward Spatial Span resemble those of Forward Spatial Span, except that participants were instructed to tap the blocks in the reverse order of what they observed.

Color-interference test (Appendix E). The Color-Interference Test measures executive functioning (hereafter, the CIT). The task stimuli are ink blocks of different colors (condition 1) and words that are printed in both consistent (condition 2) and inconsistent colors (conditions 3 and 4) with their semantic meanings. Conditions 1 and 2 are considered to be baseline conditions in that participants either name the ink colors or read color words (printed in consistent colors) out loud. In condition 3, participants are instructed to name the ink colors of the words that are printed in inconsistent colors. In condition 4, participants were instructed to switch in between two rules, one says read the words (whenever words are enclosed in squares) and the other says name the ink colors instead (condition 4: inhibition and switching). The test manual reports the internal consistency (split-half coefficients corrected by the Spearman-Brown formula) to be between 0.62 and 0.86 across age groups (Homack, Lee, & Riccio, 2005).

Tower test (Appendix F). Tower Test also measures executive functioning. The task stimuli involve a solid wooden base with three wooden pegs attached to the base and five ring discs (varying in sizes). To complete the task, the participants need to move around a few ring discs and construct the designs printed in the stimulus book. The test contained nine items with

the item difficulty increases incrementally as more discs are involved in completing the design. Participants were instructed to adhere to two rules throughout the test: never move more than one disc at a time and never place a big disc on top of a small one. The total score, which measures the number of moves taken by the participants to complete each of the nine designs in the stimulus book, was computed. The test manual reports the internal consistency of the Tower test to be ranging from 0.50 to 0.80 across the age groups.

Vandenberg Kuse mental rotation test (Appendix G). The Mental Rotation Test (hereafter, the MRT) was used to measure participants' spatial ability (mental rotation). It was administered with a seven-minute time limit, as recommended by the test booklet. There were 20 items on this test. There were four answer choices for each item on the right side of the target item, two of which were correct rotated views of the target item on the left. The participants would score a point only if both choices were correctly selected. The MRT has a split-half reliability (applying the Spearman-Brown formula) of 0.86 when administered to undergraduate students with a 6-minute time limit (Qubeck IV, 1997). The internal consistency (applying the Kuder-Richardson formula 20) of the MRT is 0.88 when administered to 3,268 adults and adolescents older than 14 years of age with a 10-minute time limit (Wilson, DeFries, McClearn, Vandenberg, Johnson, & Rashad, 1975). Using a similar sample of 336 participants, the test-retest reliability of the MRT is 0.83 when re-tested within a year (Vandenberg & Kuse, 1978).

Solid figure turning (Appendix H). The Solid Figure Turning also measures mental rotation spatial ability (thereafter, the SFT). There are 22 items on this test. Participants were instructed to complete the test within a five-minute time limit. There are four answer choices per item. Only one of the four choices is the correct answer. The correct answers are identical irregular-shaped objects shown on the far left. Correctly answering each item earns one point.

The test developer did not provide information regarding the reliabilities or the validities of the SFT.

Demographic survey (Appendix I). In addition to the measures described in this section, a demographic survey was administered at the end of the study. The survey asked participants to self-report demographic information (gender, age, college majors, and ethnicity) and the total achievement score on the SAT.

<div align="center">

Results

</div>

Scoring

Because executive functioning is sensitive to aging, the reaction time on each of the four conditions of the CIT and the total achievement score on the Tower Test were converted into scaled scores provided in the test manuals. These scaled scores were normalized by age groups, thereby ensuring that the performances of one age group were comparable to the performances of a different age group. This approach may be understood as the Classical Testing Theory's approach to "mean equate," (Kolen & Brennan, 1995) which is similar to "vertical equating," an Item Response Theory's (Baker, 1983) approach to place scores of different subgroups onto a common scale so that they are comparable.

Although working memory is also sensitive to aging (see Thomason, Race, Burrows, Whitfield-Gabrieli, Glover, & Gabrieli, 2008), the scoring manual for the Wechsler Memory Scale (Wechsler, 1997) does not provide separate scaled scores for the Forward Digit Span and Backward Digit Span tests. Instead, a single scaled score was provided for the composite total score of the two tests. Because the Forward and Backward Digit Span tests measure the storage and processing aspects of the VWM construct, respectively, they were treated as separate indicators of VWM in this study. Therefore, standardized scaled scores for the Forward and the

Backward Digit Span tests were computed separately by the researcher using the age norms

provided in the test manual. To ensure that the scores for the Forward and the Backward Digit

Span tests and the scores for the Forward and the Backward Spatial Span tests were comparable,

separate z scores by age groups were also computed for the Forward and the Backward Spatial

Span using the SPSS program (version 17.0, Chicago: SPSS Inc., 2008), even though the test

manual provides separate scaled scores for the Forward and the Backward Spatial Span tests. To

compute age-normed z scores for the raw total scores of Forward Digit Span, Backward Digit

Span, Forward Spatial Span, and Backward Spatial Span, the dataset was first split by the age

groups provided in the test manual. Next, separate z scores for each age group were computed.

These scores were then saved as new variables in the dataset and were used to create the variance

and covariance matrix to be used in the ensuing analyses.

 In this study, percent correct index was used to indicate participants' performances on the

two mental rotation tests. Percent correct was computed by dividing the number of correctly

answered items by the number of attempted items by the participants. The percent correct index

was previously used in Voyer and Hou (2006) study and has the advantage of placing all test

scores on a common metric. Percent correct was not mean equated by age groups because neither

the MRT nor the SFT test developers recommended this approach in scoring the two tests.

Data Screening

 The three models described previously (one dominant and two alternative) were analyzed

using the structural equation modeling method. Kline (2011) recommends to screen the dataset

for issues such as multivariate normality, collinearity, and the nature of missing data, i.e.,

whether missing data is at random (MAR), completely at random (MCAR), or not at random

(MNAR), before proceeding onto the actual analyses. Because structural equation modeling

requires variables included in the analysis to be approximately multivariate normally distributed, preliminary analysis was performed on all variables of interests to ascertain that this assumption is met.

Univariate normality is a prerequisite for multivariate normality. To check for univariate normality, the skewness and kurtosis statistics of all the variables, i.e., the mean-equated total scores on Forward Digit Span, Backward Digit Span, Forward Spatial Span, Backward Spatial Span, the scaled total scores on the Tower Test, and the scaled total scores on the Color-Interference Test, were obtained. According to Kline (2011), variables with absolute z scores of univariate skewness greater than 3.0 and absolute z scores of univariate kurtosis greater than 8.0 are considered "extreme" relative to a univariate normal distribution. Preliminary screening of the distribution of each variable of interest using the PRELIS 2 (Version 2.8, Scientific Software International Inc., 2006) showed that the distributions of most variables were approximately univariate normally distributed, judging both by the skewness and kurtosis statistics and by the shapes of the histograms and the q-q plots, with the exceptions of the "citsw" and the "satq" variables. An effort was made to normalize "citsw" and "satq." While a logarithm-based transformation (lg10) successfully normalized the distribution of the scores on the mathematics section of the SAT, no normal transformation method was successful in normalizing the distribution of citsw, i.e., the scaled scores on the switching condition of the CIT. Therefore, citsw was removed from the ensuing analyses. After removing citsw, the multivariate normality assumption was checked by invoking the Relative Multivariate Kurtosis (RMK) index using the PRELIS 2. The RMK index for the dataset of this study was 1.002, which was very close to the ideal value of 1. Thus, this dataset appears to have met the multivariate normality assumption.

To detect whether multi-collinearity among the independent variables was present, regression diagnostic procedures provided by the SPSS program were invoked. According to Kline (2011), tolerance values that are smaller than 0.1 or a variance inflation factor (VIF) that is greater than 10.0 indicate extreme multi-collinearity. After executing these procedures, none of the tolerance values of the independent variables exceeded 0.1; none of the VIF of these variables was greater than 10.0. Therefore, multi-collinearity issue did not seem to pose a threat to this dataset.

Most of the variables had no missing data. Of the few variables that had missing data, the proportion of missing data did not exceed six percent. Regarding the nature of the missing data, there was no a priori reason to believe that participants who had missing data on any given variable differed systematically in how they responded to the other variables being analyzed. Therefore, the MAR assumption may be assumed for this study.

Descriptive Statistics

The upper portion of Table 3.1 presents the zero order bivariate correlations among all observed variables ($N = 135$, listwise deletion). Note that in Table 3.1, the zero order bivariate correlation between the scaled scores of the inhibition condition of the CIT, i.e., the "citin" variable, did not correlate with any other observed variables. Most importantly, it did not even correlate with the other indicator variable of executive functioning, the scaled total achievement scores of the Tower Test ($r = 0.032$, $p > 0.05$). Therefore, citin was removed from the ensuing analyses due to its poor validity in tapping executive functioning in this sample. The lower portion of Table 3.1 presents the descriptive statistics of all of the observed variables. Because the MAR assumption can be assumed and the proportion of missing data was not substantial (less than six percent of the sample size), subsequent analyses were performed using listwise

deletion. In comparison to pairwise deletion, listwise deletion has the advantage of ensuring all computations to be based on the same number of cases.

Table 3.1

Zero-Order Bivariate Correlations among Observed Variables for the Full Sample

Observed Variable	1	2	3	4	5	6	7	8	9
1. CITIN	1	1	—	—	—	—	—	—	–
2. TOWERA	0.03	0.17	1	—	—	—	—	—	–
3. MRTA	0.08	0.21*	0.51**	1	—	—	—	—	–
4. SFTA	0.05	0.19*	0.19*	0.15	1	—	—	—	–
5. ZDIGIFR	0.17	0.26**	0.19*	0.19*	0.56**	1	—	—	–
6. ZDIGIBR	0.13	0.16	0.25**	0.23**	0.25**	0.24**	1	—	–
7. ZCORSIFR	0.11	0.28**	0.43**	0.51**	0.15	0.17	0.39**	1	–
8. ZCORSIBR	0.07	0.19*	0.25**	0.32**	0.14	0.20*	0.17	0.28**	1
9. LOGSATQ	-0.01	1	—	—	—	—	—	—	–

Note. ** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed). Method of missing data deletion, listwise, $N = 135$. CITIN = scaled contrast score on the inhibition condition of the Color-Interference Test. TOWERA = scaled total score on the Tower Test. MRTA = percent correct on the Mental Rotation Test, computed by dividing the number of correctly answered items by the number of attempted items on the MRT. SFTA = percent correct on the Solid Figure Turning, computed by dividing the number of correctly answered items by the number of attempted items on the SFT. ZDIGIFR = z transformed raw total score on Forward Digit Span based on the age norm of the current sample. ZDIGIBR = z transformed raw total score on Backward Digit Span based on the age norm of the current sample. ZCORSIFR = z transformed raw total score on Forward Spatial Span based on the age norm of the current sample. ZCORSIBR = z transformed raw total score on Backward Spatial Span based on the age norm of the current sample. LOGSATQ = Lg 10 transformed self-reported scores on the mathematics section of the SAT.

Table 3.1 (cont'd)

Means and Standard Deviations of the Observed Variables for the Full Sample

Observed Variable		*M*	*SD*
1.	CITIN	12.111	2.068
2.	TOWERA	10.111	2.094
3.	MRTA	0.524	0.228
4.	SFTA	0.786	0.128
5.	ZDIGIFR	0.025	1.006
6.	ZDIGIBR	0.026	0.995
7.	ZCORSIFR	0.032	0.977
8.	ZCORSIBR	0.033	0.978
9.	LOGSATQ	2.775	0.063

Confirmatory Factor Analysis of the Measurement Model

Next, confirmatory factor analysis was performed to examine whether the observed variables adequately measured the four latent variables: VSWM, VWM, executive functioning, and mental rotation. Before presenting some of the fit indices reported in the LISREL output, a short introduction of the key functions of those fit indices and the rules of thumb regarding their interpretations is warranted. Chi-Square (χ^2) tests the "exact-fit" hypothesis that there are no discrepancies between the population covariance and those predicted by the model (Kline, 2011). Thus, a non-statistically significant *p*-value associated with the Chi-Square value suggests that the sample data fit well with the proposed model. The approximate fit index RMSEA is considered to be a "badness-of-fit" index where a value of zero indicates the best fit. The Bentler Comparative Fit Index (CFI) is another approximate fit index that measures the relative improvement in the fit of the proposed model over that of a baseline model (Kline, 2011). The closer this index approaches 1, the better fitting the proposed model is considered to be. The third approximate fit index SRMR is a measure of the mean absolute correlation residual, i.e., the overall difference between the observed and the predicted correlations among observed variables (Kline, 2011). Hu and Bentler (1999) suggest models with SRMR index ≤ .08 have an acceptable model fit (Kline, 2011).

A four-factor measurement model (see Figure 3.4) was run with the hypothesized indicators loaded on the hypothesized factors. Specifically, the completely standardized loadings of Forward and Backward Spatial Span on VSWM were 0.45 and 0.86, respectively; the completely standardized loadings of Forward and Backward Digit Span on VWM were 0.67 and 0.83, respectively; the completely standardized loadings of the Vandenberg Kuse Mental Rotation Test and Solid Figure Turning on mental rotation (MR) were 0.67 and 0.76. Because

the scaled scores of the inhibition condition of the CIT, the other indicator of executive

functioning, was removed, leaving the Tower Test the only indicator of executive functioning,

the loading of the Tower Test on executive functioning was fixed at 1. Mathematics achievement

was not included in the measurement model because only a single observed variable, i.e., the

scores on the mathematics section of the SAT, was used to measure this construct to start with.

The fit of the four-factor measurement model was evaluated using the LISREL (Version 8.8 for

Windows, Scientific Software International Inc., 2006). The default estimation method of

LISREL 8.8, Maximum Likelihood (ML), was used to analyze the covariance matrix of the

sample data. All completely standardized loadings of the observed variables on the latent

constructs were statistically significant. The magnitude of these loadings was all positive,

ranging from 0.45 to 0.86, which suggests that most of the observed variables adequately

measured the constructs they were supposed to measure.

The aforementioned fit indices (Chi-Square, RMSEA, and CFI) are global fit indices

(Kline, 2011). Judging by these global fit indices, the four-factor exogenous variables CFA

model with independent error terms fit the data reasonably well ($\chi^2 = 7.01$, $df = 9$, $p = 0.64$,

RMSEA < 0.01, CFI $= 1.00$, SRMR $= 0.042$). Kline (2011) recommends attending to local fit

indices such as standardized residuals and the magnitude and the signs of the standardized path

coefficients in addition to the global fit indices when evaluating model fit. According to Kline

(2011), standardized residuals with absolute values greater than 2 warrant some attention. The

LISREL output showed that the smallest and the largest standardized residuals (-1.36 and 2.19)

had absolute values that were either less than 2 or slightly above, which is fairly good. As shown

in Figure 3.4, the magnitude and the signs of the completely standardized path coefficients were

consistent with what would be expected from prior research. Therefore, the four-factor

measurement model was retained.
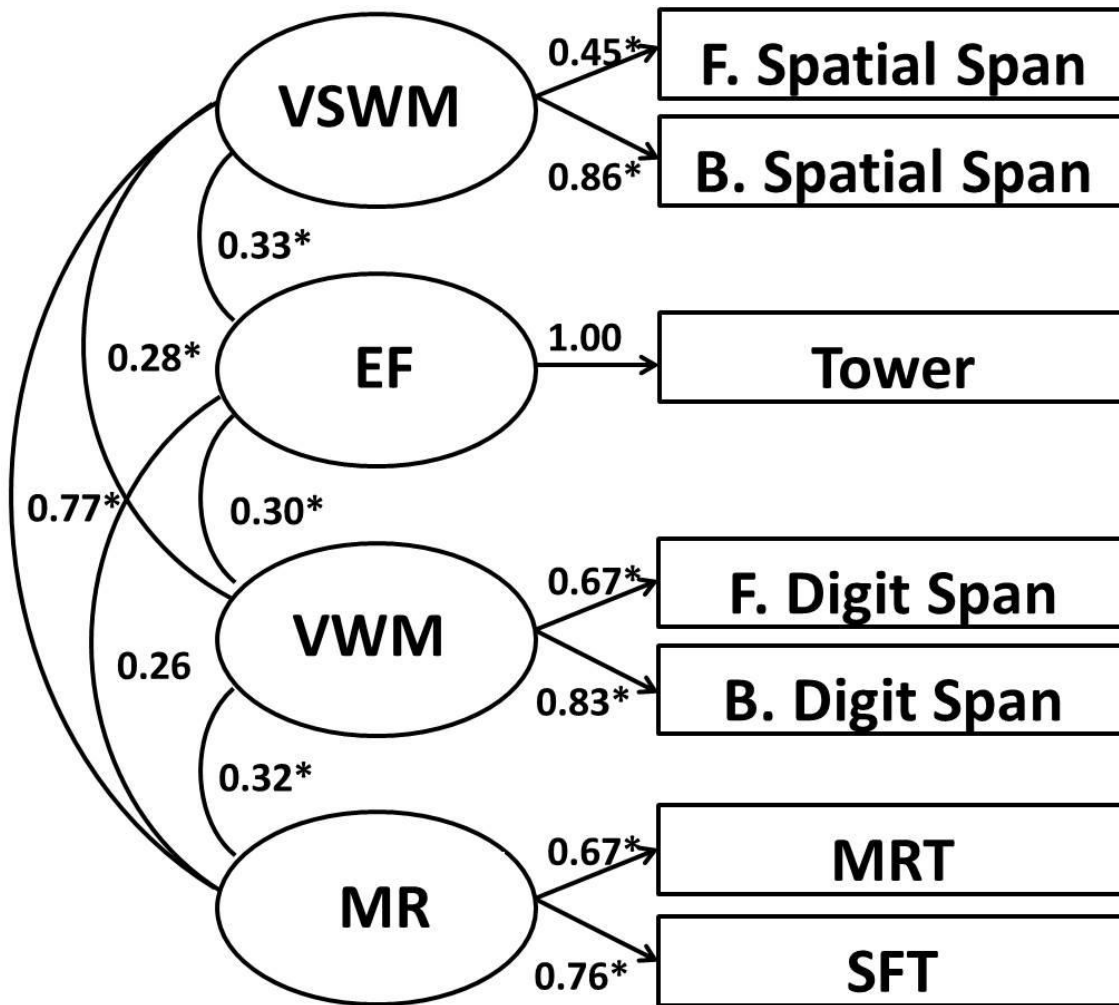
Figure 3.4. Four-Factor Measurement Model

*P < 0.05

Full Structural Equation Models

After testing the measurement model, the three structural equation models that reflect the directional relationships among VSWM, VWM, executive functioning, mental rotation, and mathematics achievement were tested for fit (see Figures 5, 6, and 7). As shown in Figure 3.5, VSWM and VWM directly predict mental rotation, which in turn predicts mathematics achievement. In addition to indirectly through mental rotation, VWM and VSWM also directly predict mathematics achievement. Model 1 fit reasonably well with the sample data, judging by the global fit indices (χ^2 = 9.94, df = 13, p = 0.70, RMSEA < 0.01, CFI = 1.00, SRMR = 0.06). Regarding the local fit indices, the smallest and the largest standardized residuals were -0.34 and 2.60, respectively. The largest standardized residual was slightly off the best-fitting range, i.e., less than 2 in absolute value, as suggested by Kline (2011). Also shown in Figure 3.5 are all the completely standardized path coefficients, among which the path coefficients associated with the paths from executive functioning to VSWM, from executive functioning to VWM, and from VSWM to mental rotation were statistically significant.

Table 3.2

Unstandardized Path Coefficients, Standard Deviations (SD), and t Values for Models 1-4

Model	$B_1(SD)$	t	$B_2(SD)$	t	$B_3(SD)$	t	$B_4(SD)$	t
1.	0.06 (0.03)	2.45	0.09 (0.04)	2.44	0.25 (0.07)	3.63	0.00 (0.01)	-0.01
2.	0.06 (0.03)	2.46	0.09 (0.04)	2.49	0.25 (0.07)	3.63	0.00 (0.01)	0.06
3.	0.07 (0.03)	2.79	0.09 (0.04)	2.49	0.28 (0.08)	3.61	0.00 (0.01)	-0.57
4.	0.06 (0.03)	2.45	0.09 (0.04)	2.49	0.25 (0.07)	3.66	0.00 (0.01)	0.10

$B_5(SD)$	t	$B_6(SD)$	t	$B_7(SD)$	t	$B_8(SD)$	t	$B_9(SD)$	t
0.04 (0.02)	1.52	0.14 (0.08)	1.80	0.00 (0.03)	0.11	0.00 (0.00)	0.73	0.01 (0.01)	0.95
0.04 (0.02)	1.49	0.14 (0.08)	1.75	0.01 (0.03)	0.26	–	–	0.01 (0.01)	1.21
0.04 (0.02)	1.46	–	–	0.05 (0.02)	2.96	–	–	0.02 (0.01)	1.65
0.04 (0.02)	1.49	0.16 (0.05)	3.50	–	–	–	–	0.01 (0.01)	1.20

Note.
B_1 = EF to VSWM
B_2 = EF to VWM
B_3 = VSWM to MR
B_4 = EF to MR
B_5 = VWM to MR
B_6 = MR to MATH
B_7 = VSWM to MATH
B_8 = EF to MATH
B_9 = VWM to MATH
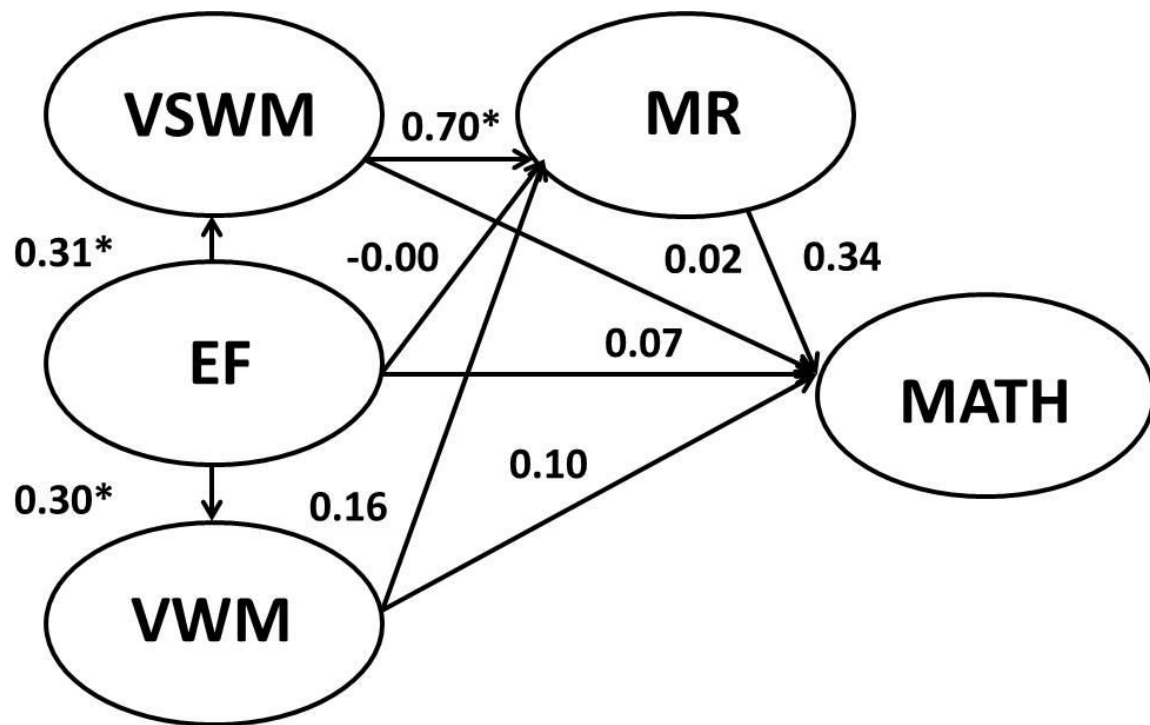
Figure 3.5. Model 1 with Standardized Path Coefficients
*P < 0.05

As described previously, Model 2 is identical with Model 1, with the exception of having one path less, i.e., the direct path from executive functioning to mathematics achievement. Thus, Model 2 is nested within Model 1. Similar to Model 1, Model 2 fit the data quite well (χ^2 = 10.49, df = 14, p = 0.73, RMSEA < 0.01, CFI = 1.00, SRMR = 0.06). Regarding the local fit indices, the smallest and the largest standardized residuals were -0.40 and 2.59, respectively. Again, the largest standardized residual was slightly off the best-fitting range suggested by Kline (2011). Shown in Figure 3.6 are all the completely standardized path coefficients, among which the path coefficients associated with the paths from executive functioning to VSWM, from executive functioning to VWM, and from VSWM to mental rotation were statistically significant. Thus, the statistically significant completely standardized path coefficients were identical in Models 1 and 2.
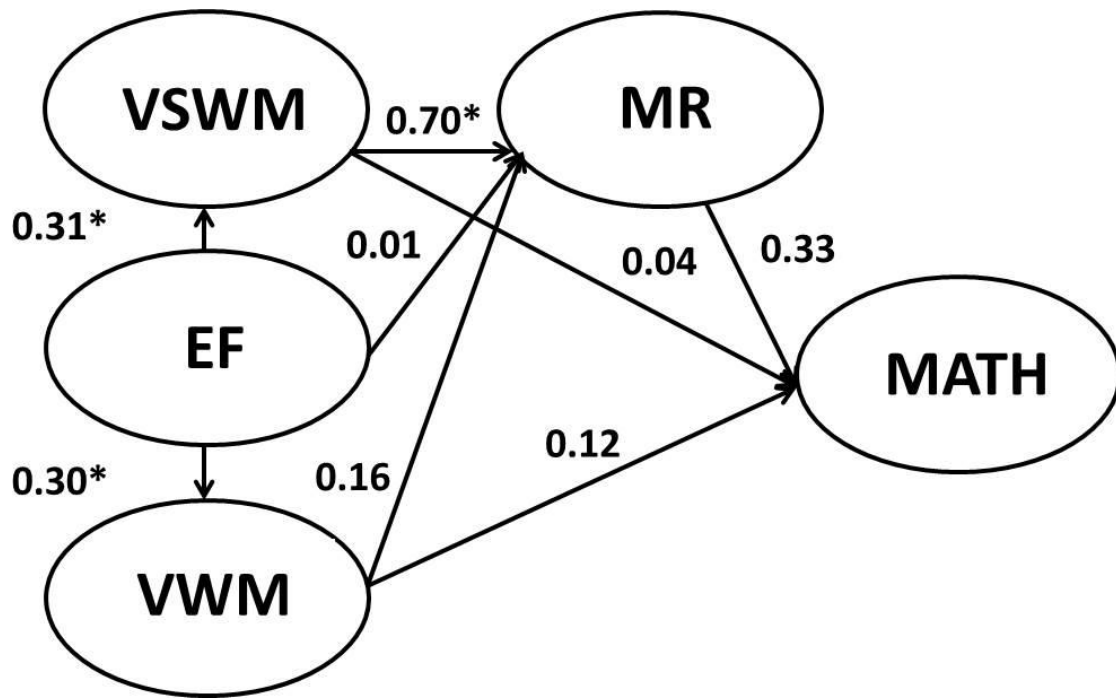
Figure 3.6. Model 2 with Standardized Path Coefficients
*P < 0.05

Also as discussed previously, Model 3 differs from Model 2 in only one respect, i.e., by removing the path from mental rotation to mathematics achievement. Therefore, Model 3 is nested within Model 2. In Model 3, it is assumed that the connection between mental rotation and mathematics achievement (the removed path) was due to both factors being predicted by VSWM. Model 3 also fit the data reasonably well (x^2 = 12.77, df = 15, p = 0.62, RMSEA < 0.01, CFI = 1.00, SRMR = 0.06). The smallest and the largest completely standardized residuals were -0.93 and 2.55, respectively. Thus, like Model 2, the largest standardized residual went slightly over the best-fitting range. Shown in Figure 3.7 are all the completely standardized path coefficients, among which the path coefficients associated with the paths from executive functioning to VSWM, from executive functioning to VWM, from VSWM to mental rotation, and from VSWM to mathematics achievement were statistically significant. Thus, by removing the path from mental rotation to mathematics achievement, VSWM emerged as a statistically significant predictor of mathematics achievement.
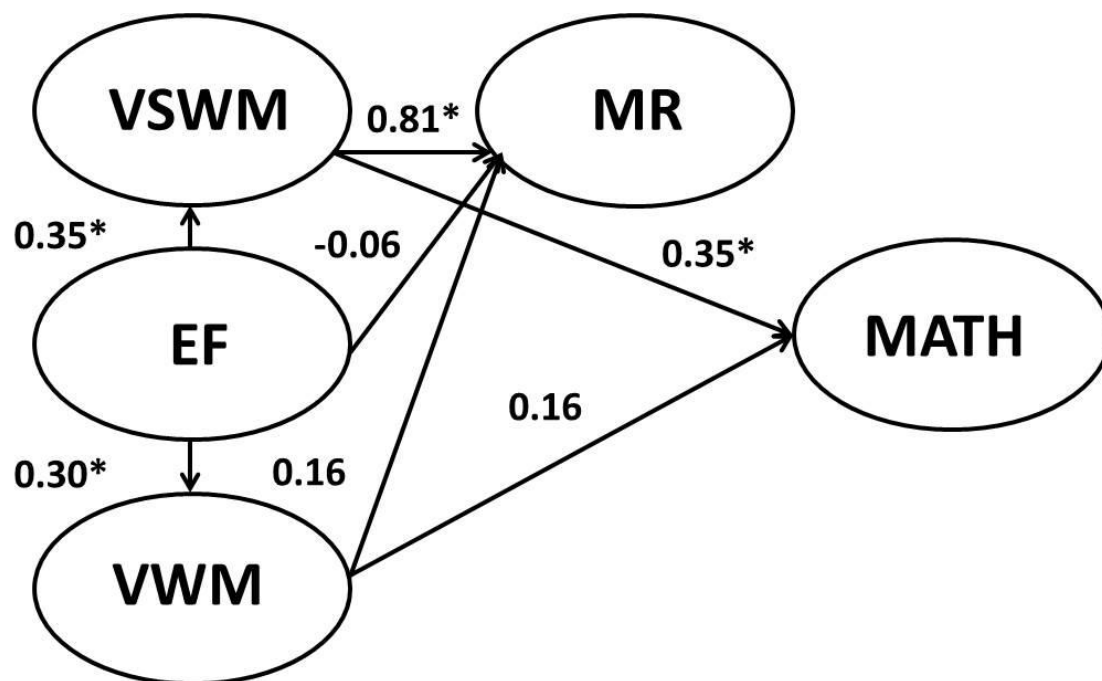
Figure 3.7. Model 3 with Standardized Path Coefficients
*p < 0.05

Because it is theoretically plausible that mental rotation and VSWM are the same or close to identical constructs, it is of interest to test Model 4 (see Figure 3.8), where the path from VSWM to mathematics achievement was removed instead of the path from mental rotation to mathematics achievement. If similar fit statistics were obtained between Models 4 and 3, the theoretical possibility that VSWM and mental rotation might be the same or close to identical constructs would be tenable. It that were the case, the problem with neither VSWM nor mental rotation being a statistically significant predictor of mathematics achievement in Models 1 and 2 is most likely due to the variance in those models were split. Model 4 fit the data quite well (χ^2 = 10.56, df = 15, p = 0.78, RMSEA < 0.01, CFI = 1.00, SRMR = 0.06). The smallest and the largest completely standardized residuals were -0.34 and 2.59, respectively. Shown in Figure 3.8 are all the completely standardized path coefficients, among which the path coefficients associated with the paths from executive functioning to VSWM, from executive functioning to VWM, from VSWM to mental rotation, and from VSWM to mathematics achievement were statistically significant, just like in Model 3.
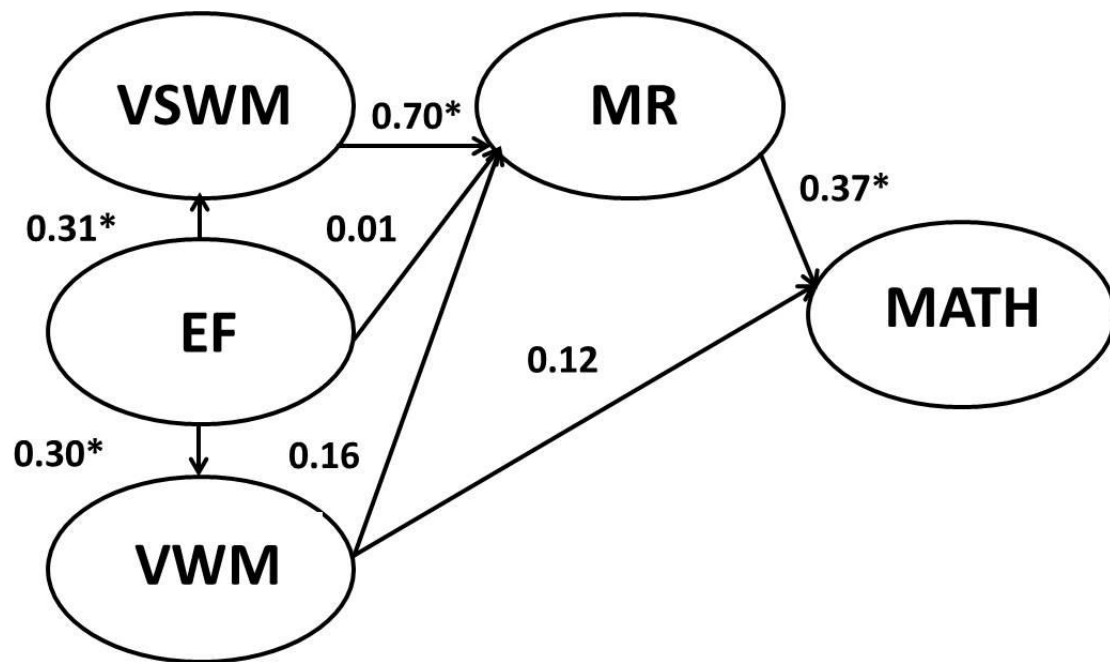
Figure 3.8. Model 4 with standardized path coefficients
*$p < 0.05$

Because Models 1, 2, and 3 are nested models, it was possible to perform Chi-Square difference tests to select the best-fitting model among the three models. The comparison between Model 2 and Model 1 favors Model 2. This is because $\Delta \chi^2 = 0.55$, $p = 0.46$. The non-statistically significant Chi-Square difference between the two nested models suggests that the more parsimonious model (Model 2) better describes the data. The comparison between Model 3 and Model 2 favors Model 3. Again, this is because the Chi-Square difference between the two nested models was not statistically significant ($\Delta \chi^2 = 2.28$, $p = 0.13$) and Model 3 is more parsimonious than Model 2. In addition, there were also few differences in the other fit statistics between Models 3 and 2, and between Models 2 and 1.

Because Model 4 and Model 3 have the same degrees of freedom, a Chi-Square difference test on Models 4 and 3 cannot be performed. However, because Model 4 is nested within Model 2, it was possible to perform a Chi-Square difference test on Models 4 and 2. The results of this comparison showed no statistically significant differences in fit between Models 4 and 2 ($\Delta \chi^2 = 0.07$, $p = 0.79$). Thus, Models 4 is a preferred model to Model 2 for the same reason Model 3 is a preferred model to Model 2. While a direct comparison between Model 3 and Model 4 based on the Chi-Square difference test could not be done, other fit statistics associated with the two models are quite similar. Therefore, Model 3 and Model 4 appear to describe the data similarly well.

In sum, this section presented the results of the preliminary analysis (scoring, data screening, and descriptive statistics), the fit statistics of a four-factor measurement model, and the fit statistics of four structural equation models that derived from the implicit model suggested by the literature. Among the four structural equation models tested, Models 3 and 4 best explained the data. Model 3 showed that of the three components of working memory, VSWM is

the best predictor of mental rotation and mathematics achievement. Model 4 showed that after removing the path from VSWM to mathematics achievement, mental rotation changed from a non-statistically significant predictor of mathematics achievement in Models 1 and 2 to a statistically significant predictor of the latter.

Discussion

Individual differences in spatial ability may be understood as a function of differences in the three components of working memory, i.e., VSWM, VWM, and executive functioning (see Kaufman, 2007; Miyake et al., 2001). Individual differences in mathematics achievement may also be understood as a function of the complex interplay among these three working memory components (see Bull et al., 2008; Tolar et al., 2009). Mental rotation is one of the three categories of spatial abilities defined by Linn and Peterson (1985) where individual differences in task performance as predictors of mathematics achievement are most well-documented. Therefore, in this study, mental rotation tests were used to measure spatial ability. The connection between spatial ability and mathematics achievement has been noted by researchers (see Carr, Steiner, Kyser, & Biddlecomb, 2008). However, we do not understand the cognitive mechanisms underlying this connection.

In this study, three models that described the connections between the three components of working memory with spatial ability (mental rotation) and with mathematics achievement were tested first. Because prior studies included only subsets of all relevant variables, the purpose of this study is to fill that gap in the literature by simultaneously estimating the path coefficients associated with all relevant variables. Model 1, the dominant model, is directly supported by the literature. Model 2 is otherwise identical with Model 1, with the exception that it assumes that the impact of executive functioning on mathematics achievement is completely

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mediated by mental rotation. It was tested because there was evidence that executive functioning predicts mathematics achievement even after the shared variance between, one, executive functioning and VSWM and, two, between executive functioning and VWM are both controlled (see St Clair-Thompson & Gathercole, 2006; Swanson, 2006). Model 3 assumes the connection between mental rotation and mathematics achievement is due to a common third predictor variable, VSWM. Model 3 is otherwise identical with Model 2. It was tested because it is possible that the connection between mental rotation and mathematics achievement actually reflects the impact of VSWM on both variables. Thus, by removing the path from mental rotation to mathematics achievement, this possibility can be tested.

After testing Models 1, 2, and 3, Model 4, another logical possibility, which retains the path from mental rotation to mathematics achievement, but removes the path from VSWM to mathematics achievement, was also tested. The main objective of testing Model 4 was to explore whether VSWM and mental rotation are identical constructs. The results showed that they are close to identical constructs in that the standardized path coefficients and the fit indices of Models 3 and 4 are similar enough to warrant this conclusion.

Overall, the results of this study showed that comparing to Models 1 and 2, Models 3 and 4 better explain the data, although there are few differences between Models 3 and 4. These findings may be interpreted as follow: of the three working memory components, VSWM best predicts mental rotation and mathematics achievement; VSWM and mental rotation may be treated as a single construct in future studies; and of all four models tested, the statistically significant paths from executive functioning to VSWM and from executive functioning to VWM are consistent with Baddeley's (1986) working memory model, which theorizes that executive functioning supervises the two modality-specific slave systems (VSWM and VWM). In other

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words, executive functioning is expected to predict VSWM and VWM. In all four models tested, the path from executive functioning to mental rotation is not statistically significant. This finding is inconsistent with prior studies that showed elderly (Libon et al., 1994) and young adults' (Miyake et al., 2001) performances on executive functioning and spatial ability tasks were highly correlated.

Two unexpected findings were the non-statistically significant paths from VWM to mental rotation and from VWM to mathematics achievement. In a prior study by Kaufman (2007), who studied the relationships among gender, VSWM, VWM, and spatial ability using structural equation modeling, it was found that the path from VWM to spatial ability was statistically significant. In another study by Tolar et al. (2009), who studied the relationships among VWM, computational fluency, spatial ability, and mathematics achievement, also using structural equation modeling, it was also found that the path from VWM to mathematics achievement was statistically significant. However, there are at least two pieces of counterevidence regarding the connection between VWM and mathematics achievement (see St. Clair-Thompson & Gathercole, 2006; Reuhkala, 2001). The non-statistically significant path from VWM to mathematics achievement in the three structural equation models tested in this study may also be taken as supporting the view that unlike its counterpart, VSWM, VWM plays a minor role in explaining individual differences in mathematics achievement. It is also possible that a greater statistical power than this study may be needed to detect the significance of the path from VWM to mental rotation or the path from VWM to mathematics achievement. It could also be that VWM does not contribute significantly to mental rotation ability or mathematics achievement when VSWM and executive functioning are simultaneously considered. To verify

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which interpretation was the case, a follow-up study could be done using a larger sample size to increase the power of the analyses.

The critical finding that sets apart Models 3 and 4 from Models 1 and 2 is the presence of a statistically significant path from VSWM to mathematics achievement in Model 3 and the presence of a statistically significant path from mental rotation to mathematics achievement in Model 4; whereas in Models 1 and 2, none of the hypothesized predictors of mathematics achievement statistically significantly predicted the latter. There is strong evidence for the connection between VSWM and mathematics achievement and between mental rotation and mathematics achievement, as reviewed previously. Thus, from a theoretical point of view, among the four structural equation models tested, Models 3 and 4 are more consistent with the literature. The similar fit between Models 3 and 4 suggests that VSWM and mental rotation are close to identical constructs that may be treated as a single construct in future studies.

Regarding why the scaled scores for the inhibition and switching conditions of the CIT, i.e., citin and citsw, were poor indicators of executive functioning in this study, there are two possible explanations. One may be due to a lack of precision in the assessment of these variables. Performance scores on the CIT were based on the participants' reaction times. The researcher manually recorded participants' reaction times using an electronic stopwatch. Therefore, it is possible that measurement errors due to manual operations rendered participants' scores on these conditions unreliable.

Another possible cause of why citin and citsw were poor indicators of executive functioning might not necessarily be due to the two variables being poorly measured but, rather, due to the fact that citin and citsw did not reflect the errors made by the participants on the inhibition and the switching conditions of the CIT. It is possible that participants who responded

faster on the inhibition and the switching conditions of the CIT also made more errors along the way. Thus, by not jointly considering participants' reaction times and error rates when evaluating their performances, one dimension of the task performance, accuracy, has been neglected. In other words, accuracy (error rate) may be another dimension of the CIT task performance that future studies using the CIT to measure executive functioning might need to attend to.

Limitations and Future Directions

Because the relationships among the five constructs included in the structural equation models may differ by gender, it would be of interest to test structural and metric equivalence between males and females by fitting separate structural equation models by gender. Unfortunately, the sample size for this study is not large enough to perform separate analyses by gender. A power analysis based on the full sample (after listwise deletion, $N = 135$), using an approach proposed by MacCallum, Browne, and Sugawara (1996), showed that the power for the test of close fit that is based on the RMESA and non-central chi-square distributions close-fit hypothesis ($H_0 : \epsilon_0 = 0$) is 0.32. Thus, the power of this study is much smaller than the ideal value of 0.80. Researchers interested in replicating the current study may want to use a larger sample size. Researchers interested in testing the structural or the metric invariance assumption between males and females would need an even larger sample size and preferably with a balanced number of males and females.

A second limitation of this study is that participants of this study were invited to self-report their test scores on the mathematics section of the SAT. These self-reported SAT scores are used as the only indicator of mathematics achievement in this study. Retrospective self-reporting is subjective to memory distortions or untruthful reporting due to a variety of reasons, e.g., hoping to be seen in a positive light. However, the fact that the majority of the participants

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either brought their official SAT score reports with them or looked up that information online as they were filling out the demographic survey suggests that the mathematics SAT scores collected for this study are most likely to be credible and accurate. On the other hand, the inter-individual differences in the time lags between when the SAT was taken and when the scores were collected poses a threat to the validity of using the mathematics SAT scores as the sole indicator of mathematics achievement. This is because for some participants the lag was less than one year, whereas for others it could be several years. Future studies may consider including multiple indicators of mathematics achievement in addition to the SAT scores, such as mental arithmetic, word problems, and number line estimation.

Conclusions

Overall, through testing four structural equation models that included all working memory components (VSWM, VWM, and executive functioning), mental rotation, and mathematics achievement, this study lent support to the tripartite structure of Baddeley's (1986) working memory model. This study also highlighted the role of VSWM, the ability to temporarily hold and actively process visuospatial information, in predicting individual differences in mental rotation and mathematics achievement. Neither executive functioning nor VWM statistically predicted mental rotation or mathematics achievement in this study. These findings shed light on the relative importance of different components of working memory in explaining individual differences in spatial ability and mathematics achievement. Finally, this study also showed that VSWM and mental rotation are close to identical constructs that may be treated as a single construct in future studies.

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Appendix A

RECRUITING FLYER

Fun Psychology Experiment

Are you interested in learning more about the spatial ability? Past research showed that spatial ability has an important role to play in occupational success in the fields of dentistry, architecture and engineering. Yet, research on spatial ability lags behind research on linguistic ability and many other forms of cognitive abilities considerably.

Would you like to be a contributing member of a historically under-researched topic in a meaningful way? You can make a difference by participating in this hour-long study that looks at the relationships among attention, memory and the ability to visualize images.

We are looking for healthy volunteers (i.e., students without psychological or physical impairments that require special accommodations) who are at or over 18. We anticipate the risks involved in your participation are less than minimal. If you believe you are eligible and are interested in participating, please contact the researcher at: luw@uga.edu. We appreciate your participation!

Department of Educational Psychology & Instructional Technology

University of Georgia

Appendix B

CONSENT FORM

I, _____, agree to take part in a research study titled

understanding the relationship between working memory and various components of spatial

ability, conducted by Ms. Lu Wang, Department of Educational Psychology and Instructional

Technology, UGA, and 857-445-5675 under the direction of Dr. Martha Carr, Department of

Educational Psychology and Instructional Technology, UGA, and 706-542-4504. My

participation is voluntary; I can refuse to participate or stop taking part at any time without

giving any reason, and without penalty, or loss of benefits to which I am otherwise entitled. I

understand that data will be anonymously collected and kept.

The purpose of the study is to better understand the relationships among spatial ability,

short-term memory, working memory and executive control/inhibition. I understand that at the

end of the study, I will have a chance to enter a drawing to win $50 and/or several smaller prizes

that include a well-respected mechanical aptitude and spatial relations study guide, a headlight

lens restorer, microfiber automotive cloths, and a set of dishes. Since cumulatively, I will not

receive monetary compensation/gifts at an amount greater than $100, I will not be asked to

provide my SSN# to track the incentive payments. Instead, I will be asked to provide an email

address of my choice for the purpose of tracking payments (from the drawing). I understand that

my participation is not required in order to enter the raffle and I can withdraw from the study

without penalty at any point during the study. However, I also understand that withdrawal can

only occur while participating since data are not identifiable later during the study. If I volunteer to take part in this study, I will be asked to do all of the following things:

- I will take two spatial ability tests (tapping mental rotation ability, which is considered to be a component of spatial visualization ability), two short-term memory tests (one test for verbal short-term memory, one test for spatial short-term memory), two tests for executive control, and one test for verbal working memory.

- Finally, I will be asked to self-report my SAT-Q and SAT-V scores anonymously.

- I will be taking these tests in a regular classroom. My participation in the study is about one hour in duration.

I am aware that no discomforts or stresses are expected in this study other than discomfort related to sitting for an hour to complete the forms. The results of this participation will be kept anonymously. This means all data will be linked using ID numbers, and thus, I will be asked not to put down any personal identifiable information on any of the instruments I am given (e.g., names, SSN#. I understand that the researcher will answer any further questions about the research, now or during the course of the project, and can be reached by telephone at: 857-445-5675. I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form).

Appendix C

DIGIT SPAN

11. Digit Span (Optional)

Digits Forward

Item/Trial		Response	Score 0 or 1
1.	Trial 1	1 – 7	
	Trial 2	6 – 3	
2.	Trial 1	5 – 8 – 2	
	Trial 2	6 – 9 – 4	
3.	Trial 1	6 – 4 – 3 – 9	
	Trial 2	7 – 2 – 8 – 6	
4.	Trial 1	4 – 2 – 7 – 3 – 1	
	Trial 2	7 – 5 – 8 – 3 – 6	
5.	Trial 1	6 – 1 – 9 – 4 – 7 – 3	
	Trial 2	3 – 9 – 2 – 4 – 8 – 7	
6.	Trial 1	5 – 9 – 1 – 7 – 4 – 2 – 8	
	Trial 2	4 – 1 – 7 – 9 – 3 – 8 – 6	
7.	Trial 1	5 – 8 – 1 – 9 – 2 – 6 – 4 – 7	
	Trial 2	3 – 8 – 2 – 9 – 5 – 1 – 7 – 4	
8.	Trial 1	2 – 7 – 5 – 8 – 6 – 2 – 5 – 8 – 4	
	Trial 2	7 – 1 – 3 – 9 – 4 – 2 – 5 – 6 – 8	

Forward Total Score
Range = 0 to 16 [ ]

Digits Backward

Item/Trial		(Correct Response)/Response	Score 0 or 1
1.	Trial 1	2 – 4 (4 – 2)	
	Trial 2	5 – 7 (7 – 5)	
2.	Trial 1	6 – 2 – 9 (9 – 2 – 6)	
	Trial 2	4 – 1 – 5 (5 – 1 – 4)	
3.	Trial 1	3 – 2 – 7 – 9 (9 – 7 – 2 – 3)	
	Trial 2	4 – 9 – 6 – 8 (8 – 6 – 9 – 4)	
4.	Trial 1	1 – 5 – 2 – 8 – 6 (6 – 8 – 2 – 5 – 1)	
	Trial 2	6 – 1 – 8 – 4 – 3 (3 – 4 – 8 – 1 – 6)	
5.	Trial 1	5 – 3 – 9 – 4 – 1 – 8 (8 – 1 – 4 – 9 – 3 – 5)	
	Trial 2	7 – 2 – 4 – 8 – 5 – 6 (6 – 5 – 8 – 4 – 2 – 7)	
6.	Trial 1	8 – 1 – 2 – 9 – 3 – 6 – 5 (5 – 6 – 3 – 9 – 2 – 1 – 8)	
	Trial 2	4 – 7 – 3 – 9 – 1 – 2 – 8 (8 – 2 – 1 – 9 – 3 – 7 – 4)	
7.	Trial 1	9 – 4 – 3 – 7 – 6 – 2 – 5 – 8 (8 – 5 – 2 – 6 – 7 – 3 – 4 – 9)	
	Trial 2	7 – 2 – 8 – 1 – 9 – 6 – 5 – 3 (3 – 5 – 6 – 9 – 1 – 8 – 2 – 7)	

Backward Total Score
Range = 0 to 14 [ ]

Total Score
Range = 0 to 30 [ ]

(Sum Forward Total Score & Backward Total Score)

SPATIAL SPAN

9. Spatial Span

	DISCONTINUE RULE	RECORDING:	SCORING RULE
	After scores of 0 on both trials of any item. For both Spatial Span Forward & Spatial Span Backward, administer both trials of each item even if Trial 1 is passed.	All responses verbatim	0-1 pt. for each trial

Spatial Span Forward

Item/Trial		Response	Score 0 or 1
1.	Trial 1	3 – 10	
	Trial 2	7 – 4	
2.	Trial 1	1 – 9 – 3	
	Trial 2	8 – 2 – 7	
3.	Trial 1	4 – 9 – 1 – 6	
	Trial 2	10 – 6 – 2 – 7	
4.	Trial 1	6 – 5 – 1 – 4 – 8	
	Trial 2	5 – 7 – 9 – 8 – 2	
5.	Trial 1	4 – 1 – 9 – 3 – 8 – 10	
	Trial 2	9 – 2 – 6 – 7 – 3 – 5	
6.	Trial 1	10 – 1 – 6 – 4 – 8 – 5 – 7	
	Trial 2	2 – 6 – 3 – 8 – 2 – 10 – 1	
7.	Trial 1	7 – 3 – 10 – 5 – 7 – 8 – 4 – 9	
	Trial 2	6 – 9 – 3 – 2 – 1 – 7 – 10 – 5	
8.	Trial 1	5 – 8 – 4 – 10 – 7 – 3 – 1 – 9 – 6	
	Trial 2	8 – 2 – 6 – 1 – 10 – 3 – 7 – 4 – 9	

Forward Total Score
Range = 0 to 16 [ ]

Spatial Span Backward

Item/Trial		(Correct Response)/Response	Score 0 or 1
1.	Trial 1	7 – 4 (4 – 7)	
	Trial 2	3 – 10 (10 – 3)	
2.	Trial 1	8 – 2 – 7 (7 – 2 – 8)	
	Trial 2	1 – 9 – 3 (3 – 9 – 1)	
3.	Trial 1	10 – 6 – 2 – 7 (7 – 2 – 6 – 10)	
	Trial 2	4 – 9 – 1 – 6 (6 – 1 – 9 – 4)	
4.	Trial 1	5 – 7 – 9 – 8 – 2 (2 – 8 – 9 – 7 – 5)	
	Trial 2	6 – 5 – 1 – 4 – 8 (8 – 4 – 1 – 5 – 6)	
5.	Trial 1	9 – 2 – 6 – 7 – 3 – 5 (5 – 3 – 7 – 6 – 2 – 9)	
	Trial 2	4 – 1 – 9 – 3 – 8 – 10 (10 – 8 – 3 – 9 – 1 – 4)	
6.	Trial 1	2 – 6 – 3 – 8 – 2 – 10 – 1 (1 – 10 – 2 – 8 – 3 – 6 – 2)	
	Trial 2	10 – 1 – 6 – 4 – 8 – 5 – 7 (7 – 5 – 8 – 4 – 6 – 1 – 10)	
7.	Trial 1	6 – 9 – 3 – 2 – 1 – 7 – 10 – 5 (5 – 10 – 7 – 1 – 2 – 3 – 9 – 6)	
	Trial 2	7 – 3 – 10 – 5 – 7 – 8 – 4 – 9 (9 – 4 – 8 – 7 – 5 – 10 – 3 – 7)	
8.	Trial 1	8 – 2 – 6 – 1 – 10 – 3 – 7 – 4 – 9 (9 – 4 – 7 – 3 – 10 – 1 – 6 – 2 – 8)	
	Trial 2	5 – 8 – 4 – 10 – 7 – 3 – 1 – 9 – 6 (6 – 9 – 1 – 3 – 7 – 10 – 4 – 8 – 5)	

Backward Total Score
Range = 0 to 16 [ ]

Total Score
Range = 0 to 32 [ ]
(Sum Forward Total Score & Backward Total Score)

Appendix E

COLOR-WORD INTERFERENCE TEST
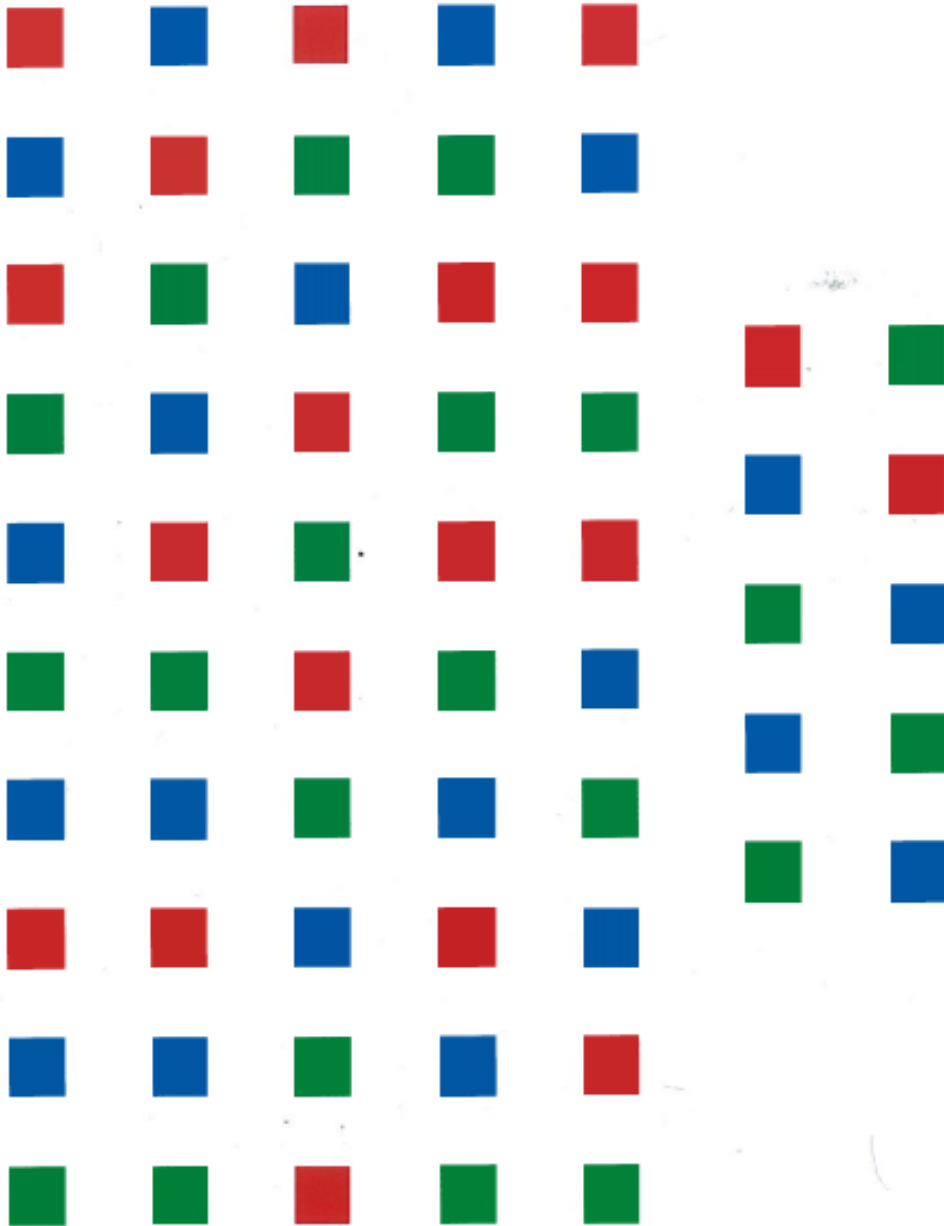
red   blue   green   red   blue

green   blue   green   red   green

green   red   blue   green   blue   red   blue   green   blue   green

red   green   blue   green   red   blue   green   red   blue   red

red   green   blue   green   blue   green   red   blue   red   green

blue   green   red   blue   green   red   blue   green   blue   red

green   red   blue   red   blue   green   red   blue   red   green

Rule:
Name the ink color.

red blue green blue green

red blue red green red

blue green blue red blue red blue red

blue green blue green blue red green red blue

red green red blue green red green red blue green

blue green blue red green blue red green blue red green

blue green blue red green blue red green red green red green

green blue red blue green red blue green red blue green red blue

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Rules:

1. blue – Name the ink color.

2. red – Read the word.

blue   red   green   red   blue

green   red   green   red   blue

green   blue   red   green   red   blue

red   blue   green   blue   red   blue

green   blue   red   green   red   blue

blue   red   green   red   green   blue

blue   green   red   green   red

blue   green   green   red   green   red

green   red   blue   red   green   red

Appendix F

TOWER TEST

(ONLY ITEM 1 IS SHOWN)

Rules

1. Move only one at a time.
2. A big one may not be placed on top of a little one.

Item 1

Pointing to the five disks and then to the ending position illustration for Item 1, say,

I want you to use these pieces to build a tower that looks like this picture. Before you start, I will put the pieces in place. I want you to build the tower using the fewest number of moves possible.

Pointing to the rules on the stimulus page, say,

There are two rules to follow. First, move only one piece at a time, using just one hand. And second, never place a big piece on top of a little piece. Do you have any questions?

Place Disks 1 and 2 on the pegs as shown in the starting position illustration for Item 1. Then turn the page to expose again the ending position illustration for Item 1 to   . the examinee.

Examiner's Perspective

Item 1 Starting Position

Ages 8–89

Materials

- Record Form
- Stimulus Booklet
- Tower Wooden Base
- Five Tower Wooden Disks
- Stopwatch

Discontinue

Discontinue Item 1 after 30 seconds. Otherwise, discontinue the Tower Test after three consecutive item failures.

Prompts

- The first time an examinee violates each rule, stop him or her immediately, explain the error, and return the disk(s) to its last location. For all subsequent violations of the same rule for the entire test, stop the examinee immediately, state that he or she has made an error, and, *without explaining the rule*, return the disk(s) to its last location. Keep the stopwatch running.
- If an examinee completes a move, then indicates that he or she has made a mistake, say, **There are different ways to build the tower. Just try to build it in the fewest number of moves possible from where you are.**
- If an examinee appears to be rushing, say, **Remember, work carefully so that you build the tower using the fewest number of moves possible.** Provide this prompt only once for the entire test.

One-Move Criteria

Move Initiation: Disk is lifted completely off peg.

Move Completion: Examinee takes hand completely off disk.

Minimum Moves for Item 1 Completion: 1

D-KEFS Tower Test

Item 1 (continued)

Pointing to the ending position illustration on the stimulus page, say,

Now make yours look like the one in this picture. Begin.

Start timing. Record the following information in the spaces provided in the record form:

• Estimated first-move time (optional)
• Total number of moves
• Number of rule violations (optional)
• Total completion time
• Tower correct (Y or N)

If the examinee does not solve Item 1 in one move, demonstrate the correct one-move solution.

Remove the disks from the wooden base and place them with the others, close to the wooden base.

Examiner's Perspective

Item 1 Ending Position

Ages 8–89

Materials

• Record Form
• Stimulus Booklet
• Tower Wooden Base
• Five Tower Wooden Disks
• Stopwatch

Discontinue

Discontinue Item 1 after 30 seconds. Otherwise, discontinue the Tower Test after three consecutive item failures.

Prompts

• The first time an examinee violates each rule, stop him or her immediately, explain the error, and return the disk(s) to its last location. For all subsequent violations of the same rule for this entire test, stop the examinee immediately, state that he or she has made an error, and, without explaining the rule, return the disk(s) to its last location. Keep the stopwatch running.

• If an examinee completes a move, then indicates that he or she has made a mistake, say, There are different ways to build the tower. Just try to build it in the fewest number of moves possible from where you are.

• If an examinee appears to be rushing, say, Remember, work carefully so that you build the tower using the fewest number of moves possible. Provide this prompt only once for the entire test.

One-Move Criteria

Move Initiation: Disk is lifted completely off peg.

Move Completion: Examinee takes hand completely off disk.

Minimum Moves for Item 1 Completion: 1

D–KEFS Tower Test

Item 1

Appendix G

VANDENBERG AND KUSE MENTAL ROTATIONS TEST

11.

12.

13.

14.

15.

16.

17.

18.

19.

20.

DO NOT TURN THIS PAGE UNTO ASKED TO DO SO.   STOP

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Appendix H

SOLID FIGURE TURNING

Appendix I

DEMOGRAPHIC SURVEY

Gender:

Age:

Ethnicity:

College Major/Current Occupations:

Years of education:

Experience playing video games: Please quantify by indicating the cumulative number of years played.

Is there any video game you played before that resembles one of the tests you took today? If so, please specify:

SAT scores: Please give your best estimate even if you cannot recall the exact numbers. Thanks.

SAT (reading) and the year taken:

SAT (mathematics) and the year taken:

CHAPTER 4

DISSERTATION CONCLUSION

The two papers included in this dissertation are motivated by the accumulating evidence

that performance on spatial ability tasks is best construed as jointly determined by working

memory and strategy use, as described in the first paper, and spatial ability and mathematics

achievement are intrinsically related, as described in the second paper. The first paper is a

theoretical paper that reviews prior research, which showed the connection among working

memory, strategy use, and performance on spatial ability tasks. Based on a comprehensive

review of the literature, a model is proposed that suggests strategies used on spatial ability tasks

are determined by test-takers' relative strengths of visuospatial working memory (VSWM) to

verbal working memory (VWM). Assuming individuals tend to play to their strengths when

tackling problems in a cognitive domain, the type of strategies used to solve spatial problems

would be expected to be consistent with those strengths. Specifically, the use of holistic

strategies would be expected if test-takers have a higher VSWM to VWM ratio, whereas the

converse would be true if test-takers have a higher VWM to VSWM ratio. Holistic strategies and

analytic strategies are two broad categories of strategies adopted by test-takers. The proposed

model also suggests that strategy use, in turn, predicts performance on spatial ability tasks. There

is evidence that superior performance on spatial ability tasks is linked to holistic strategy use,

with a few exceptions (e.g., low-VSWM and high-VWM individuals). Though the literature

suggests holistic strategies are more commonly adopted by high-VSWM individuals, the

proposed model suggests that the mechanism that determines strategy use is not VSWM or

VWM per se but, rather, the relative strength of VSWM to VWM expressed as a ratio. This is true regardless of test-takers' levels of VWM. Overall, the paper concludes that performance on spatial ability tasks is jointly determined by the relative strength of VSWM to VWM and test-takers' strategy use, which results from their cognitive strength.

The second paper is an empirical paper that investigates the relationship between spatial ability (mental rotation) and mathematics achievement through the lens of information processing theory. A review of the literature on this topic suggests that there exists an implicit model that best describes the relationships among working memory components, mental rotation, and mathematics achievement. While there is evidence supporting the relationships among subsets of the variables in the implicit model, no prior studies have explicitly tested that implicit model. In this empirical study, three models that derive from this implicit model and, eventually, a fourth model that serves as an alternative model to the third model were tested. The results showed that Models 3 and 4 best describe the sample and are more consistent with the findings of prior research. In addition, the two models are also more parsimonious than Models 1 and 2. There are few differences in fit statistics between Models 3 and 4, however. Therefore, both Models 3 and 4 are retained as final models. Overall, this study shows two important findings: VSWM is the best predictor of mathematics achievement among all hypothesized predictors of the latter (Model 3); VSWM and mental rotation are almost identical constructs and may be treated as the same construct in future studies (Model 4).