THE COMMON ELEMENTS OF WORKING MEMORY CAPACITY AND FLUID INTELLIGENCE: PRIMARY MEMORY, SECONDARY MEMORY AND EXECUTIVE ATTENTION

A Dissertation
Presented to
The Academic Faculty

by

Zachary M. Shipstead

In Partial Fulfillment
of the Requirements for the Degree
Doctoral Degree in the
School of School of Psychology

Georgia Institute of Technology
December, 2012

THE COMMON ELEMENTS OF WORKING MEMORY CAPACITY AND FLUID INTELLIGENCE: PRIMARY MEMORY, SECONDARY MEMORY AND EXECUTIVE ATTENTION

Approved by:

Dr. Randall W. Engle, Advisor
School of Psychology
Georgia Institute of Technology

Dr. Paul Verhaeghen
School of Psychology
Georgia Institute of Technology

Dr. Daniel H. Spieler
School of Psychology
Georgia Institute of Technology

Dr. Eric H. Schumacher
School of Psychology
Georgia Institute of Technology

Dr. David A. Washburn
Department of Psychology
Georgia State University

Date Approved: July 25, 2012

ACKNOWLEDGEMENTS

I would like to thank my wife, Kori, for being willing to pick up and change lives every few years as I pursued my degree.

I would also like to thank my PhD advisor, Randy Engle, and my master's advisor, Keith Hutchison, both of whom provided me with the opportunity and guidance that got me here. Additionally, I would like to acknowledge the role of my committee who asked several difficult questions that improved all phases of this project. Finally, this work would not have been possible without the effort of the Georgia Tech Attention and Working Memory Lab. In particular, I recognize the contributions of Dakota Lindsey and Robyn Marshall who were asked to go above and beyond the normal role of undergraduate assistants, and delivered.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

WMspan	working memory - span tasks
WMva	working memory - visual arrays tasks
Gf	general fluid intelligence
PM	primary memory
SM	secondary memory
ATTN	attention control
ExATTN	executive attention
Ospan	operation span
SymSpan	symmetry span
RunLett	running letter span
RunDigit	running digit span
VA1	visual arrays task 1
VA2	visual arrays task 2
VA3	visual arrays task 3
VA4	visual arrays task 4
PM_Word	primary memory - words
SM_Word	secondary memory - words
PM_Numb	primary memory - numbers
SM_Numb	secondary memory - numbers
SSblue	split span blue
SSred	split span red
CPA	continuous paired associates
Raven	Raven's advanced progressive matrices

NumSer	number series
EFA	exploratory factor analysis
df	degrees of freedom
RMSEA	root mean square error of approximation
SRMR	standardized root mean square residual
NNFI	non-normed fit index
CFI	confirmatory factor analysis
AIC	Akaike's information criterion
CommWM	common working memory capacity

SUMMARY

Working memory is a mental system that is related to cognitive control and higher cognition. Although the topic of working memory is well researched, there is a great deal of debate about the mechanisms that drive individual differences in working memory capacity. Moreover, little is known about the direct relationships between different types of working memory tasks. The present study uses structural equation modeling to examine three varieties of working memory task: The complex span, running memory span, and visual arrays. It is found that, while complex and running span performance is directly predicted by immediate memory and retrieval from long-term memory, visual arrays is directly predicted by attention control. Despite these differences, all tasks are found to be united by executive attention, which is conceptualized as an executive process that is apparent across several types of attention and memory task. A second analysis examines the relationship between working memory and general fluid intelligence. It is concluded that, while executive attention accounts for the largest portion of the correlation between working memory and fluid intelligence, immediate memory and retrieval from long term memory are also critical to explaining this relationship.

CHAPTER 1

INTRODUCTION

> *....working memory is not a memory system in itself, but a system for attention to memory....*
>
> Oberauer, Süß, Wilhelm, & Sander (2007)

Working memory is the cognitive system that allows people to retain access to a limited amount of information, in the service of complex cognition. More succinctly, as stated above, working memory allows people to attend to goal-relevant memories. While this perspective is generally accepted in one form or another (Conway et al., 2007; Miyake & Shah, 1999), the aspects of memory and attention that account for individual differences in working memory capacity remain unresolved.

Many tasks are available to researchers who study working memory. These include the complex span (Daneman & Carpenter, 1980), the running memory span (Pollack, Johnson, & Knaff, 1959), visual arrays (Luck & Vogel, 1997), the n-back (Kirchner, 1958) and any number of specialized tasks designed for testing specific hypotheses (Oberauer, Süß, Wilhem, & Wittman, 2003), or elucidating specific executive processes (Miyake et al., 2000; Unsworth, Miller et al., 2009). This abundance of tasks poses daunting problems for the study of working memory. Beyond the question of whether any given task truly reflects working memory (or a separate construct; e.g., Engle et al., 1999), an ever present concern regards the cognitive processes that account for task performance. Answers tend to vary based upon the surface features of the task (e.g., simple retention, interruption) and the processes that a given researcher assumes to be important to working memory (e.g., attention, storage, retrieval).

The present study adopts the position that working memory is best understood by studying the relationships between working memory tasks, rather than by studying the tasks themselves. That is, working memory is construed as an ability that accounts for the correlations between disparate types of task. Thus, understanding these correlations provides a more concrete understanding of the fundamental processes of working memory. The present study specifically (1) assesses the degree to which performance on several types of working memory task is best represented by common or distinct latent factors, (2) accounts for relationship between these factors in terms of memory and attention, and (3) applies a similar analysis to the correlation between working memory and novel reasoning ability (i.e., general fluid intelligence).

The Structure of Working Memory

There are many proposed models of working memory (Conway et al., 2007; Miyake & Shah, 1999). Presently, Cowan's (1988; 1999) embedded process model is preferred due to its simple, yet developed, structure. This model assumes that working memory functions within several levels of memory and attention. Although Cowan proposes that working memory is largely defined by one aspect (focal attention; Cowan, 1999; 2001) his model allows for the possibility that working memory is actually composed of several mechanisms that function in concert. Thus, while different researchers bring different assumptions to the embedded process model, it has proven influential and flexible structure in which many perspectives of working memory are discussed (cf. Colom et al., 2008; Cowan et al., 2005; Engle et al., 1999; Oberauer et al., 2007). However, it should be noted that while I conceptualize working memory within the general embedded process structure, I do not strictly adhere to Cowan's specific assumptions. Instead, the present discussion is also influenced by the perspectives of Unsworth and Engle (2007a, 2007b, 2007c), Kane, Conway, Hambrick, and Engle (2007) and Oberauer, Süß, Wilhelm, and Sander (2007).

Primary Memory

Within the embedded process model (Cowan, 1988; 1999) activated units of memory are referred to as short-term memory. There is no assumed limit to how many units of short-term memory may be activated at any moment. However, activation is assumed to constantly decay toward a baseline resting state, at which point the representation becomes inaccessible. This decay is counteracted by the focus of attention.

The capacity of focal attention is assumed to vary among people. The typical individual can ostensibly attend to between 3 and 5 fully-integrated items at any one point in time (Cowan, 2001). For present purposes, individual differences in this capacity limit will be referred to as *primary memory* (cf. Unsworth & Engle, 2007c; Unsworth & Spillers, 2010). Because attended information is assumed to be protected from decay toward inactivation, it is also protected from retrieval-based proactive interference. People with larger primary memories can therefore retain access to a larger number of disparate concepts, and are therefore capable of making a greater number of novel connections (Cowan et al., 2005; Oberauer et al., 2007).

Researchers disagree as to the exact properties of the primary memory component of working memory. While many endorse Cowan's multi-item storage perspective (e.g., Awh, Barton, & Vogel, 1997; Colom et al., 2008; Fukuda et al., 2010; Luck & Vogel, 1997, Rouder et al., 2011; Unsworth & Engle, 2007c), others argue that attention has a one-item capacity. For instance, several studies have required test-takers to perform either mental comparisons or updates on serially presented information (e.g., does the currently presented item match one that was presented n-items ago). In these tasks, response times are typically slowed for operations that are conducted on any item in the series, relative to the most recently presented item (Garavan, 1998; McElree, 2001; Verhaeghen & Basak, 2005). This slowing is interpreted as the time taken to reorient a one-item focus of attention, and thus contradicts the assumption that attention allows immediate access to 3-5 items: If people can simultaneously attend to multiple units of memory, then inflated response times (and decreased accuracy) would only be apparent after several items have intervened.

The 3-5 item capacity is therefore sometimes construed as a person's ability to form temporary associations between disparate memory units (Oberauer, 2002; Oberauer et al., 2007). These *bindings* provide facilitated access between discrete units of memory, though unlike Cowan's (2001) interpretation, a degree of interference is assumed to be present (Oberauer, 2001; Shipstead & Engle, 2012). This second perspective necessitates an assumption that the size of a person's primary memory is largely determined by the efficacy with which new bindings are created and dissolved. In other words, some type of executive process functions within primary memory.

Despite disagreements regarding the exact properties of primary memory, it is generally agreed that primary memory, in one form or another, is an important component of working memory (Colom et al., 2008; Fukuda, Vogel, Mayr, Awh, 2010; Luck & Vogel, 1997; Oberauer et al., 2007; Saults & Cowan, 2007; Unsworth & Engle, 2007c). However, while some argue that it is parsimonious to construe working memory capacity in terms of this mechanism (Colom et al., 2008; Cowan, 1999), others assume that working memory capacity is multiply determined (Conway, Getz, MacNamara, & Engel de Abreu, 2010; Miyake et al., 2000; Shipstead, Redick, Hicks, & Engle, 2012; Unsworth & Spillers, 2010). Thus I consider other relevant aspects of Cowan's (1988, 1999) model.

Secondary Memory

While it is parsimonious to assume that individual differences in working memory capacity are purely driven by individual differences in primary memory, many working memory tasks require test-takers to manage more than 3-5 units of information. Thus, regardless of the capacity of a person's primary memory, some to-be-remembered information is likely to be displaced and therefore require retrieval from long-term storage (Unsworth & Engle, 2007a).

The *secondary memory* component of the embedded process model (Cowan, 1988; 1999) consists of inactive units of long-term memory. While there is no assumed limit to the amount of information that may be stored in long-term memory, its contents are not directly accessible. Instead, inactive secondary memory must be cued by the environment or by currently attended information.

Since many working memory tasks do not contain explicit retrieval cues, recovery of information from secondary memory requires self-generation of cues that are based on available context. For instance, test takers may cue secondary memory via temporal context (e.g., "most recent trial"; Baddeley, 1976; Unsworth & Engle, 2006; Watkins, 1979) or by using associations between already recalled information and yet-to-be recalled information (Norman, 1968; Raaijmakers & Shiffrin, 1981; Spillers & Unsworth, 2011). By the account of Unsworth and Engle (2006; 2007c) working memory capacity is partially defined by the efficacy with which a person selects and uses these retrieval cues to circumscribe memory searches. Vague cues will recover several candidates, whereas specific cues will recover a limited set. To the degree that the context of a cue recovers an abundance of candidates, retrieval will be impeded by proactive interference (Watkins & Watkins, 1975; Wixted & Rohrer, 1994). That is, the probability of retrieving critical information will decrease as the number of irrelevant candidates increases. On the other hand, specific retrieval cues reduce the number of potential retrieval candidates. In turn, proactive interference is reduced and critical information is located with a greater probability.

Retrieval from secondary memory is not traditionally assumed to be a mechanism of working memory. Rather, it is often assumed (both implicitly and explicitly) that working memory is a maintenance system that reduces the need for retrieval of important information (e.g., Cowan, 2001; Luck & Vogel, 1997). Nonetheless, Unsworth and colleagues (Spillers & Unsworth, 2011; Unsworth & Engle, 2006; 2007b; 2007c; Unsworth & Spillers, 2010; Unsworth, Spillers, & Brewer, 2010) have provided abundant evidence that secondary memory retrieval is critical to the performance of at least some working memory tasks (in particular, complex span). This information will be discussed in turn.

Executive Attention and Attention Control

Finally, the environment in which working memory operates may contain any number of distractions to which attention is drawn. This is reflected in the embedded process model through the assumption that the only capacity limit of short-term memory is decay-of-activation. In other words, there is no assumed limit to the number memories or behavioral tendencies may be accessible at any point in time. The ability to select goal-relevant information and responses is thus critical when the current environment (or a memory search) activates conflicting information or prepotent responses.

The embedded process model thus includes a central executive component (e.g., Baddeley, 1986; Posner & Snyder, 1975; Norman & Shallice, 1986) that directs attention to specific units of memory based upon current goals and motivations (Cowan, 1999). This component is at the heart of the *executive attention* theory of working memory capacity championed by Engle, Kane and colleagues (Engle, 2002; Engle & Kane, 2004; Engle et al., 1999; Kane et al., 2004; Kane, Conway, Hambrick, & Engle, 2007). From this perspective, individual differences in working memory capacity are primarily defined by the ability to proactively engage the processes that guide attention (e.g., Braver, Gray, & Burgess, 2007).

Executive attention is conceptualized as an interaction between memory and attention in the service of complex cognition. Some researchers propose that this interaction represents attentionally-guided search and selection of memory (e.g. Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Healy & Miyake, 2009; Kane & Engle, 2000). Others have argued that executive attention represents the successful maintenance of attentional-relevant goals in a highly accessible state (e.g., Kane & Engle, 2003; Lavie, Hirst, de Fockert, & Viding, 2004). The present perspective is largely agnostic as to whether attention causes memory, or memory causes attention. Rather, I assume that either or both perspectives may be valid.

Individual differences in executive attention are typically studied using low-memory-load attention control tasks (e.g., Roberts, Hager, & Heron, 1994). These tasks require test takers to resolve competition between goal-relevant and inappropriate (often prepotent) responses. Relevant examples include (1) the anti-saccade task (e.g., Hutchison, 2007; Kane et al., 2001; Unsworth, Schrock & Engle, 2004) in which test takers override the reflexive response of looking toward a peripheral flash, and instead look in the opposite direction, (2) the flanker task (e.g., Heitz & Engle, 2007; Redick & Engle, 2006; Shipstead, Harrison, & Engle, 2012) in which test takers must rapidly report the central item from an array in which flanking items are potentially distracting (e.g., ← ← → ← ←) and (3) the Stroop task (e.g., Hutchison, 2007; Kane & Engle, 2003; Miyake et al., 2000; Shipstead & Broadway, 2012; Unsworth & Spillers, 2010) in which test-takers must state the hue in which a word has been written, rather that overly reading the word (e.g., "BLUE" typed in red ink).

The relationship between working memory tasks and these types of attention control tasks has proven informative to general working memory research (Engle, 2002; Engle & Kane, 2004). At the same time, attention control tasks do not fully capture the essence of executive attention theory. Specifically, Kane, Conway, Hambrick, and Engle (2007) conceptualize executive attention as a domain-general process that is responsible for sustaining the activation of information outside of primary memory and guiding the retrieval of information to which access has been lost. While attention control tasks give researchers a good idea of the efficacy with which a person selects information from the environment, these tasks do not, in and of themselves, inform the researcher as to efficacy with which a person applies attention to "internal" events. For instance, maintaining critical information in primary memory or guiding searches of long term memory. In effect, "executive" attention is a much broader concept than is captured by attention control tasks.

For present purposes, attention control will be construed as the ability to override prepotent responses that have been activated by the environment and will be represented through performance on attention tasks, as described above. This ability, however, is only one component of executive attention. The aspects of individual differences in attention control that are critical to executive attention (and therefore working memory in general) should be apparent across both attention control tasks and more basic memory tasks that are simply intended to measure primary and secondary memory.

Working Memory Tasks

Given the assumptions made by the embedded process model, it is reasonable to assume that different working memory tasks may reflect different mechanisms of working memory. It is therefore understandable if different types of working memory task are not perfectly related. At the same time, due to their measurement of components of a common cognitive system, it is expected that these tasks will be strongly related.

This expectation is not always met. For instance, a great deal of research on working memory is conducted using either the complex span (i.e., memory for lists during distraction) or the n-back (i.e., recognizing that a currently presented item was also presented n-items ago). However, the correlation between individual differences in complex span and n-back performance is, at best, weak (Jaeggi, Buschkuehl et al., 2010; Kane, Conway, Miura, & Colflesh, 2007; Unsworth, Miller et al., 2009). Moreover, these tasks may not even predict the same aspects of higher cognition (Kane, Conway et al., 2007). This is disparity is also apparent in the working memory training literature, where training on n-back tasks has not been found to improve complex span performance (Jaeggi et al., 2008; Jaeggi, Studer-Luethi et al., 2010; Li et al., 2008; Redick et al., 2012; Shipstead, Redick, & Engle, 2012). Thus, when working memory is defined via the n-back, it is unlikely that the results of a given study are applicable to working memory as defined by the complex span (or vice versa).

If working memory is to be conceptualized as an ability that drives the performance of several tasks (Engle, 1999; Kane et al., 2004; Oberauer, 2005), then such findings are disconcerting. In isolation, the absence of a strong relationship between two working memory tasks implies the absence of a common ability. Thus, the lack of correlation between complex span and n-back performance may be taken as evidence that either (1) one task is not a measure working memory or that (2) a general construct does not even exist. Fortunately, this second concern is mitigated by strong relationships between the complex span and other working memory tasks. In particular: The running

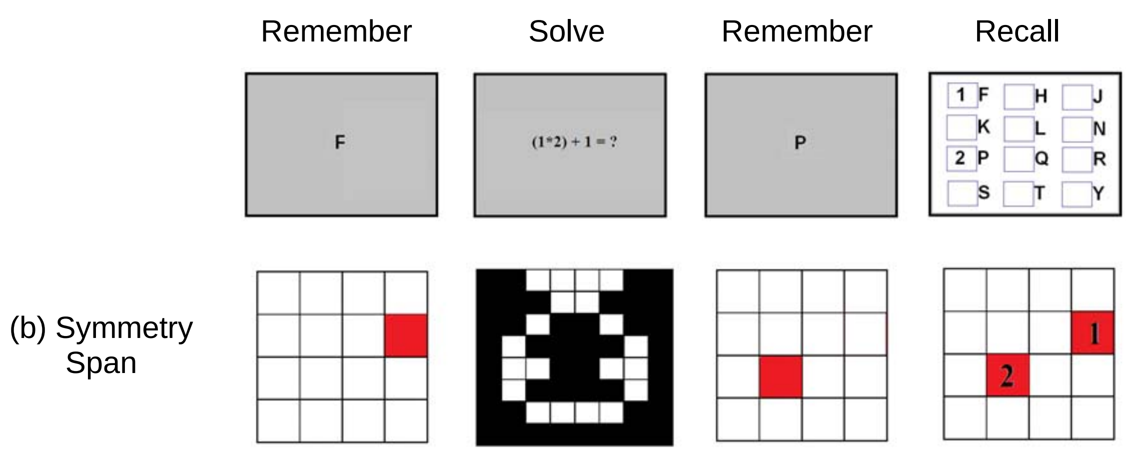


Figure 1. Examples of complex span tasks. Operation span (a) presents a letter, then requires a participant to solve a simple mathematical equation. After several such pairings, the test-taker uses the “recall” screen to indicate the letters that had been presented, in the order that they were originally presented. The Symmetry span (b) presents a spatial location on a grid, followed by a picture that must be judged as symmetrical or asymmetrical. Following several such pairings, the test-taker uses the “recall” screen to indicate which locations had been presented, in the order that they were originally presented.

span and visual arrays tasks.

Complex Span

The complex span task (Daneman & Carpenter, 1980) is a classic measure of individual differences in 'working memory capacity', particularly as these differences relate to complex cognition (cf. Engle & Oransky, 1999). Two variations, known as the operation and symmetry span, are depicted in Figure 1. Like many memory tasks, complex spans require test-takers to remember a series of serially-presented items (e.g., letters, words, spatial locations). Unique to complex span tasks, each to-be-remembered item is followed by a processing task that must be completed before the next item is shown. For the operation span task (Figure 1a), this is a mathematical equation that must be solved. For the symmetry span task (Figure 1b) this is a picture that must be judged as either symmetrical or non-symmetrical. After several pairs of items and processing tasks have been presented (generally 2-7), test-takers attempt to reconstruct the list of items in the order in which they were originally presented.

In general, high complex-span-performers outperform low-performers on attention control tasks (Engle, 2002). This association is interpreted as a reflection of the common need to engage executive attention when performing both complex span and attention control tasks (Engle, 2002; Kane et al., 2007). However, while complex span tasks predict a person's attention control, performance is likely multifaceted.

For instance, high performers on complex span are also less susceptible to buildups of proactive interference that occur over the course of several trials (Kane & Engle, 2000; Friedman & Miyake, 2004; see also May, Hasher, & Kane, 1999). More importantly, complex span tasks best predict performance on higher cognition tasks when proactive interference is high (Bunting, 2006; Lustig, May, & Hasher, 2001). In other words, the predictive powers of complex span tasks seem to be partially determined by the ability to perform searches of secondary memory, particularly when the need to minimize proactive interference is at a premium (Unsworth & Engle, 2007c).

Although it might be argued that executive attention is responsible for guiding these searches, Unsworth and Spillers (2010) found that attention control and secondary memory are not only dissociable, but each also explains a portion of the relationship between complex span performance and fluid intelligence. At the same time, attention control and secondary memory did not fully explain the relationship between working memory and fluid intelligence. This residual relationship was attributed to primary memory (which was not measured by Unsworth & Spillers, 2010). Indeed, separate studies (Unsworth & Engle, 2007b; Unsworth, Spillers, & Brewer, 2010) have found that both the recency (i.e., primary memory) and pre-recency (i.e., secondary memory) components of free recall tasks independently predict complex span performance and contribute to explaining its relationship to higher cognition. Thus, at present it seems that complex span performance may require all three aspects of Cowan's embedded process model.

Running Memory Span

Explanations of why complex span performance relates to higher cognition are varied but often take the interpolated processing task into account. For example, Cowan et al. (2005) proposed that constant interruption from the processing task prevents people from strategically grouping to-be-remembered information into "chunks" and thus allows for a purified measure of working memory capacity. Barrouillet, Bernardin, and Camos

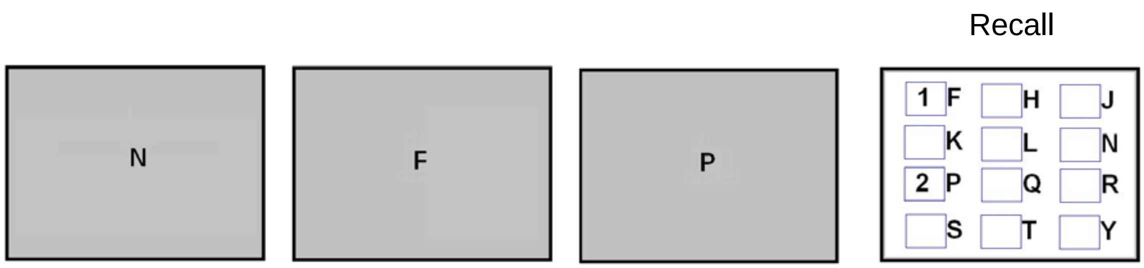


Figure 2. Example of the running memory span task. In this task as series of to-be-remembered items are displayed, one at a time. In this case, it is three letters. After the last item, the recall screen cues the test-taker to remember a subset of these letters. In this case it is the last 2 items.

(2004), on the other hand, argued that people with high working memory capacity are particularly skilled at alternating between solving the processing task and using attention to refresh the decaying traces of to-be-remembered information. Finally, Unsworth and Engle (2006; 2007c) proposed that the act of completing the processing task displaces to-be-remembered information from primary memory, thus requiring retrieval from secondary memory.

Each of these explanations has its own intuitive appeal, and may elucidate important aspects of the complex span task. However, several recent studies have concluded that the same processes that are tapped by complex span tasks are also apparent in running memory span performance (Broadway & Engle, 2010; Cowan et al., 2005; Shipstead, Redick, Hicks and Engle, 2012). Critically, the running span does not include an interpolated processing task (Figure 2). Instead, this task requires test-takers to attend to a series of serially presented items (e.g., letters, words), then recall a specified subset (e.g., the last 3-7 items in the series). Despite obvious differences between these tasks, both Cowan et al. (2005) and Broadway and Engle (2010; also Broadway, 2008) reported that complex and running span tasks predict the same variance in fluid intelligence. Furthermore Shipstead, Redick, Hicks, and Engle (2012) found that these tasks load on the same latent factor. Such results indicate that inferences about complex span performance cannot be readily generalized to the concept of working memory capacity.

However, while the complex and running span are highly related at the latent level, the process that are critical to running span performance may be subject to certain aspects of task-administration. Specifically, studies such as Broadway and Engle (2010) and Shipstead, Redick, Hicks, and Engle (2012) used a running span in which items were presented at the rate of 2 per second. Bunting, Cowan, and Saults. (2006), however, have demonstrated that test-takers recall fewer items when the rate of item presentation is increased from 1 item per second to 4 items per second. Specifically, this occurs when test-takers are required to recall more information than can be maintained in primary memory. This manipulation, however, does not affect performance when test-takers need to recall an amount that can be readily stored in primary memory (i.e., 2-3 items). Bunting et al. (2006) interpret this trend as evidence that speeding the presentation rate affects rehearsal and chunking processes, but does not affect pure storage in primary memory. Whether this purification also prevents retrieval from secondary memory or the presence of executive attention is currently unknown.

Visual Arrays

While the complex span task is often assumed to provide a strong reflection of the executive attention component of working memory (Engle, 2002; Kane et al., 2007), the visual arrays task is almost universally treated as a process-pure reflection of primary memory (Awh, Barton, & Vogel, 2007; Chuderski, Taraday, Nęcka, Smoleń, 2012; Cowan et al., 2005; Fukuda et al., 2010; Luck & Vogel, 1997; McNab & Klingberg,

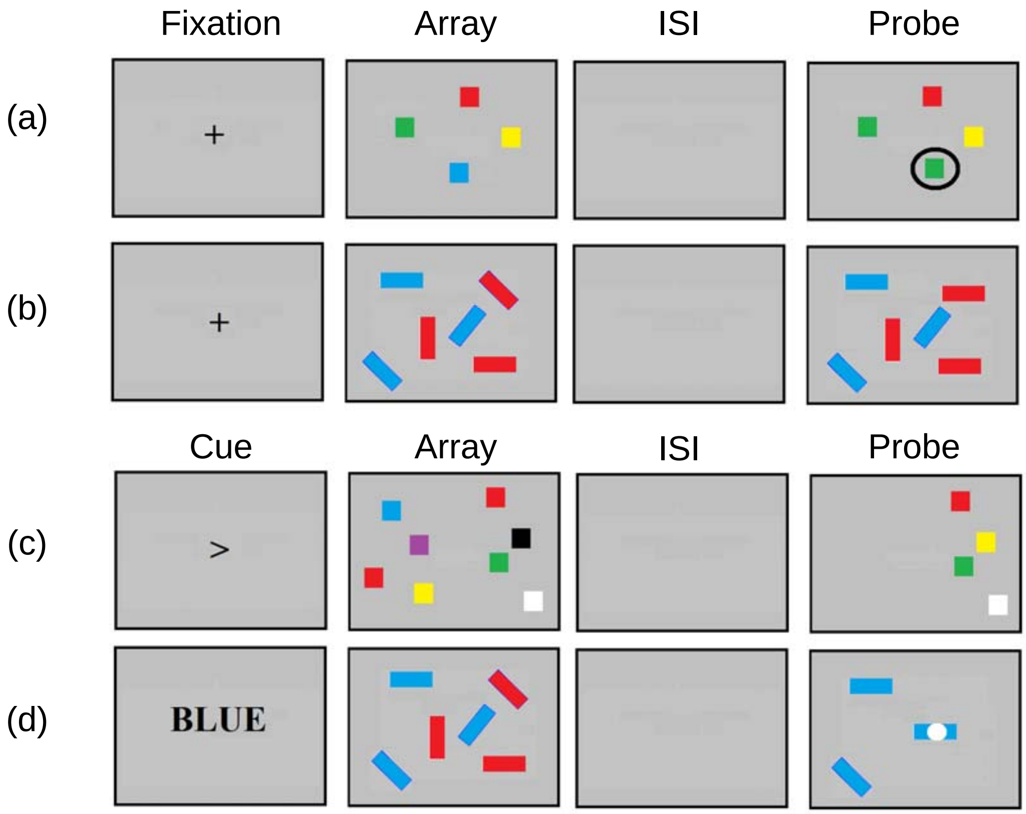


Figure 3. Examples of visual arrays tasks used in the present study. (a) and (b) begin with fixation, which is followed by a target array of to-be-remembered items, then an inter-stimulus interval (ISI). For (a) the test-taker must indicate whether the encircled box has changed colors. For (b) the test-taker must indicate whether any box has changed its orientation. (c) and (d) begin with a cue that indicates which information will be relevant. This is followed by the array of to-be-remembered items, along with distractors. After the ISI, the probe array appears with only cued information presented. For (c) the test-taker must indicate whether any box has changed color. For (d) the test-taker must indicate whether the box with the white dot has changed orientation.

2008; Rouder et al., 2011; Saults & Cowan, 2007). In the classic example of this task (Figure 3a), an array of items (e.g., colored squares) is briefly presented via computer. This is followed by an inter-stimulus interval (ISI), during which the display is blank. The array eventually reappears with one item encircled. The test-taker's task is to indicate whether or not this item has changed, relative to its initial presentation.

On trials in which arrays contain 4 or fewer items, change-detection accuracy is high (Luck & Vogel, 1997). However, beyond this 4-item limit, accuracy progressively declines (Luck & Vogel, 1997; Vogel, Woodman & Luck, 2001). This is interpreted as evidence that to-be-remembered information has exceeded the capacity of primary memory storage. In other words, when the probed object is maintained in primary memory, responses will be accurate. When the probed object is not stored, responses reflect guessing. Assuming a fixed-capacity primary memory, the number of items that can be stored will remain stable across set sizes, while the probability of guessing will increase with set size. Taking these assumptions into account, statistical corrections have been developed that allow researchers to estimate a person's storage capacity, independent of the number of objects contained within an array (Cowan et al., 2005; Pashler, 1988; Rouder et al., 2011; see below, Chapter 2, Methods). Once these adjustments are made, it can be demonstrated that, even through overall accuracy declines as set size increases, the number of objects to which a person accurately responds (*k*) actually remains stable (cf. Cowan et al., 2005).

Although this explanation of visual array performance is generally accepted, there is evidence that controlled attention and retrieval from secondary memory are also important to performance. For instance, recent studies by Fukuda and Vogel (2009, 2011) have demonstrated that performance on the visual arrays task predicts the speed with which people recover from attentional capture. This implies that, despite the lack of any obvious selective component (i.e., in the basic task, all information is relevant; Figure 3a, 3b), visual arrays predicts at least some aspects of attention control.

Additionally, several studies have reported that retrieval from secondary memory is also important to visual arrays performance. For instance, people have difficulty detecting changes when similar information appears on consecutive trials (Makovski &

Jiang, 2008; see also Hartshorne, 2008). This suggests that performance on visual arrays is partially constrained by a person's ability to manage proactive interference arising from no-longer-relevant information (but see Lin & Luck, in press). More directly, Shipstead and Engle (2012) demonstrated that when two trials are presented close to one another in time (relative to previous trials), estimates of storage capacity shrink. On the other hand, estimates of storage capacity increase when two trials are separated in time (relative to previous trials). That is, when time-based cuing (e.g. Unsworth & Engle, 2006) of memory is made difficult, less information can be recalled into immediate awareness. When time-based cuing of memory is made easy, more information can be recalled into immediate awareness.

Thus there is reason to believe that visual arrays performance reflects more than a 3-5 item primary memory. Perhaps even the same set of cognitive mechanisms believed to function in the seemingly disparate complex span and running span tasks.

Further Research and the Present Study

Two latent-level analyses of the same data set will be performed in order to examine the cognitive mechanisms that are common to several working memory tasks.

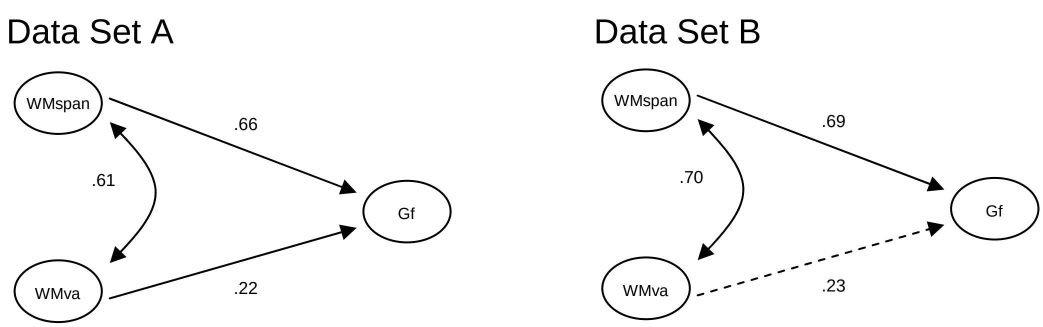


Figure 4. Structural equation models reported by Shipstead, Redick, Hicks, and Engle (2012). WMspan = working memory as defined by span tasks; WMva = working memory as defined by visual arrays tasks; Gf = general fluid intelligence. Dashed lines were not statistically significant.

The first analysis is designed to clarify the similarities and differences between span-based measures of working memory capacity and visual arrays. The second analysis is focused on extracting only the variance that is common to these tasks and examining its relationship to fluid intelligence.

Analysis 1: The Common and Distinct Aspects of Working Memory Tasks

The first round of analyses expand on a recent study by Shipstead, Redick, Hicks, and Engle (2012) that examined the latent relationship between complex span and visual arrays tasks. In this study, confirmatory factor analysis determined that, while complex span and visual arrays are strongly related, they are nonetheless best described through separate latent factors.

Shipstead, Redick, Hicks, and Engle (2012) also examined the relationship of these working memory factors to fluid intelligence via structural equation model. The data were best described by a solution in which visual arrays and complex span were allowed to uniquely predict fluid intelligence (Figure 4)[1]. A subsequent regression analysis revealed that complex span performance accounted for 16-17% of the variance in Gf above-and-beyond processes shared with visual arrays, while, vice-versa, visual arrays performance uniquely accounted for 7% of the variance in Gf.

These results (Shipstead, Redick, Hicks, & Engle, 2012) indicate that complex span and visual arrays have both similarities and differences as measures of cognitive ability. However, there are important issues that these data cannot address. Most

---

[1] Although it is clear in Figure 3 that the path from visual arrays to Gf is not significant for Data Set B, this was argued to be power-related. Note the consistency of the magnitude of the paths, between models.

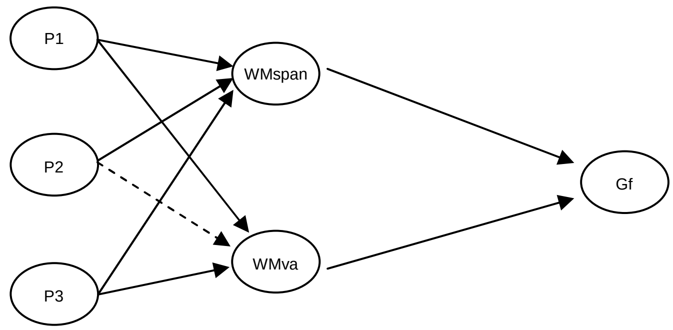


Figure 5. Illustrative model of structural equation model used in Analysis 1. Predictor variables (P1, P2, P3) account for correlation between WMspan and WMva via common prediction of both variables. P1 = predictor 1; P2 = predictor 2; P3 = predictor 3; WMspan = working memory as defined by span tasks; WMva = working memory as defined by visual arrays tasks; Gf = general fluid intelligence. Dashed lines were not statistically significant.

obviously, what accounts for the correlation between these factors and how are they different?

The present study uses structural equation modeling to express the relationship between the two working memory factors via several potential mechanisms. This technique is made explicit in Figure 5. As can be seen, the rightmost aspect of this figure replicates the logic of Figure 4. The exception is that a new level of predictor variables has been added on the right hand side (i.e., P1, P2, and P3[2]). Additionally, there is no explicit correlation between WMspan (working memory - span tasks) and WMva (working memory - visual arrays tasks). Rather the correlation is implied by the predictor variables. In this figure, P1 and P3 each have significant paths to both WMspan and WMva. Thus it could be confidently stated that they are common to both of the working memory factors and thus contribute to the correlation between the two. P2, on the other

---

[2] From this point forward, abbreviations (e.g., WM, PM, Gf) will refer to factors presented in models, while the general concepts that these factors are intended to represent will continue to be referred to by proper names (e.g. working memory, primary memory, fluid intelligence)

hand, only predicts WMspan. While this factor describes variance in WMspan, it does not predict WMva. In effect, it does not account for the relationship between WMspan and WMva.

In place of P1, P2 and P3, three factors will be formed based upon current assumptions regarding the embedded process model. These will be PM (primary memory), SM (secondary memory) and either ATTN (attention control) or ExATTN (executive attention). Although many tasks will be used, PM and SM will be largely defined by the free recall scoring method of Tulving and Colotla (1970). The full procedure will be detailed below; however, primary memory roughly corresponds to the recency portion of recall, while secondary memory roughly corresponds to the pre-recency portion. Attention control will be measured using traditional selective attention tasks that are believed to carry low memory loads (e.g., Roberts, Hager, & Heron, 1994). This factor will thus be construed as the ability to engage task-relevant behaviors, in the face of prepotent influence. The executive attention factor, on the other hand, will be formed by allowing the memory tasks to cross-load onto the attention factor. This will create a factor that represents attention as it operates in memory tasks. As a consequence, whenever ExATTN appears in a model, PM and SM will be memory variables that are independent of attention-related variance.

Shipstead, Redick, Hicks, and Engle (2012) created their visual arrays factor using a single type of visual arrays task (see Figure 3a). In the present analysis, four types of visual arrays task will be used. This allows for a greater variety of change detection demands and furthermore allows for a separate test of the hypothesized mechanisms of visual arrays. In particular, two visual arrays tasks (Figure 3c, 3d) include a selective attention component (arrow pointing to critical information in one task, attending to only critical colors in another; see Luck & Vercera, 2002; Vogel, McCollough & Machizawa, 2005; Vogel, Woodman, & Luck, 2005). The logic of this component is that, to the degree that a person is not able to use attention to selectively filter out irrelevant information, primary memory will be occupied by irrelevant information.

If the results of Fukuda and Vogel (2009; 2011) do indeed indicate that visual arrays performance reflects attention control, all four visual arrays tasks should be explained by one common factor: Attention will be important to task performance, regardless of whether selection is required. On the other hand, if standard visual arrays is a strict primary memory task, a two factor solution should obtain, with all four tasks loading a common factor (i.e., primary memory), but the selective versions also loading on a separate task-specific factor (i.e., attention control).

Analysis 2: The Relationship of Common Variance to Fluid Intelligence

The second analysis is designed to extend the work of Cowan et al. (2005) who, unlike Shipstead, Redick, Hicks, and Engle (2012), report a complete overlap of predictive power among the complex span, running memory and visual arrays tasks. Although the first analysis of the present study does find that working memory span and visual arrays load on distinct factors, an alternate model will be created in which these tasks load on a common factor, along with separate task-specific factors. Key to this analysis will be the inclusion of a rapid running digit span task (Cowan et al., 2005; Bunting, Cowan, & Saults, 2006).

The rapid running digit span displays to-be-remembered items at a rate of four-per-second, via headphones. After up to 20 digits have been played, the test-taker is cued to remember the last 6. This contrasts with a slower running letter span that is used in the first analysis, which features shorter lists and a slower presentation rate (2 items per second). By the account of Bunting et al. (2006), the rapid running digit span should be less subject to the influence of task-specific strategies and thus provide a relatively pure estimate of the mechanisms involved in working memory capacity.

Cowan et al. (2005) found that the inclusion of rapid running digits in a regression analysis produced a result in which running digits, visual arrays and complex span all predicted the same variance in several aptitude measures (e.g., ACT scores, high school grades). Shipstead, Redick, Hicks, and Engle (2012) argued that this result may have been produced by the inclusion of the visual array and running span in one step of the regression and the complex span tasks in another. Since complex span and running span apparently measure the same latent processes, this would lead to redundancy of prediction. However, if rapid running digits does indeed represent a purified measure of working memory capacity, then its inclusion in the second analyses would not only facilitate the formation of a common working memory factor, but may necessitate it.

Following formation of the common factor, its relationship to fluid intelligence will subsequently be analyzed through PM, SM, and ExATTN factors. This will involve techniques similar to those used to examine the relationship between WMspan and WMva in Analysis 1.

CHAPTER 2

METHOD

Participants

All participants were between the ages of 18-30, had normal or corrected-to-normal vision and had learned English by age 5. Participants were recruited from undergraduate psychology classes at Georgia Tech and Georgia State University, and from the general Atlanta community via Craigslist and newspaper ads. Participants were compensated with $30 per session. Georgia Tech students were given the option of receiving credit toward course requirements.

In total, 273 people consented to participate in a two session study. Twenty-seven, either did not return for a second session or requested to drop out of the study. Twenty-nine were either removed from a session or from further analysis for reasons including disruptive behavior, copying of to-be-remembered items and not following instructions on one or more tasks. Finally, two participants who completed both sessions were removed from further analysis because their demographics sheets indicated that they did not meet our inclusion criteria.

In the final sample of 215 participants the mean age was 22.31 years (SD = 3.70). One hundred four (48%) were female. One hundred twenty nine (60%) indicated that they were currently attending or had graduated from college. Seventy five were from Georgia Tech, 35 were from Georgia State, and the remaining 19 students were from other colleges.

Table 1
Order in which tasks were performed .

	Session	
	1	2
Task	OSpan	SymSpan
	RunLett	RunDigit
	Reasoning Mix	Raven
	VA1	VA3
	LetterSets	NumbSeries
	FRword	FRnumb
	VA2	VA4
	Anti-Saccade	Flanker
	CPA	Split Span
	Digit Span	Stroop
		Beauty Contest

note. Ospan = operation span; RunLett = running letter span; VA1 = visual arrays task 1; Frword = free recall of words; VA2 = visual arrays task 2; CPA = continuous paired associates; SymSpan = symmetry span; RunDigit = running digit span; Raven = Raven's Advanced Progressive Matrices (odd set); VA3 = visual arrays task 3; NumbSeries = Number Series; FRnumb = free recall of numbers; VA4 = visual arrays task 4; Flanker = arrow flanker task.

Procedure

The study was conducted in two 2-hour sessions that were run on separate days. On average, approximately 6 days passed between sessions. All but 4 participants completed the study within a month of the first session. Participants were run in groups of 1-5.

Table 1 provides the order in which tasks were administered. This study doubled as a general screening procedure. As such, two tasks (i.e., ReasoningMix and Beauty Contest) were part of separate projects and are not discussed further. All tasks were administered via computer. 18" CRT monitors were used.

Working Memory Tasks (Span Tasks)

In all working memory span tasks, participants provided responses via mouse-click. In three tasks (operation span, symmetry span and running letters), items were presented visually. In running digits, items were presented auditorally, via headphones. In all tasks the dependent variable was the number of items recalled in their correct serial positions. Abbreviated names are provided for reference against figures and tables.

Operation span (Ospan). The automated operation span (Unsworth et al., 2005) required participants to remember a series of letters while alternately solving simple mathematical equations. Lists lengths ranged between 3-7 items and were randomly presented. Each list length occurred 3 times.

Symmetry span (SymSpan). The automated symmetry span (Unsworth, Redick et al., 2009) task required participants to remember a series of spatial locations while alternately deciding whether a pattern of blocks was symmetrical. List lengths ranged between 2-5 items. Each list length occurred 3 times.

Running letter span (RunLett). The automated running letter span (Broadway & Engle, 2010) presented a series of 5-9 letters and required participants to remember the last 3-7. Participants were informed of how many items they would need to remember at the beginning of a block of three trials. Blocks were randomly presented. There were a total of 15 trials. Items were presented for 300 ms followed by a 200 ms pause.

Running digit span (RunDigit). The automated digit span (Cowan et al., 2005) presented a series of 12-20 digits and required participants to remember the last 6. Participants performed 18 critical trials. Digits were presented at the rate of four per second via headphones.

Working Memory Tasks (Visual Arrays)

Four variations of the visual arrays task were used. Two tasks explicitly involved a selective attention component (VA3 and VA4) which required participants to ignore specific distractor items. Two did not (VA1 and VA2). In calculating the dependent variable, *k,* "N" was always defined as the number of valid target-items on a screen. Thus, if ten targets-items are presented, but 5 are to-be-ignored, then N equaled 5.

Two tasks required test-takers to respond as to whether a relevant characteristic of a probed item had changed (VA1 and VA4). For these tasks, *k* was calculated using the partial report correction of Cowan et al., (2005): $k = N * (hits + correct\ rejections - 1)$. Two tasks required test-takers to decide whether a relevant characteristic of any item had changed (VA2 and VA3). For these tasks, *k* was calculated using the whole report correction of Pashler (1988): $k = N * (hits - false\ alarms / 1 - false\ alarms)$. In all cases, *k* was first computed for each set size, and then the set sizes were averaged.

In all tasks, participants responded via keypress. 'S' (same) and 'D' (different) stickers were placed on the keyboard keys 'f' and 'j'. Set sizes, as well as change and no-change trials were randomly distributed. At a distance of 45 cm items were presented within a silver 19.1° × 14.3° field. Items were separated from one another by at least 2° and were all at least 2° from a central fixation point.

VA1 (color judgment; Figure 3a). Array sets were 4, 6, or 8 colored blocks. Possible colors included white, black, red, yellow, green, blue, and purple. Arrays were presented for 250 ms followed by a 900 ms ISI. Participants responded as to whether or not one encircled item had changed color. 28 trials of each set size were included. 14 were no-change, 14 were change.

VA2 (orientation judgment; Figure 3b). The orientation judgment task was based on one of the conditions used by Luck and Vogel (1997). Arrays consisted of 5 or 7 colored bars, each of which was either horizontal, vertical, or slanted 45° to the right or left. Participants needed to judge whether any bar had changed orientation. Colors included red and blue, and did not change within a trial. 40 trials of each set size were included. 20 were no-change, 20 were change.

VA3 (selective color judgment; Figure 3c). This task was based on Experiment 2 of Vogel, Woodman & Luck (2005). In order to minimize eye movements, the sequence of events in VA3 was speeded, relative to other tasks. Each trial began with a left- or right-pointing arrow at the center of a computer monitor for 100 ms, followed by a 100 ms interval. Next, two equally-sized arrays of colored blocks were presented on the right and left sides of the screen for 100 ms. Each array contained either 4, 6, or 8 items. After a 900 ms delay, the boxes reappeared on the side of the screen to which the arrow had pointed. Participants indicated whether any of these relevant boxes had changed color. 28 trials of each set size were included. 14 were no-change, 14 were change. Seven of each occurred each side of the screen.

VA4 (selective orientation task; Figure 3d). This task is similar to the orientation task listed above. Partial report of an item was used. This item was presented with a white dot superimposed on it. Each trial began with an instruction to attend to either the red or blue items (200ms), followed by a 100 ms interval. Next, 10 or 14 bars were presented for 250 ms. Half of all bars were compatible with the to-be-attended color. Following a 900 ms delay, the to-be-attended bars returned. 40 trials of each set size were included. 20 were change and 20 were no-change.

Primary and Secondary Memory Tasks

Free recall of words (PM_Word; SM_Word). Participants saw a series of 12 nouns, each of which was presented for 750 ms, followed by a 250 ms delay. Following the 12th word, participants were signaled to recall as many words as possible. The end of the recall period (30 seconds) was signaled by a beep that was played via headphones. Due to concern that community participants might have less typing experience than college students, responses were written on a sheet of paper. Participants were not required to recall the words in any order, however, the instructions stressed that recall should begin from the end of the list. Two practice trials were followed by 10 critical trials.

Using the methods of Tulving and Colotla (1970), two dependent variables were extracted from these tasks. If seven or fewer items (either presented or recalled) intervened between the presentation and recall of a given word it was deemed to have been recalled from primary memory (PM_Word). All other correct responses were deemed to have been recalled from secondary memory (SM_Word). Both dependent variables were the average number of words recalled from primary and secondary memory across all critical lists.

Free recall of three-digit numbers (PM_Numb; SM_Numb). This task was the same as FRword, with the exception that participants saw three-digit numbers, rather than words.

Split span free recall (SSblue; SSred). In this task participants (1) saw a series of to-be-remembered grid locations, (2) were momentarily distracted by a mental rotation task, then (3) saw a second series of to-be-remembered locations (see Appendix A).

Each trial began with a 4 × 4 grid in which squares were highlighted in red one-at-a-time. Each item was highlighted for 750 ms, followed by a 250 ms delay. Following the fifth red square, participants saw a capital letter ('F', 'G', 'J', or 'R') that had been rotated by between 45 and 315 degrees. Participants needed to indicate whether the letter was facing in the appropriate direction, or was mirror reversed. Following 1-3 rotation trials a 6 × 6 grid appeared. Squares within the grid were highlighted in blue one-at-a-time. Each item was highlighted for 200 ms, followed by a 50 ms delay.

After the 5th blue item was presented, an empty grid appeared on the screen with either the word "RED" (4 × 4 grid) or "BLUE" (6 × 6 grid) above it. This was a signal to recall either the red or the blue squares. Participants used the mouse to indicate which squares had been highlighted on the most recent trial. In order to prevent liberal responding, participants were only allowed 5 responses per trial. Recall could occur in any order.

The intent of the rotation task was to increase the likelihood that red items would be displaced into secondary memory. The number of rotations was varied to prevent participants from anticipating the presentation of the blue items, and thus minimize strategic grouping of these items. The faster presentation of blue items on a larger grid was also intended to minimize strategic grouping. Finally, instructions requested that participants begin their recall of blue items with the final item.

Thus, it was predicted that recall of red items would largely reflect secondary memory, while the recall of blue items would largely reflect primary memory. 20 trials were performed, half of which required recall of red items. The mix of red and blue recall was pre-randomized in order to prevent participants from anticipating the critical demand of a trial.

Digit Span (DigitSpan). In the digit span task participants saw a series of digits presented at the rate of 4 per second (200 ms presentation; 50 ms interval). Participants began with three trials. Each of these trials consisted of a 2-item list. If two of the three lists were correctly recalled, then three more trials were performed with 3-item lists. This continued until participants either completed three trials with 9-item lists, or were unable to correctly recall 2 lists of a given length (at which point testing ended).

Participants received one point per fully-recalled list. The intent of this all-or-none scoring method (i.e., rather than the method used with the above WM span tasks) was to minimize retrieval from secondary memory (cf. Unsworth & Engle, 2007b). Responses were entered via mouse-click. The dependent variable was the number of lists correctly recalled.

Continuous paired associates (CPA). This task included two types of trial. On "study" trials participants saw a two-digit number paired with an upper case letter (e.g., "18 - Q"). On "test" trials participants saw a previously presented two-digit number above 5 upper case letters (B, N, Q, T, X). Participants used the mouse to click on the letter that had been paired with the given number.

Numbers were not reused within a session. Any previous pairings of a given letter with a number were nullified by the letter's most recent appearance in a study trial. Study to testing of a specific number-letter pairing was separated by 0-5 events (e.g., Lag 0-5). Events could be either study or test trials.

Each lag was tested 5 times. The dependent variable was accuracy at lags of 2-5. This was done with the intent of maximizing the roll of secondary memory in responding (cf. Rowe & Smith, 1973; Unsworth, Brewer, & Spillers, 2011).

Attention Control Tasks

Antisaccade task (AntiSacc). The antisaccade task (Hallet, 1978) was a modified version of the one used by Hutchison (2007; see Appendix B). Each trial began with a "+" fixation which lasted for either 1,000 or 2,000 ms. This was immediately followed by a "*" that flashed on either the right or left hand side of the screen for 300 ms. Participants were required to divert their gaze to the opposite side of the screen where an O or Q was displayed for 100 ms and then masked by "##". The participant was given 5,000 ms to indicate which letter was presented. Responses were made via keypress.

Participants performed 16 practice trials in which the critical letter was presented for 500 ms, followed by 16 practice trials at normal speed. The dependent variable was accuracy on 48 critical trials.

Stroop task. The Stroop (1939) task was based on the task used by Unsworth and Spillers (2010). This task included 486 trials in which participants quickly indicated the hue in which a word was printed (e.g., ink hue: red; word: "BLUE"). Blue, green, and red were used. On 66% of all trials the hue and word were congruent. On the remaining 33% of trials the hue and word were incongruent. Each color and word was used with equal regularity. A self-paced rest break was given every 162 trials. Participants responded by pressing one of three colored stickers that were affixed to keypad keys 1 (green), 2 (blue), and 3 (red). Incorrect responses were followed by a beep played via headphones. The dependent variable was response time differences between congruent and incongruent trials.

Flanker task. The arrow flanker task was based on the task used by Unsworth and Spillers (2010). A fixation point was presented for 900 ms, after which an array of five items was shown. The middle item was always an arrow. The participant's task was to indicate which direction this arrow was pointing. Flanking characters were congruent arrows (e.g., → → → → →), incongruent arrows (e.g., ← ← → ← ←) or neutral items (e.g., ─ ─ → ─ ─). Participants responded with the "z" and "." keys, on which arrow-stickers had been placed. Three blocks of 72 trials were run, giving a total of 72 congruent, 72 incongruent and 72 neutral trials. The dependent variable was incongruent RT minus neutral RT.

General Fluid Intelligence

Raven's advanced progressive matrices (Raven; Raven, 1990; Odd problems). Participants saw a 3×3 matrix in which 8 abstract figures have been placed. Participants chose which of several options belonged in the ninth box. Ten minutes were given to complete 18 problems. The dependent variable was the number of correct responses.

Letter sets (LetterSet; Ekstrom et al., 1976). Participants saw five sets of four-letter sequences. They needed to discover the rule that was common to four of the sets and then indicate which set does not belong. Five minutes were given to complete 30 problems. The dependent variable was the number of correct responses.

Number series (NumSer; Thurstone, 1938). Participants saw a series of numbers and selected which of several options completed the series. Five minutes were given to complete 15 problems. The dependent variable was the number of correct responses.

Data Pre-Screening and Preparation

Response times for the Stroop and flanker tasks were examined for outliers using the non-recursive method of Van Selset and Jolicoeur (1994). Only trials on which a correct response was provided were included. Outliers were replaced with a cutoff score that was based on the total number of valid trials.

For all tasks, univariate outliers were defined as an individual mean score that exceeded 3.5 standard deviations from the respective grand mean. Out of a total of more than 4,700 observations, 12 met this criterion. These scores were replaced with the cutoff value. Multivariate normality was tested using Maridia's PK. This test indicated that multivariate kurtosis was 1.01, which is considered normal (Byrne, 2008).

Finally, there were a total of 15 missing values. This was attributable to equipment malfunction and experimenter error. Because these values totaled less than 1% of the entire matrix of scores (typical cutoff is < 10%; Kline, 1998) and because there was no reason to believe that missing values were systematically related to a specific portion of the distribution (i.e., Missing Completely At Random; Allison, 2002), multiple imputation was used to replace the missing values. Imputation was favored over deletion in order to preserve power.

Exploratory Factor Analysis

Although the present models were theoretically motivated, exploratory factor analysis (EFA) was conducted in order to allow for observations and hypotheses that were independent of preexperimental assumptions. Principal axis factoring was used for extraction, along with varimax rotation. Varimax was preferred due to its tendency to distribute variance across factors, rather than applying it to a general factor (Loehlin, 2004).

Fit Statistics

Several fit statistics are reported for each model. In addition to reporting chi-square (χ^2) and remaining degrees of freedom (*df*), χ^2/df served as a "badness-of-fit" statistic. Values above 2 are assumed to reflect a significant difference between the observed and reproduced covariance matrices. Additional statistics include root mean square error of approximation (RMSEA), which estimates the model fit to the population, and standardized root mean square residual (SRMR), which reflects average deviation of the reproduced covariance matrix from the observed. For these indices, values below .05 are ideal, but up to .08 is acceptable (Browne & Cudeck, 1993; Kline, 1998). Non-normed fit index (NNFI) and comparative fit index (CFI) compare the hypothesized model relative to one in which observed variables are assumed to be uncorrelated. For these statistics, values above .95 represent a good fit (Hu & Bentler, 1999). Model parsimony was assessed through Akaike's (1987) information criterion (AIC), which takes in account both goodness-of-fit and number of to-be-estimated parameters. Smaller values are preferred.

CHAPTER 2

RESULTS AND DISCUSSION

Table 2

Descriptive Statistics

Task	M	SD	Range	Skew	Kurtosis	I.C.
1. OSpan	56.11	13.64	9.00 - 75.00	-.94	.66	.84[a]
2. SymSpan	26.46	8.74	3.00 - 42.00	-.50	-.30	.84[a]
3. RunLett	39.57	12.20	9.00 - 73.00	-.16	-.14	.81[a]
4. RunDigit	53.60	18.12	3.00 - 94.00	-.45	.18	.88[a]
5. VA1	3.52	1.18	-.65 - 5.71	-1.17	1.86	.78[a]
6. VA2	3.04	1.34	-1.66 - 5.45	-.73	.55	.74[a]
7. VA3	2.01	1.44	-3.31 - 4.91	-.63	.76	.54[a]
8. VA4	1.66	1.23	-.80 - 4.88	.15	-.39	.70[a]
9. PM_Word	2.63	.67	.60 - 4.20	-.32	-.07	.80[a]
10. PM_Numb	1.54	.43	.03 - 3.00	-.36	.73	.68[a]
11. DigitSpan	13.37	4.06	3.00 - 23.00	-.17	.10	.80[a]
12. SSblue	25.43	8.40	4.00 - 45.00	-.11	-.35	.86[a]
13. SM_Word	1.90	.85	.00 -4.92	.75	1.06	.78[a]
14. SM_Numb	.67	.43	.00 - 2.18	.88	.69	.65[a]
15. CPA	.43	.18	.00 - .90	.31	-.06	.80[a]
16. SSred	27.82	6.94	11.00 - 48	.11	-.32	.73[a]
17. AntiSacc	.74	.15	.21 - 1.00	-.67	-.16	.85[a]
18. Flanker	96.88	49.23	12.73 - 273.52	1.23	1.74	.81[b]
19. Stroop	138.96	85.37	-39.66 - 453.54	.90	.86	.92[b]
20. Raven	8.92	3.77	1.00 - 17.00	-.24	-.82	.80[a]
21. LetterSet	15.12	4.54	3.00 - 25.00	-.38	-.22	.82[a]
22. NumSer	8.73	3.08	1.00 - 15.00	-.37	-.22	.76[a]

note. Ospan = Operation Span; SymSpan = Symmetry Span; RunLett = Running Letter Span; RunDigit = Running Digit Span; VA1 = Visual Arrays 1; VA2 = Visual Arrays 2; VA3 = Visual Arrays 3; VA4 = Visual Arrays 4; PM_Word = Primary Memory, Free Recall, Words; PM_Numb = Primary Memory, Free Recall, Numbers; SSblue = Split Span, Blue Squares; SM_Word = Secondary Memory, Free Recall, Words; SM_Numb = Secondary Memory, Free Recall, Numbers; CPA = Continuous Paired Associate; SSred = Split Span Red; AntiSacc = Antisaccade; Flanker = Arrow Flanker; NumSer = Number Series; I.C. = Internal Consistency; a = Cronbach's Alpha; b = Odd-Even Split-Half Reliability.

Table 3

Correlations among all tasks

Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1. OSpan	-																					
2. SymSpan	.52	-																				
3. RunLett	.49	.45	-																			
4. RunDigit	.42	.36	.65	-																		
5. VA1	.30	.39	.30	.40	-																	
6. VA2	.27	.38	.29	.39	.59	-																
7. VA3	.21	.32	.27	.35	.50	.42	-															
8. VA4	.23	.36	.36	.42	.44	.59	.54	-														
9. PM_Word	.31	.40	.54	.47	.38	.35	.27	.38	-													
10. PM_Numb	.23	.34	.34	.42	.31	.24	.35	.31	.42	-												
11. DigitSpan	.30	.29	.65	.54	.37	.26	.30	.30	.41	.33	-											
12. SSblue	.29	.59	.41	.43	.53	.54	.42	.49	.49	.32	.33	-										
13. SM_Word	.24	.25	.28	.18	.27	.25	.21	.22	.11	.13	.17	.20	-									
14. SM_Numb	.21	.21	.19	.14	.16	.16	.21	.14	-.03	-.03	.22	.12	.27	-								
15. CPA	.26	.29	.39	.36	.34	.33	.30	.42	.41	.28	.37	.38	.30	.30	-							
16. SSred	.32	.54	.31	.32	.45	.38	.33	.43	.35	.27	.21	.50	.33	.30	.34	-						
17. AntiSacc	.23	.40	.33	.34	.41	.42	.44	.45	.39	.28	.31	.46	.23	.12	.39	.43	-					
18. Flanker	-.18	-.23	-.16	-.18	-.25	-.21	-.25	-.22	-.19	-.19	-.06	-.24	-.11	-.06	-.24	-.23	-.28	-				
19. Stroop	-.17	-.24	-.12	-.04	-.12	-.09	-.14	-.22	-.08	-.03	-.03	-.15	-.07	-.01	-.07	-.15	-.13	.23	-			
20. Raven	.34	.49	.51	.51	.45	.41	.39	.43	.41	.30	.34	.54	.33	.18	.38	.41	.44	-.23	-.07	-		
21. LetterSet	.29	.41	.50	.48	.36	.34	.30	.37	.49	.38	.40	.44	.28	.11	.37	.36	.37	-.09	-.10	.54	-	
22. NumSer	.30	.41	.51	.43	.38	.37	.31	.36	.42	.32	.39	.47	.30	.20	.39	.34	.36	-.15	-.08	.58	.54	-

note. Ospan = Operation Span; SymSpan = Symmetry Span; RunLett = Running Letter Span; RunDigit = Running Digit Span; VA1 = Visual Arrays 1; VA2 = Visual Arrays 2; VA3 = Visual Arrays 3; VA4 = Visual Arrays 4; PM_Word = Primary Memory, Free Recall, Words; PM_Numb = Primary Memory, Free Recall, Numbers; SSblue = Split Span, Blue Squares; SM_Word = Secondary Memory, Free Recall, Words; SM_Numb = Secondary Memory, Free Recall, Numbers; CPA = Continuous Paired Associate; SSred = Split Span Red, AntiSacc = Antisaccade; Flanker = Arrow Flanker; NumSer = Number Series; NumSer = Number Series.

Descriptive statistics are displayed on Table 2 and correlations among tasks are available on Table 3. Extreme skew is indicated by a value greater than 3 and extreme kurtosis is indicated by a value greater than 10 (Kline, 1998). None of the values exceeded these cutoffs.

Cronbach's alpha was calculated for OSpan, SymSpan, and RunLett using the procedure of Kane et al. (2004) in which the first, second, and third presentations of each list length were summed and then entered into the analysis. For the visual arrays tasks, *k* at each set size was entered into the analysis. Across tasks, internal consistency was generally good, with the exception of VA3 (Table 1). However, the simple correlations between VA3 and all other tasks were generally similar to the other three visual arrays tasks. Moreover, a consistency score was generated across all four visual arrays tasks, which produced a Cronbach's alpha of .83. Thus, it is apparent that even though one task is somewhat unstable, all four tasks are united by a common factor. VA3 was therefore retained for further analysis.

One potential concern regards minimum scores on the visual arrays tasks (particularly VA2 and VA3). Extremely negative values (< -1) on these tasks may indicate that certain participants had misunderstood instructions and reversed the response keys. These participants would thus be candidates for removal from further analysis. The data were searched for cases in which a participant had consistently negative *k* values across all four visual arrays scores (all four tasks < -1). No participant met this criterion. Negative *k* values were therefore interpreted as random noise associated with participants whose true *k* score is at, or near, zero (i.e., more prone to guessing; see Shipstead, Redick, Hicks, & Engle, 2012).

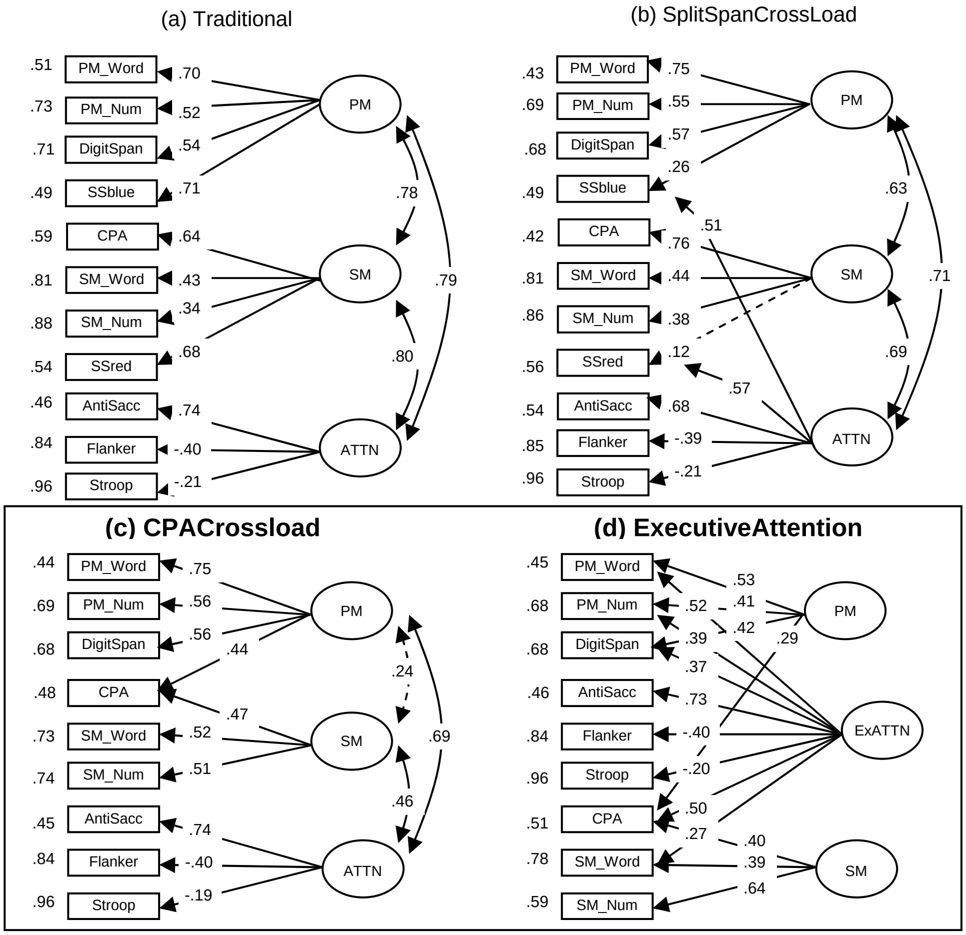


Figure 6. Confirmatory factor analyses for primary memory (PM), secondary memory (SM) and executive attention (ExATTN). PM_Word = Primary memory, free recall, words; PM_Numb = Primary memory, free recall, numbers; SSblue = Split span, blue squares; CPA = Continuous paired associates; SM_Word = Secondary memory, free recall, words; SM_Numb = Secondary memory, free recall, numbers; SSred = Split span red squares; AntiSacc = antisaccade; Dashed lines are not significant at the .05 level. Models inside the box were retained for further analysis.

Table 4

Modeling Memory and Attention

	χ2	df	χ^2/df	RMSEA	SRMR	NNFI	CFI	AIC
Traditional	88.56	41	2.16	.07	.06	.92	.94	138.56
SplitSpanCrossload	71.35	39	1.83	.06	.06	.94	.96	125.35
CPACrossload	**32.96**	**23**	**1.43**	**.05**	**.05**	**.96**	**.97**	**76.96**
ExecutiveAttention	**31.33**	**21**	**1.49**	**.05**	**.05**	**.95**	**.97**	**79.33**

note. CPACrossload = Continuous paired associates crossloaded. Models in bold are preferred.

Initial Confirmatory Analyses

Before commencing the main analyses, models of memory and attention were developed. These models served as the predictor variables in subsequent structural equation models (i.e., P1, P2, and P3 in Figure 5). The first series of models (Figure 6a-c) delineated primary memory, secondary memory, and attention control. The second (Figure 6d) introduced an executive attention factor by allowing the memory tasks to load on the attention factor (cf. Friedman et al., 2008; McVay & Kane, 2012).

Primary Memory, Secondary Memory, and Attention Control

The model labeled *Traditional* on Figure 6a displays the primary memory, secondary memory and attention tasks distributed among three factors. The initial division of memory tasks was specifically based upon the traditional assumption that primary memory reflects the amount of information a person can simply maintain at any one instant, while secondary memory reflects retrieval from beyond primary memory, or following a distraction (e.g., Tulving & Colotla, 1970; Unsworth & Engle, 2007c; Unsworth, Spillers, & Brewer, 2010; Waugh & Norman, 1965). The fit statistics (Table 4), however, were sub-optimal.

The model was thus adjusted within two a priori constraints. First, since the primary and secondary memory components of free recall are the traditional measures of these memory systems (Tulving & Colotla, 1970; Watkins, 1974), they were required to load on separate factors. Second, primary and secondary memory components of free recall generally show little-to-no correlation (Engle, 1999; Unsworth, Spillers, & Brewer, 2010). This trend can be seen in the present data by examining the relationship of

PM_Word and PM_Numb to SM_Word and SM_Numb on Table 3. Thus, weaker correlations between the primary and secondary memory factors are preferred.

On these points, the EFA (Table 5) is informative. The first factor largely reflected primary memory, as indicated by the loadings of PM_Word and PM_Numb. The second factor reflected secondary memory, as indicated by the loadings of SM_Word and SM_Numb. Finally, antisaccade, flanker and Stroop loaded on the third factor, indicating that it reflected attention control.

The first adjustment to the model allowed SSblue and SSred to cross load on attention, which is consistent with the EFA. The resulting model is displayed in Figure 6b (SplitSpanCrossload). Both tasks loaded more strongly on the attention factor than either of their respective memory factors. Although, the fit of this model was good (Table

Table 5
Exploratory Factor Analysis for Primary Memory, Secondary Memory and Attention Control

Task	Factor 1	Factor 2	Factor 3
PM_Word	**.74**	-.02	.21
PM_Numb	**.54**	.00	.15
DigitSpan	**.59**	.27	-.08
SSblue	**.53**	.18	**.42**
SM_Word	.14	**.40**	.19
SM_Numb	-.01	**.75**	-.02
CPA	**.47**	**.39**	.20
SSred	**.33**	**.39**	**.47**
AntiSaccade	**.45**	.20	**.42**
Flanker	-.15	-.06	**-.45**
Stroop	-.01	-.02	**-.34**

note. PM_Word = Primary memory, free recall, words; PM_Numb = Primary memory, free recall, numbers; SSblue = Split span blue squares; SM_Word = Secondary memory word; SM_Numb = Secondary Memroy Number; CPA = Continous paired assoiates; SSred = Split span red squares.

4), it creates conceptual confusion. Specifically, the split span tasks do not contain a component of selection in the face of distraction. Thus, loading these tasks on the ATTN would blur the distinction between memory and attention, and prevent extraction of an unqualified attention control factor. The split span tasks were therefore dropped from the model.

Dropping the split span tasks led to an acceptable fit to the data (model not presented; χ^2/df = 1.69; RMSEA = .06). However, the EFA (Table 5) also indicated that CPA and SSred reflect primary and secondary memory to roughly equal extents. Both of these tasks had been designed to minimize the role of a primary memory system that reflected simple storage. Specifically (and as outlined in the Methods section), lags of 0 and 1 were removed from the CPA, meaning that between the study and test of a given number-letter pair, 2-5 pairs were either studied or tested (4-10 items). SSred, on the other hand, was followed by a letter rotation task and 5 more to-be-remembered items (i.e., SSblue). In both cases, intervening information should have been sufficient to displace the contents of limited-capacity primary memory.

The relationship between primary memory and CPA is, therefore, curious if one assumes that primary memory is a passive storage system. However, this relationship is principled within perspectives that assume primary memory actively maintains access to critical information (rather than passively storing the most recent information; e.g., Oberauer et al., 2007). CPA was therefore allowed to cross load on both the primary and secondary memory factors. As can be seen on Figure 6c (*CPACrossload*), both loadings were significant and the fit was good (Table 4). Moreover, CPA loaded evenly on both

PM and SM, suggesting that both of these aspects of memory are important to CPA, even at longer lags.

Relative to the initial model (Figure 6a), the correlation between PM and SM is noticeably reduced to the point of non-significance (from .78 to .24). Thus, this path brings the correlation between PM and SM in line with previous studies involving latent-level analysis of primary and secondary memory (Unsworth & Engle, 2007b; Unsworth, Spillers, & Brewer, 2010). CPACrossload was therefore the preferred model for examining the relationships between primary memory, secondary memory and attention control.

Primary Memory, Secondary Memory, and Executive Attention

Executive attention is conceptualized as a synergistic relationship between attention and memory processes (cf. Kane et al., 2007), and should thus be present in both attention control and memory tasks. In Figure 6c this is represented through the strong correlations between ATTN and the two memory factors.

From an operational perspective, the model in Figure 6d forms an executive attention factor by allowing all memory tasks to cross-load both on the attention factor (ExATTN) and their respective PM or SM factors. This method is consistent with previous studies conducted by McVay and Kane (2012) and Friedman et al. (2008). The resulting model fit well (Table 4) and was thus retained for further analyses[3].

---

[3] Note in Figure 9d that SM_Numb did not load significantly on ExATTN and this path was thus excluded.

Table 6
Exploratory Factor Analysis for Working Memory Tasks.

Task	Factor 1	Factor 2
OSpan	.17	**.63**
SymSpan	**.35**	**.52**
RunLett (slower)	.17	**.81**
RunDigit (rapid)	**.34**	**.64**
VA1	**.67**	.26
VA2	**.73**	.22
VA3	**.63**	.19
VA4	**.70**	.25

note . OSpan = Operation Span; SymSpan = Symmetry Span; RunLett = Running Letter Span; RunDigit = Running Digit Span; VA = Visual Arrays. Loadings above .3 are in bold.

Analysis 1: The Common and Distinct Aspects of Working Memory Span and Visual Arrays tasks

The first series of structural equation models examined the relationship between working memory span tasks and visual arrays tasks in terms of the memory and attention models in Figure 6c and 6d. The first steps in this analyses (Figure 7a-c) were to verify that, within the present data set, working memory span and visual arrays tasks do indeed load on separate factors (Shipstead, Redick, Hicks, & Engle, 2012). Secondarily, I tested whether the introduction of filtering components to the visual arrays tasks introduced processes that were otherwise absent (Figure 7d).

Confirmatory Analysis of the Two-Factor Working Memory Model

The EFA that included all working memory tasks resulted a two-factor solution (Table 6). All visual arrays tasks loaded on the first factor, while the span tasks loaded more strongly on the second factor. Of present interest, VA3 and VA4 did not load separately from VA1 and VA2. This suggests that the inclusion of an attention-filtering

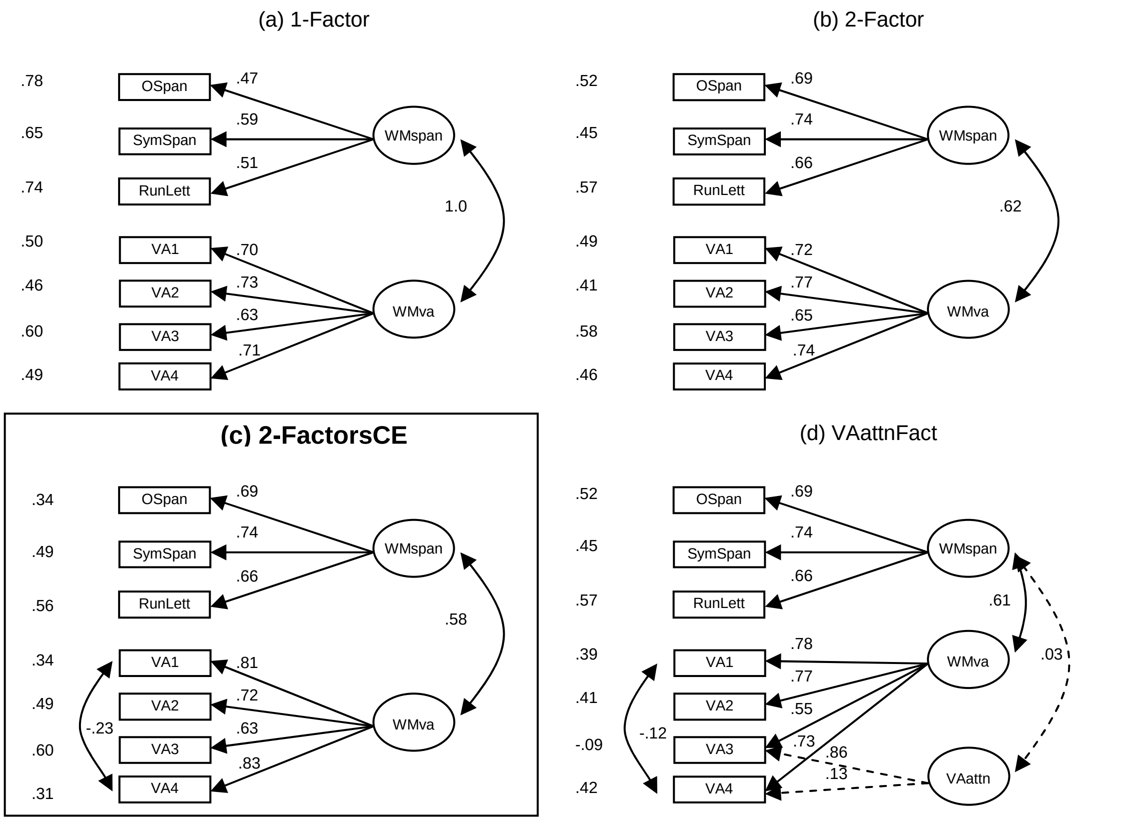


Figure 7. Confirmatory factor analyses involving working memory span (WMspan) and visual arrays tasks (WMva). OSpan = Operation Span; SymSpan = Symmetry Span; RunLett = Running Letter Span; VA = Visual Arrays; 2-FactorsCE = Two Factors Correlated Errors; VAattnFact = Visual Arrays Attention Factor; VAattn = Visual Arrays Residual Attention. Dashed lines are not significant at the .05 level. The box indicates a model that was retained for further analysis.

component did not introduce any processes that are absent from the more basic visual arrays tasks (i.e., attention control is either present or absent in all).

The confirmatory analysis verified that WMspan and WMva tasks formed separate factors. On the basis of previous research (Broadway & Engle, 2010; Shipstead, Redick, Hicks, & Engle, in press), OSpan, SymSpan, and RunLett were loaded onto one factor, while the four visual arrays tasks loaded on a second (rapid RunDigit will be examined in Analysis 2).

Table 7
Confirmatory Factor Analyses for Working Memory Tasks

	$\chi 2$	df	χ^2/df	RMSEA	SRMR	NNFI	CFI	AIC
1-Factor	106.60	14	7.61	.18	.09	.83	.88	134.60
2-Factors	30.99	13	2.38	.08	.04	.95	.97	60.99
2-FactorsCE	**13.85**	**12**	**1.15**	**.03**	**.03**	**.99**	**1.00**	**45.85**
VAattnFact	14.70	10	1.47	.05	.03	.99	.99	50.70

note. 2-FactorsCE = Two Factors, Correlated Errors; VAattnFact = Visual Arrays Attention Factor.

In the first model (1-Factor; Figure 7a) the path between WMspan and WMva was fixed at 1. This simulated a 1-factor solution, while maintaining the structure of a 2-factor model. Across all statistics, 1-Factor provided a poor fit to the data (Table 7). Examination of the task loadings reveals lower loadings for the WMspan tasks than for the WMva tasks. This implies that there are aspects of WMspan that are not captured by variance that is common to WMva. Moreover, it replicates Shipstead, Redick, Hicks and Engle (2012) who found that these tasks are best described by separate factors.

Thus, the path between WMspan and WMva was freed (2-Factors; Figure 7b; Table 7). The model fit was improved, as indicated by a significant decrease in χ^2 ($\Delta\chi^2$ = 75.61; p < .001) and a lower AIC. Moreover, the loadings for WMspan tasks were noticeably higher. However, while many fit statistics were acceptable, others were less than optimal (e.g., χ^2/df > 2; RMSEA of .08).

Although the EFA indicated that SymSpan may load on both factors[4], LISREL indicated the presence of negative correlations between the error residuals of VA1 and VA4 as well as VA2 and VA3. These task-pairs contain the same report-type (respectively, partial- and whole-report), but differ in terms of change detection (color vs.

---

[4] A model with SymSpan cross-loaded on both factors was examined, but did not lead to an appreciable change in the fit statistics, relative to the model in Figure 7b.

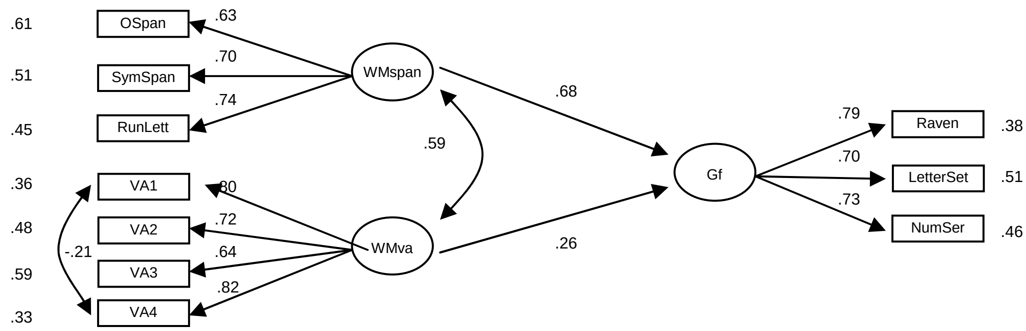


Figure 8. Structural equation model in which working memory span (WMspan) and visual arrays tasks (WMva) predict fluid intelligence (Gf). OSpan = Operation Span; SymSpan = Symmetry Span; RunLett = Running Letter Span; VA = Visual Arrays; Raven = Raven's Advanced Progressive Matrices; NumSer = Number Series.

Table 8

Replication of Shipstead et al. (2012)

	χ2	df	χ^2/df	RMSEA	SRMR	NNFI	CFI	AIC
2-FactsPredictGf	38.23	31	1.23	.03	.04	.99	.99	86.23

note. 2-FactsPredictGf = Two working memory factors predicting general fluid intelligence.

angle) and selective filtering requirements (no-filter vs. filter). This may be an indication that attention demands (i.e., the need to select within a report-type) interacted with change-detection type.

2-Factors was subsequently re-run with correlated errors between the negatively-related tasks (2-FactorsCE; Figure 7c). The relationship between VA1 and VA4 was significant. In the interest of removing this influence from subsequent analyses, this correlated error was retained. The resulting fit statistics for this model were excellent (Table 7) and improved relative to 2-Factors ($\Delta\chi^2$ = 17.14; p < .001).

Confirmatory Analysis of Selective vs. Non-Selective Visual Arrays

Although the EFA indicated that the visual arrays tasks were explained via one factor, VAattnFact (Figure 7d) tested whether the addition of a selective-filtering requirement in VA3 and VA4 introduced a selective attention component that was absent from VA1 and VA2. While the fit statistics (Table 7) indicated this model may be tenable, neither VA3 nor VA4 loaded significantly on the new factor (Table 7d; due to relatively high standard error). Moreover, the new factor was not related to WM span, further indicating that this variance is not critical to the prediction of WM capacity. VAattnFact was therefore not retained: The attention-filtering requirement did not introduce new processes to visual arrays performance. Further analysis will conclude that this is due to the presence of attention control in all visual arrays tasks.

Relating WMspan and WMva to Gf

Before exploring the relationship between WMspan and WMva, I verified that the present data replicated the model of Shipstead, Redick, Hicks, and Engle (2012). As can be seen in Figure 8 (relative to Figure 4), the same basic pattern was present. Both WMspan and WMva predicted Gf. The path from WMspan to Gf was stronger than the path from WMva to Gf. Finally, the two WM factors were strongly correlated. The model fit was good (Table 8).

Memory and Attention as Explanations of the Relationship between WMspan and WMva

Although working memory span and visual arrays tasks load on separate factors, these factors are correlated (Figures 7 & 8) and each predicts Gf (Figure 8). Thus, the next step in this analysis was to understand which memory and attention components best describe each working memory factor and, by extension, explain the correlation between WMspan and WMva.

Both models in Figure 9 are conceptual expansions of Figure 8, and each fit the data well (Table 9). Note that the three rightmost factors (WMspan, WMva, and Gf)

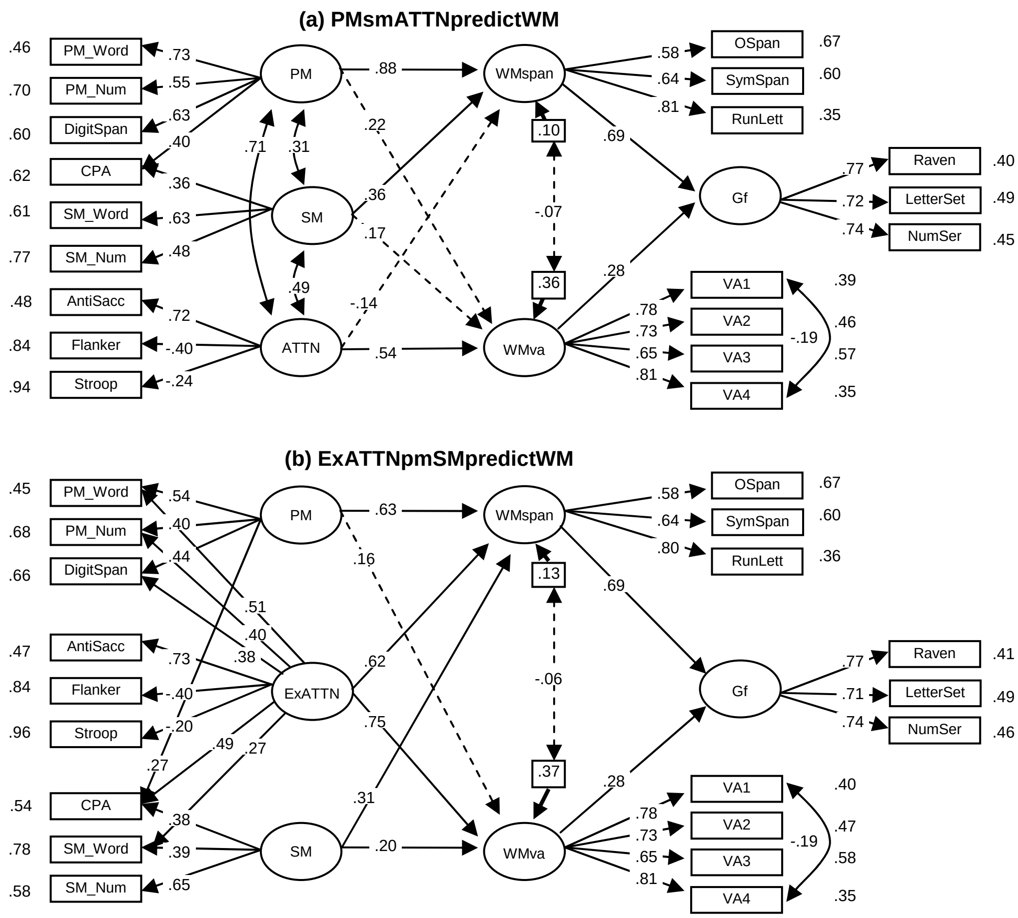


Figure 9. Structural equation models in which primary memory (PM), secondary memory (SM) and either attention control (ATTN), or executive attention (ExATTN) predict working memory span (WMspan) or working memory visual arrays (WMva). OSpan = Operation Span; SymSpan = Symmetry Span; RunLett = Running Letter Span; RunDig = Running Digits; VA = Visual Arrays; NumSer = Number series; PM_Word = Primary memory, free recall, words; PM_Numb = Primary memory, free recall, numbers; SSblue = Split span, blue squares; CPA = Continuous paired associates; SM_Word = Secondary memory, free recall, words; SM_Numb = Secondary memory, free recall, numbers; SSred = Split span red squares; AntiSacc = antisaccade; Dashed lines are not significant at the .05 level.

replicate the basic structure of Figure 8. The leftmost factors, on the other hand, clarify the cognitive mechanisms that are present within WMspan and WMva.

Examining Figure 9a (PMsmATTNpredictWM), the significant paths from both PM and SM to WMspan in indicate that span task performance is most directly explained by both primary and secondary memory (e.g., Unsworth & Engle, 2007c). The significant

Table 9

The Relationship between WMspan and WMva

	$\chi 2$	df	χ^2/df	RMSEA	SRMR	NNFI	CFI	AIC
PMsmATTNpredictWM	202.99	138	1.47	.05	.05	.98	.98	306.99
ExATTNpmSMpredictWM	204.51	148	1.38	.04	.06	.98	.98	288.51

note. PMsmATTNpredictWM = Primary memory, secondary memory and attention control predict working memory; ExATTNpmSMpredictWM = Executive attention, primary memory and secondary memory predict working memory.

path from ATTN to WMva, on the other hand, indicates that visual arrays performance is strongly related to attention control (e.g., Fukuda & Vogel, 2011). However, while each of the leftmost factors had one significant path to either WMspan or WMva, none was directly related to both working memory factors. Thus, neither PM, SM, nor ATTN provide a direct account of the correlation between WMspan and WMva. Rather, it is the relationship of PM and SM to ATTN (and vice versa) that accounts for the correlation between WMspan and WMva. In other words, these working memory factors are united by the executive processes that are apparent across attention and memory tasks.

The executive attention factor (ExATTN), which represents these common processes was therefore included in Figure 9b (ExATTNpmSMpredictWM). In contrast to the first model, significant paths extend from ExATTN to both WMspan and WMva. This not only indicates that executive attention is a strong predictor of both WMspan and WMva, but it also explains a sizeable portion of the correlation between these two types of working memory task.

It is also noteworthy that in Figure 9b both PM and SM retained significant relationships to WMspan. That is, even after attention has been removed from primary and secondary memory, these variables continue to be related to working memory span tasks. This explains why the path from WMspan to Gf is consistently stronger than the path from WMva to Gf: Complex- and running span tasks reflect important aspects of memory, above-and-beyond executive attention, while visual arrays tasks do not (at least not to the same degree).

Correlated Disturbance Terms

Both models in Figure 9 include disturbance terms for WMspan and WMva (i.e., numbers in boxes next to the factors). Disturbance terms represent the portion of a factor that is not explained by the current model. Correlations between disturbance terms further represent between-factor correlations that are not explained by the current model.

In essence, if mechanisms other than primary memory, secondary memory and attention were needed to explain the relationship between WMspan and WMva, the disturbance terms between these two factors would have been correlated. This was not the case. Of note, the disturbance term for WMspan was not significant in either model. Stated simply, primary memory, secondary memory and executive attention provide a complete account of working memory capacity as it is measured by complex- and running span tasks.

Summary

Different types of working memory task can reveal different mechanisms of working memory. Tasks such as the complex- and running memory span are more strongly associated with the memorial aspects of working memory than the attention aspects (e.g., Colom et al., 2008; Cowan et al., 2005; Unsworth & Engle, 2007a; 2007b; 2007c). Visual arrays performance, on the other hand, is strongly related to attention control. However, in keeping with the traditional definition of working memory as a system in which memory and attention interact to produce complex cognition (cf. Miyake

& Shah, 1999) these tasks were mutually explained by ExATTN, a factor that represented attention as it operates within memory (and vice versa).

The finding that working memory span tasks are explained by primary and secondary memory fits within the perspective of Unsworth and Engle (2007a; 2007b; 2007c). These researchers argue that working memory is the product of stable maintenance in primary memory and effective recall from secondary memory. In particular, they contend that attention control stems from stable maintenance of goals in primary memory. This view is not contradicted by the present results. Interestingly, the work of Unsworth and Engle (2007a; 2007b; 2007c) was conducted using complex span tasks as measures of working memory capacity. Thus, their view of working memory may be guided by the type of task that was employed.

The finding that visual arrays is strongly associated with controlled attention supports the work of Fukuda and Vogel (2009; 2011) who have used visual arrays tasks to predict individual differences in the ability to recover from attention capture. This topic will be further explored in the General Discussion.

Finally, it is noteworthy that SM emerged as a common predictor of WMspan and WMva in the second model (i.e., Figure 9b). This finding is supported by previous research that argued for the presence of retrieval in visual arrays tasks (Hartshorne, 2008; Makovski & Jiang, 2008; Shipstead & Engle, 2012). Although it is curious that this path was not significant in Figure 9a, it may indicate that secondary memory retrieval in visual arrays is primarily guided by attention control (which acted as a mediator in that model).

Analysis 2: The Variance that is Common to Working Memory Tasks

The second analysis examined the relationship between working memory capacity and fluid intelligence. The first step in this analysis was to integrate the rapid running digits task into the present framework of working memory (i.e., Figure 7). To preview the results, although running digits was found to be more strongly related to WMspan than to WMva, it nonetheless maintained a significant relationship to both factors. Thus, in the interest of exploring working memory capacity from a general perspective, a common

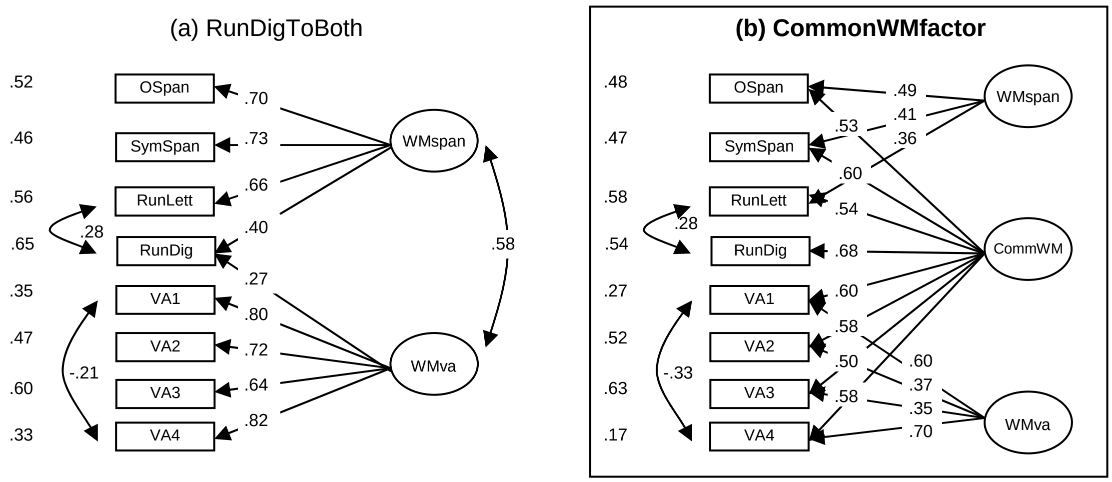


Figure 10. Confirmatory factor analyses involving working memory span (WMspan) and visual arrays tasks (WMva) and common variance (CommWM). OSpan = Operation Span; SymSpan = Symmetry Span; RunLett = Running Letter Span; RunDig = Running Digits; VA = Visual Arrays; Dashed lines are not significant at the .05 level. The box indicates a model that was retained for further analysis.

Table 10
Confirmatory Factor Analysis with Running Digits

	χ2	df	χ^2/df	RMSEA	SRMR	NNFI	CFI	AIC
RunDigToBoth	17.15	16	1.07	.02	.03	1.00	1.00	57.15
CommonWMfactor	**13.49**	**11**	**1.23**	**.03**	**.03**	**.99**	**1.00**	**63.49**

note. RunDigToBoth = Running digits loads on both working memory factors; CommonWMfactor = Common and residual working memory factors formed.

working memory factor was extracted. A subsequent structural equation model demonstrated that it is this common variance that relates working memory capacity to fluid intelligence. Finally, the correlation between working memory and fluid intelligence was decomposed into primary memory, secondary memory, and executive attention, all of which explained a significant portion of the relationship.

Confirmatory Analysis of a Common Working Memory Model

The first step in understanding the relationship between working memory and fluid intelligence involved extracting a common working memory factor. This process also allowed for validation of the rapid running digits task's place among working memory measures. In the initial model (Figure 10a), RunDigit was allowed to simultaneously load on both WM factors. In order to control for task-specific demands, a correlated error was allowed between RunLett and RunDigit. The resulting model fit the data well (RunDigitToBoth; Table 10).

As can be seen in Figure 10a, RunDigit loaded on both WMspan and WMva. This contrasts with the slower RunLett task, which singly loads on WMspan[5]. This provides empirical evidence that speeding the running memory task changes its psychometric properties (Bunting et al., 2006).

---

[5] In the present model, cross loading allowing RunLett results in a non-significant path to WMva (path loading = .05). This replicates Shipstead et al. (in press) who also report a non-significant loading of slower running letters on a visual arrays factor (path loading in that study = .08).

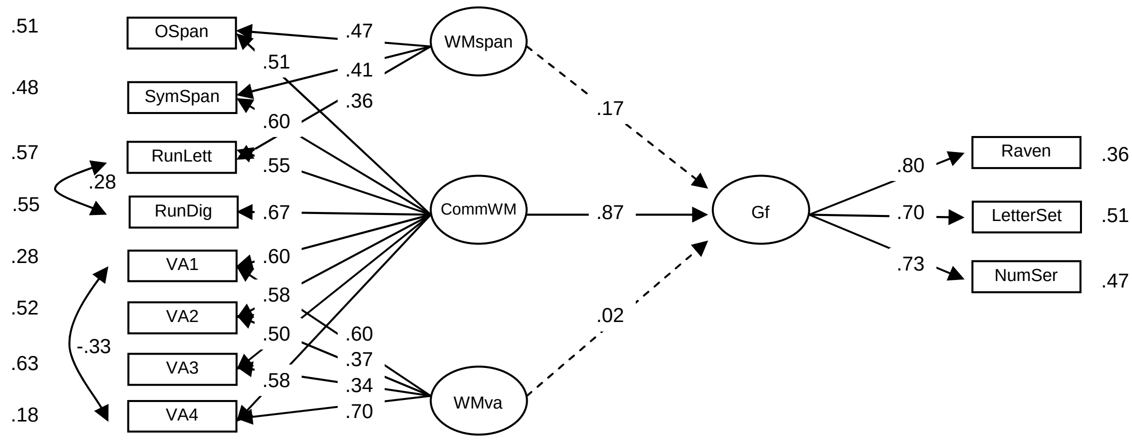


Figure 11. Structural equation model in which working memory span (WMspan) and visual arrays tasks (WMva) as well as common variance (CommWM) predict fluid intelligence (Gf). OSpan = Operation Span; SymSpan = Symmetry Span; RunLett = Running Letter Span; RunDig = Running Digits; VA = Visual Arrays; NumSer = Number series; Dashed lines are not significant at the .05 level.

Table 11

Three Factor Working Memory Model Predicts Fluid Intelligence

	$\chi2$	df	χ^2/df	RMSEA	SRMR	NNFI	CFI	AIC
WMpredictsGf	42.58	46	.93	.00	.04	1.00	1.00	82.58

note . WMpredictsGf= Working memory predicts general fluid intelligence.

Although RunDigit had a lower loading on WMva than on WMspan, both paths were significant. This observation is consistent with the working memory EFA (Table 6) in which RunDigit loaded on both working memory factors. An attempt to remove the path from RunDigit to WMva (model not included) resulted in a significant inflation of χ^2 ($\Delta\chi^2$ = 11.98; p < .001). This suggests the presence of a common working memory factor, which may be obscured by the task-specific differences between working memory span and visual arrays tasks. In the final model (Figure 10b), RunDigit was singly loaded on the common factor (CommWM), while all other tasks cross loaded on CommWM and their respective task-specific factors.

Although the fit for this three-factor model was slightly reduced relative to RunDigitToBoth, it was nonetheless good (CommonWMfactor; Table 10). Importantly, the CommWM factor allows for examination of working memory as it exists across several varieties of working memory task. This model was therefore retained for further analyses.

The Relationship of Common and Residual Working Memory to Fluid Intelligence

Figure 11 presents a structural equation model designed to test which of these three working memory factors (common and two residual) predict fluid intelligence. As can be seen, CommWM and Gf are strongly related, sharing approximately 76% of their variance (obtained by squaring the path). WMspan and WMva, on the other hand, did not predict Gf above-and-beyond their shared variance. Fit statistics were excellent (Table 11).

It should be noted that the factor labeled "CommWM" in Figure 11 is quite similar to a factor that Kane et al. (2004) termed "Executive Attention". This name change is not intended to represent an assumption that this factor is fundamentally changed. Similar to Kane et al. (2004), I assume that CommWM represents modality-independent, executive working memory processes (e.g., the central executive; Baddeley, 1986). The change in name is simply intended to distinguish CommWM from the present ExATTN factor, which was designed to approximate executive attention as it is conceived by Kane et al. (2004). That is, ExATTN is intended to reflect the "synergy" of attention and memory processes. The next analysis allowed for a test of whether this perspective of executive processes is interchangeable with CommWM.

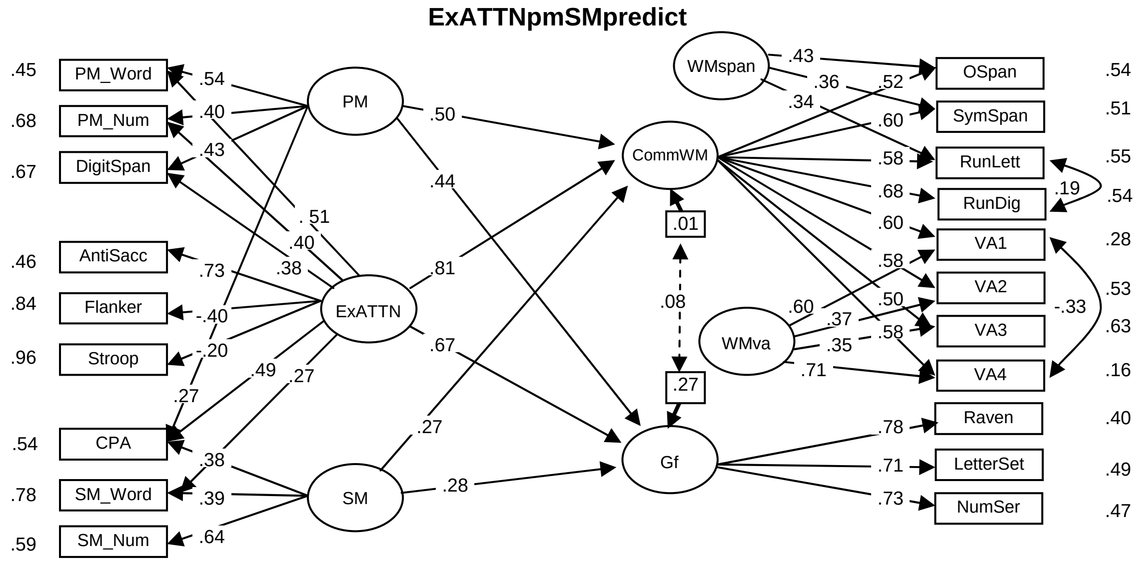


Figure 12. Structural equation model with primary memory (PM), secondary memory (SM) and executive attention (ExATTN) predicting the relationship between variance that is common to all working memory tasks (CommWM) and fluid intelligence (Gf). OSpan = Operation Span; SymSpan = Symmetry Span; RunLett = Running Letter Span; RunDig = Running Digits; VA = Visual Arrays; NumSer = Number series; PM_Word = Primary memory, free recall, words; PM_Numb = Primary memory, free recall, numbers; SSblue = Split span, blue squares; CPA = Continuous paired associates; SM_Word = Secondary memory, free recall, words; SM_Numb = Secondary memory, free recall, numbers; SSred = Split span red squares; AntiSacc = antisaccade; Dashed lines are not significant at the .05 level.

Table 12

Explaining the Relationship between Common Working Memory Variance and Fluid Intelligence

	$\chi 2$	df	χ^2/df	RMSEA	SRMR	NNFI	CFI	AIC
ExATTNpmSMpredict	243.59	172	1.42	.04	.07	.98	.98	319.59

note . ExATTNpmSMpredict = Executive attention, primary memory and secondary memory predict working memory and general fluid intelli

Memory and Attention Explaining the Relationship between Working Memory and Fluid Intelligence

With this relationship in mind, the next step involved explaining the correlation between CommWM and Gf in terms of PM, SM, and ExATTN. The rightmost factors in

Figure 12, represent the same factors included in Figure 11. However, Gf is now displayed below the working memory factors. Additionally, residual WMspan and WMva are included in Figure 12 in order to account for task-specific variance[6]. No paths extend to these factors, as they are not related to Gf (i.e., Figure 11), and thus there is no relationship to explain. As with the first analysis, any significant paths from either PM, SM or ExATTN to both CommWM and Gf is interpreted as explaining a portion of the correlation between CommWM and Gf.

As can be seen in Figure 12, ExATTN was strongly related to CommWM, and thus these factors are extremely similar. Moreover, ExATTN was also strongly related to Gf, indicating that executive attention (as it is presently operationalized) explains a large portion of the relationship between working memory and fluid intelligence.

However, executive attention does not fully explain this relationship. Both PM and SM had significant relationships to CommWM and Gf. Thus, above-and-beyond executive attention, primary and secondary memory are both critical to explaining working memory capacity, as well as its relationship to fluid intelligence. The fit for this model was good (Table 12).

Correlated Disturbance Terms

Similar to the first analysis, the models in Figure 12 included correlations between the disturbance terms for CommWM and Gf. In neither model was this

---

[6] It can be argued that the inclusion of these variables introduces unnecessary complexity to the models. The SEMs in Figure 9 were therefore run two additional times using simplified versions of the model: One in which WMspan and WMva were simply excluded and one in which the need for residual factors was obviated by the exclusion of RunLett, VA2 and VA3. Neither case resulted in substantial changes to the paths from the predictors to CommWM and Gf.

relationship significant, thus indicating that the relationship between working memory capacity and fluid intelligence is fully explained by primary memory, secondary memory and executive attention. Similar to the first analysis, this is due to a non-significant disturbance term for CommWM, which indicates that the predictor variables provide a complete account of individual difference in working memory capacity.

Summary

Analysis 2 found that a common working memory factor can be extracted from complex span, running span and visual arrays. Prior to extracting this factor, it was revealed that the fast running digit span related to both WMspan and WMva. This is consistent with the argument of Cowan and collaborators (Bunting et al., 2006; Cowan et al., 2005) that the rapid presentation of running digits items prevents test-takers from engaging task-specific strategies, and thus allows for a purified measure of the processes responsible for working memory capacity. In turn this would make running span a more general working memory task.

However, while Cowan et al. (2005; Bunting et al., 2006) contend that this purified measure represents primary memory (or more specifically, the focus of attention), the present analyses indicate that working memory capacity and its relationship to fluid intelligence is multiply determined. As represented in Figure 12, ExATTN, PM, and SM uniquely contribute to CommWM and to explaining its relationship to Gf.

Finally, the present analyses indicate that it is the interaction of attention control and memory (i.e., executive attention) that is chiefly responsible for producing working memory capacity and relating it to fluid intelligence. However, both primary- and secondary memory make contributions above-and-beyond this interaction. This indicates that the "executive" processes of working memory are not strictly reflective of attention control but also represent memory that functions independently of attention control (at least as it is reflected by the present tasks).

CHAPTER 4

General Discussion

The first analysis indicated that the processes that define working memory are dependent upon the type of task that is used to measure working memory. Span tasks (complex span and slower running letter span) are more strongly associated with the primary and secondary memory aspects of working memory capacity (e.g., Unworth & Engle, 2007a; 2007b; 2007c). Visual arrays tasks, on the other hand are more strongly associated with the attention control aspects of working memory capacity (e.g., Fukuda & Vogel, 2008; 2011). However, while these different types of working memory tasks are associated with different mechanisms, they are united by executive attention. This factor may be interpreted as attention-related guidance of memory search (e.g. Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Healy & Miyake, 2009; Kane & Engle, 2000), or memory-related maintenance of attention-relevant goals (e.g., Kane & Engle, 2003; Lavie, Hirst, de Fockert, & Viding, 2004), or perhaps both.

The second analysis examined the relationship of working memory capacity to fluid intelligence and found that a factor that is common to span and visual arrays tasks is closely related to fluid intelligence. Separate task-specific factors, however, do not. This is consistent with the findings of Cowan et al. (2005) who reported a one-factor solution when relating a variety of working memory tasks to several measures of achievement. However, while Cowan et al. (2005) interpreted this factor as the focus of attention, the present analyses indicate that the relationship of common working memory variance to fluid intelligence is explained via common relationships to at least three factors: (1) A primary memory factor that represented the amount of information to which a person could maintain access, (2) a secondary memory factor that represented retrieval of information to which access could not be maintained and (3) an executive attention factor, that represented attention as it operates in memory tasks.

At a glance, it is curious that this common working memory factor reflects primary memory, secondary memory and executive attention: Analysis 1 determined that the individual working memory factors are not directly represented by all three of these components. However, it is important to reiterate that Analysis 1 did not find that span tasks are independent of simple attention control. Nor did it find that visual arrays tasks are independent of primary and secondary memory. Rather, it found span tasks related to attention through memory and visual arrays tasks related to memory through attention (Figure 6c). Thus it is not completely surprising that, once task-specific variance was stripped away, working memory was related to both the memory and executive attention variables.

What Does Visual Arrays Performance Represent?

The present analyses indicate that performance on visual arrays tasks is strongly related to a person's attention control. Although such proposals have been made (Cusack, Lehman, Veldsman, & Mitchell, 2009; Fukuda and Vogel, 2009; 2011), they are at odds with the traditional view that visual arrays performance purely represents limited-capacity storage. Thus, the specific relationship between visual arrays and attention was further examined.

Visual Arrays, Attention, and Fluid Intelligence

A follow-up analysis was performed in which models were created based upon an analysis performed by Unsworth, Spillers, and Brewer (2009). In their study two complex

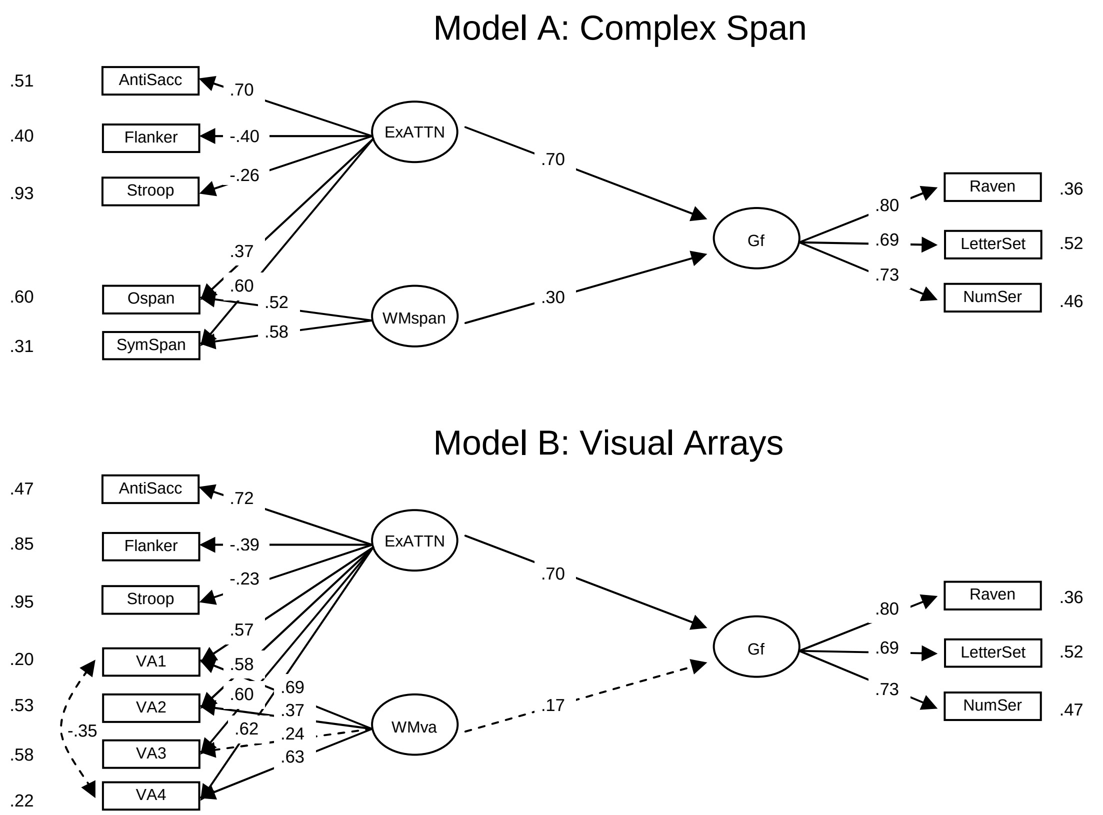


Figure 13. Structural equation models with executive attention (ExATTN) and complex span (WMspan) tasks predicting fluid intelligence (Gf), or (Model B) executive attention and visual arrays (WMva) predicting fluid intelligence. OSpan = Operation Span; SymSpan = Symmetry Span; VA = Visual Arrays; NumSer = Number series; Dashed lines are not significant at the .05 level.

Table 13
Working Memory, Executive Attention and Fluid Intelligence

	$\chi2$	df	χ^2/df	RMSEA	SRMR	NNFI	CFI	AIC
Model A: Complex Span	20.87	16	1.30	.04	.04	.99	.99	60.87
Model B: Visual Arrays	22.65	28	.81	.00	.03	1.01	1.00	76.65

span tasks were cross-loaded on a working memory factor as well as a factor composed of three attention tasks. The relationship between these factors was constrained to zero, thus forcing all attention control-related variance to the attention factor. This study (Unsworth, Spillers, and Brewer, 2009) found that both executive attention and working memory independently predicted fluid intelligence. I replicated this model using the present data (Figure 13; Model A: Complex Span) and the fit was good (Table 13).

Complex span tasks predict fluid intelligence, even after all variance associated with attention control was removed.

Extending this analysis, working memory was redefined as performance in the four visual arrays tasks (Figure 13; Model B: Visual Arrays). As with the previous analysis, visual arrays was cross loaded on the attention factor, thus forcing attention-related variance from visual arrays. The model fit was good (Table 13).

The visual arrays factor that was formed separately from attention control did not predict fluid intelligence. Instead, the entire relationship between visual arrays and fluid intelligence was explained by executive attention. Moreover, as indicated by the non-significant loading of VA3 on WMva and the non-significant correlated error between VA1 and VA4, the removal of attention control seems to have compromised the integrity of the visual arrays factor.

This finding contrasts with the view of visual arrays as a measure of passive working memory storage (Cowan et al., 2005; Chuderski et al., 2012; Luck & Vogel, 1997). Rather, the present data support recent evidence that visual arrays performance is associated with the ability to control attention. Specifically, Fukuda and Vogel (2009, 2011) found that individual differences in visual arrays performance predict people's ability to recover from attention capture. In the present models, antisaccade was the task that most strongly loaded on ATTN, and was thus the task that most strongly defined attention control. Critically, proper performance of this task requires that attention first be captured by a peripheral flash. It is a person's ability to transform this information into the appropriate behavior (e.g., the flash is on the right, look left) that drives performance. Unlike the flanker and Stoop task, efficient early selection (e.g., inhibiting the flanking arrows or activation of the word's semantic representation) would not plausibly improve antisaccade performance. Therefore, the present attention control factor, which is largely defined by the antisaccade task, is particularly well suited to the view of Fukuda and Vogel (2009, 2011), and thus extends their findings.

Visual Arrays, Attention, and Memory

The present results constrain studies that detected proactive interference in visual arrays performance (Hartshorne, 2009; Makovski & Jiang, 2008; Shipstead & Engle, 2012). Evidence of proactive interference has thus far been interpreted as evidence of secondary memory retrieval in visual arrays. However, the present data strongly imply that, to the degree that these studies have detected memory retrieval, it should be interpreted as memory retrieval that is guided by attention (e.g., Craik et al., 1996; Healy, & Miyake, 2009; Kane & Engle, 2000)

Examination of Figure 9a reveals that ATTN is strongly related to PM and SM. From a causal perspective, it might be asserted that attention control contributes to immediate awareness by selecting and maintaining information in primary memory and guiding retrieval from secondary memory. Thus, visual arrays performance may reflect a similar process: Test-takers use selective attention to maintain access to as many items as possible (during the ISI), but also use attention to guide recovery of information to which access could not be maintained. Manipulations that increase the difficulties of such retrievals (e.g., Hartshorne, 2009; Makovski & Jiang, 2008; Shipstead & Engle, 2012) do not influence the difficulty of secondary memory retrieval processes, per se, but influence the challenge that certain contexts pose to attention-guided retrieval.

Visual Arrays, Attention, and Whole Report

Another attention-related account of visual arrays performance to which the present analyses can speak is that of Cusack, Lehman, Veldsman, and Mitchell (2009). These researchers report that visual arrays tasks that require test-takers to recognize changes to specific items (i.e., partial report) predict fluid intelligence, while tasks that require memory for all items (i.e., whole report) tasks do not. These researchers hypothesize that this trend reflects test-takers ability to use attention control to constrain their memory of an array to only a few items. When partial report is used, people with strong attention control (or those who engage appropriate strategies) tend to create stable memories for a few items. People with weak attention control create ephemeral memories for several items. Whole report, on the other hand, requires attending to all information and thus eliminates these differences.

The present study is inconsistent with this hypothesis in two ways. First, although VA1 and VA4 used partial report and VA2 and VA3 used whole report, all tasks generally had equivalent correlations to the fluid intelligence and attention tasks (Table 2). Second, the factor they formed (i.e., the common variance) was predictive of ATTN, ExATTN and Gf. Thus, visual arrays reflects attention and fluid intelligence, regardless of report-type.

A major difference between the present tasks and those of Cusack et al. (2009) is that the present whole report tasks were change-detection based, while Cusack et al. (2009) required participants to report letters that had been displayed in the array. That is, the present study required information to be bound to a specific position (cf. Wheeler & Treisman, 2002), and relied on detection of change, rather than explicit recall. These aspects likely account for the differences in between-study findings. Nonetheless, the current results found a strong relationship between whole-report and attention control. This indicates that attention control does not function in visual arrays by limiting the number of items that are encoded into memory.

The Generality of Visual Arrays

Setting aside the present attention control perspective of visual arrays, this task is often assumed to reflect storage in working memory. However, the generality of that storage system is subject to debate. By Cowan's (1988; 1999; 2001) model, the focus of attention is domain-general and is therefore similarly occupied by both verbal and visuo-spatial information. However, Luck and Vogel (1997; also Vogel, Woodman, & Luck, 2001) argue that visual arrays performance specifically reflects a form of visuo-spatial working memory that is functionally independent of verbal working memory. Luck and Vogel (1997) tested this assumption by requiring participants to remember two digits during certain trials. In short, if visual arrays performance reflects a domain-general mechanism, then requiring test-takers to actively remember a 2-digit number should decrease the number of visual objects that can be stored in working memory during the ISI. It did not. Working memory capacity for visuo-spatial information was stable, thus favoring the dual-storage perspective.

Morey and Cowan (2004; 2005) challenged this interpretation under the assumption that people rely on code-specific storage (e.g., the articulartory loop; cf. Baddeley, Thomson & Buchanan, 1974) when to-be-maintained lists are short. It is only when longer lists must be maintained (about 6 list items) that domain-general resources are depleted (Baddeley & Hitch, 1974). Morey and Cowan (2004) subsequently replicated Luck and Vogel (1997) by again showing that a 2-digit load did not affect visual arrays accuracy. However, when the load was composed of 7 random digits, visual arrays accuracy did decrease. It was concluded that visual arrays performance reflects domain-general attention capacity, rather than modality-specific storage.

Shipstead, Redick, Hicks and Engle (2012) also argued in favor of the domain generality of visual arrays on the basis of the correlation between visual arrays performance and fluid intelligence. Specifically, these researchers defined fluid intelligence via four tasks: Two with a visuo-spatial bias and two with a verbal bias. The correlation between visual arrays and fluid intelligence was strong (in the range of .6-.7). Next, Shipstead, Redick, Hicks, and Engle (2012) employed a method developed by Kane et al. (2004) in which fluid intelligence was redefined as either two visual or two verbal tasks. It was found that, relative to the balanced fluid intelligence factor, the direct relationship between k and fluid intelligence was slightly stronger for the visual factor and slightly weaker for the verbal factor. Though this trend might, in isolation, signal a visuo-spatial bias, the majority of the relationship between visual arrays and fluid intelligence was mediated by a memory factor that was composed of both verbal and visuo-spatial memory tasks. This latter relationship was largely unaffected by the changes to the composition of the fluid intelligence factor. Thus, while the visual arrays task may contain a visuo-spatial storage component (Saults & Cowan, 2007), its relationship to higher cognition seems to be primarily domain-general.

The present data provide further support for this domain-general perspective, at least as the task relates to fluid intelligence. Specifically, Figure 11 indicates that only CommWM predicts Gf. This factor is composed of a variety of tasks, with a variety of demands, not the least of which was memory for verbal information in some tasks (OSpan, RunLett; RunDigit) and visuo-spatial information in others (VA1-4; SymSpan). Thus it is variance that is common to both domains that predicts the relationship between visual arrays and fluid intelligence.

However, the lack of a direct relationship between WMva, and PM and SM may reflect the fact that these memory factors are verbal in nature, while visual arrays is visuo-spatial. This reveals a limitation of the present data that must be resolved. Further research is required to determine whether visual arrays truly reflects only attention control or whether visuo-spatial primary and secondary memory tasks would also contribute to its prediction.

This concern is mitigated by the relationship of WMva to ExATTN, which contained variance that was extracted from the verbal memory tasks. Nonetheless, this limitation would have been eliminated by the inclusion of the split span tasks in the primary and secondary memory factor. However, these tasks had strong relationships to attention, rather than memory, and were thus removed from the analysis.

Primary Memory

In the present study, primary memory was largely defined via the maintenance component of free recall (Tulving & Colotla, 1970). Examination of Table 2 indicates that, on average this represented memory for less than two words and less than one three-digit number. Nonetheless, primary memory seems to reflect more than passive retention of a limited amount of information.

In particular, CPA loaded as strongly on PM as it did on SM. In this task participants first studied digit-letter pair (e.g., 35 - X) and were then tested (e.g., 35 - ?), following 0-5 interruptions. Despite the fact that lags of 0 and 1 were not included in the CPA variable (which should bias the variable toward secondary memory; Rowe & Smith, 1973; Unsworth, Brewer, & Spillers, 2011), CPA loaded as strongly on PM as it did on SM. This strongly suggests that primary memory is not simply storage of recently encountered information, but includes executive processes that actively retain associations between the present context and highly-relevant information (e.g., Oberauer et al., 2007), even when interference is high.

It is unlikely that attention control alone can account for the apparent executive aspects of primary memory. In particular, the loading of CPA on PM remained intact when the memory tasks were cross loaded on ExATTN (e.g., Figure 9). That said, attention control did account for a reasonable portion of the relationship between PM and working memory. In Analysis 1, the regression path between PM and WMspan was .88 before variance associated with attention control was removed (Figure 9a). When the memory tasks were cross loaded on ExATTN, the path from PM to WMspan dropped by .25 (Figure 9b).

Thus, executive attention is an important component of working memory-related memory (Kane, Conway, Hambrick, & Engle, 2007). However, it does not fully account for working memory capacity. Rather, there are likely a number of critical processes that require further elucidation (cf. Miyake et al., 2000; Oberauer et al., 2003; Unsworth, Miller et al., 2009). That said, in the absence of direct observation, the presence of other executive processes (e.g., updating, intentional forgetting) in the current data remains speculative. It cannot, therefore, be ruled out that primary memory is also determined by a more traditional (and more passive) storage mechanism, similar to those proposed by Cowan (2001) or Luck and Vogel (1997).

Elimination of Task-Specific Variance and the Relationship of Working Memory Capacity to Fluid Intelligence

The relationship between working memory capacity and fluid intelligence was defined strictly via CommWM (i.e., Figure 11). A related observation is noteworthy. Specifically, Oberauer, Schulze, Wilhelm and Süß (2005) argue that when working memory is defined through tasks that share similar demands (e.g., all complex span), the correlation between working memory capacity and fluid intelligence will be underestimated. This is because task-specific variance will obscure the true relationship. On the other hand, a diverse set of working memory tasks will eliminate task-specific variance and allow for an accurate estimate of the relationship.

Oberauer et al. (2005) estimate that working memory capacity and fluid intelligence share at least 70% of their variance. More conservative estimates place this relationship closer to 50% (Kane, Hambrick, & Conway, 2005) or even less (Ackerman, Beier, & Boyle, 2005). The present data set included three types of working memory task with a wide variety of demands and, as previously noted, CommWM and Gf shared 76% of their variance. Thus the present results support the estimate of Oberauer et al. (2005) in which working memory and fluid intelligence, while not isomorphic, share the majority of their variance.

Diversity of Sample

While the strong relationship between working memory and fluid intelligence was likely produced by the variety of working memory tasks that were presently employed, it may also reflect the diversity of participants that were run. While many studies rely on students from a single university, the present sample not only included students from several schools, but also a large number of community participants (40%). Thus the range of participants' cognitive abilities was likely more diverse than the average study of this kind.

It is therefore noteworthy that in Figure 9 the relationship between primary memory and WMspan was very strong. This has not been the case in other studies involving the latent relationships between primary memory and complex span performance. For instance, a recent study by Unsworth, Spillers, and Brewer (2010) reported that the relationship was .34 (see also Unsworth & Engle, 2007b). One difference between the present study and that of Unsworth, Spillers and Brewer (2010) was the way that primary memory was measured. The latter study used only free recall of words, while the present study used free recall of words, free recall of three-digit numbers, a rapid digits span and continuous paired associates. Thus the present measurement of primary memory was highly diverse.

This diversity of tasks may account for a portion of the difference between these studies, however, it should also be noted that Unsworth, Spillers, and Brewer (2010) drew their participants from a fairly selective school (i.e., University of Georgia; cf. Redick et al., in press). Thus the relatively small relationship these researchers found between primary memory and working memory may also be attributable to a relatively restricted range.

This observation introduces another factor that may affect the detectability of specific mechanisms in working memory: Sample diversity. For instance, primary memory, which ostensibly ranges between 3-5 items, is a rather coarse measure of working memory capacity. That is, there is not a tremendous range of scores that participants may obtain. This restriction is likely exacerbated when participants are of similar cognitive ability.

Retrieval from secondary memory, on the other hand, is not as restricted and thus may provide a finer grained analysis of working memory capacity when participants are similar in their cognitive abilities. That is, if secondary memory is not subject to the same capacity limits as is primary memory, test-takers can likely vary to a greater extent on measures of this ability. While these statements require further research, the critical point is that before making definitive statements regarding the mechanisms that drive individual differences in working memory capacity, researchers should not only consider the tasks that were used to measure working memory capacity, but also the diversity of participants who contributed to the data.

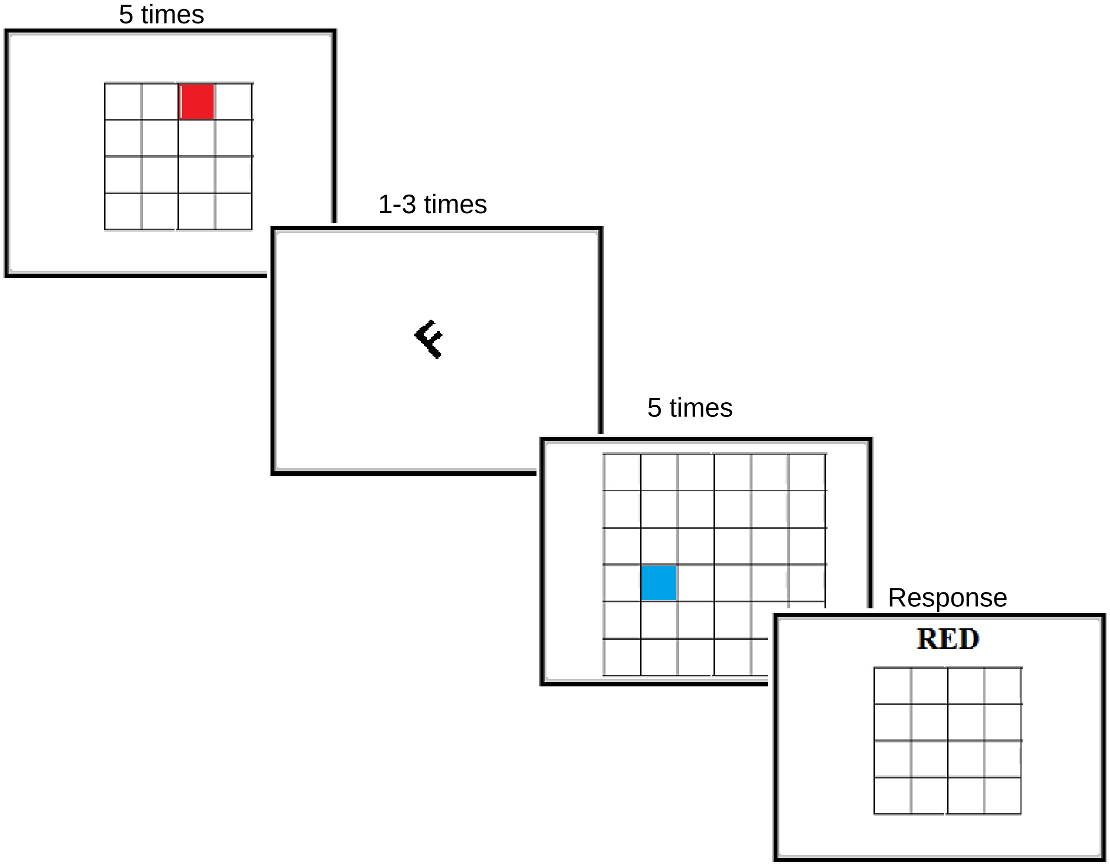
CHAPTER 5

CONCLUSIONS

Individual differences in working memory capacity can be largely construed as individual differences in three sub-factors that roughly correspond to different components of Cowan's (1988; 1999; 2001) embedded process model: Primary memory, secondary memory and executive attention. However, while these processes are important to explaining working memory and its relationship to fluid intelligence, span-based tasks were found to be more strongly related to memory, and visual arrays tasks reflected attention control. Thus, it is important to note that working memory is not only multiply determined, but the mechanisms of working memory are differently reflected in different types of working memory task.

APPENDIX A

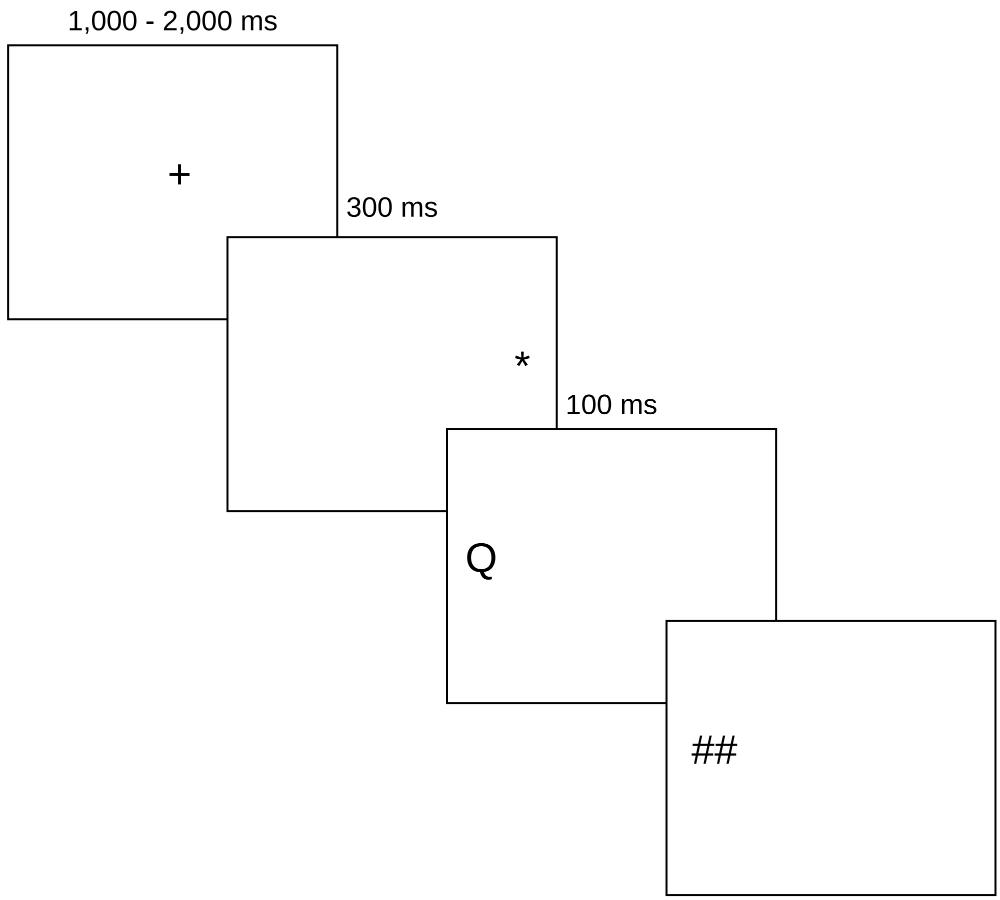
THE SPLIT SPAN TASK



The split span task begins with 5 squares in a 4 X 4 grid being highlighted one at a time (1,000 ms each). Next, the participant must decide if a rotated letter is facing in the appropriate direction or is mirror-reversed. After 1 to 3 of these decisions are made, the participant sees 5 more squares on a 6 X 6 grid (250 ms each). Finally, the participant is signaled to remember the locations of either the red or the blue squares.

APPENDIX B

THE ANTISACCADE TASK



The antisaccade task begins with a central fixation that is displayed for either 1,000 or 2,000 ms. Next a star flashes on either the right or left hand side of the screen. The test taker must look to the opposite side of the screen where either and “O” or “Q” is displayed, and then rapidly masked.

REFERENCES

Ackerman, P. L., Beier, M. E., & Boyle, M. O. (2005). Working memory and intelligence: The same or different constructs? *Psychological Bulletin, 131*, 30-60. doi:10.1037/0033-2909.131.1.30

Akaike, H. (1987). Factor analysis and AIC. *Psychometrika, 52*, 317-332.

Allison, P. D. (2002). *Missing data*. Thousand Oaks: Sage.

Awh, E., Barton, B., & Vogel, E. K. (2007). Visual working memory represents a fixed number of items regardless of complexity. *Psychological Science, 18*, 622-628.

Baddeley, A. D. (1976). *The psychology of memory*. New York: Basic Books.

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

Baddeley, A. D., Thomson, N., Buchanan, M., (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior, 14*, 575-589.

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time Constraints and Resource Sharing in Adults' Working Memory Spans. *Journal of Experimental Psychology: General, 133*, 83-100.

Bennett, R. W. (1975). Proactive interference in short-term memory: Fundamental forgetting processes. Journal of Verbal Learning and Verbal Behavior, 14, 123-144.

Braver, T. S., Gray, J. R., & Burgess, G. C. (2007). Explaining the many varieties of working memory variation: Dual mechanisms of cognitive control. In A. R. A. Conway, C. Jarrold, M. J. Kane, A. Miyake, & J. N. Towse (Eds.), *Variation in working memory* (pp. 76-106). Oxford University Press.

Broadway, J. M. (2008). *Running memory/working memory: Span tests and their prediction of higher-order cognition* (Masters Thesis). Georgia Institute of Technology, Atlanta, Ga.

Broadway, J. M. & Engle, R. W. (2010). Validating running memory span: Measurement of working memory capacity and links with fluid intelligence. *Behavior Research Methods, 42*, 563-570.

Browne, M. W., & Cudeck, R. (1993). Alternative ways of assessing model fit. In K. A. Bollen & J. S. Long (Eds.), *Testing structural equation models* (pp. 136–162). Newbury Park, CA: Sage.

Bunting, M. (2006). Proactive interference and item similarity in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*, 183-196.

Bunting, M., Cowan, N., & Saults, J. S. (2006). How does running memory span work? *The Quarterly Journal of Experimental Psychology, 59*, 1691-1700.

Byrne, B. M. (2008). *Structural equation modeling with EQS: Basic concepts, applications, and programming* (2nd ed.). New York: Routledge.

Chuderski, A., Taraday, M., Nęcka, E., & Smoleń, T. (2012). Storage capacity explains fluid intelligence but executive control does not. *Intelligence, 40*, 278-295.

Colom, R., Abad, F. J., Quiroga, M. Á., Shih, P. C., & Flores-Mendoza, C. (2008). Working memory and intelligence are highly related constructs, but why? *Intelligence, 36*, 584-606. doi:10.1016/j.intell.2008.01.002

Conway, A. R. A., Getz, S. J., Macnamara, B., & Engel de Abreu, P. M. J. (2010). Working memory and fluid intelligence: A multi-mechanism view. In R. J. Sternberg, & S. B. Kaufman (Eds.), *The Cambridge handbook of intelligence*. Cambridge, UK: Cambridge University Press. doi:10.1016/j.intell.2010.07.003

Conway, A.R.A., Jarrold, C., Kane, M.J., Miyake, A., & Towse, J.N. (2007). *Variation in working memory*. Oxford: Oxford University Press.

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin, 104*, 163-191.

Cowan, N. (1999). An embedded-process model of working memory. In A. Miyake & P. Shah (Eds.), *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control* (pp. 62-101). New York, NY: Cambridge University Press.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24*, 87-185.

Cowan, N., Elliot, E. M., Saults, J. S., Morey, C. C., Mattox, S., Hismjatullina, A., & Conway, A. R. A. (2005). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology, 51*, 42-100.

Craik, F.I.M. & Birtwistle, J. (1971). Proactive inhibition in free recall. J*ournal of Experimental Psychology, 91,* 120–123.

Craik, F. I. M., Govoni, R., Naveh-Benjamin, M., & Anderson, N. D. (1996). The effects of divided attention on encoding and retrieval processes in human memory. *Journal of Experimental Psychology: General, 12*5, 159-180.

Cusack, R., Lehman, M., Veldsman, M., & Mitchell, D. J. (2009). Encoding strategy and not visual working memory capacity correlates with intelligence. *Psychonomic Bulletin & Review, 16*, 641-647.

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

Ekstrom, R. B., French, J. W., Harman, M. H., & Dermen, D. (1976). *Manual for kit of factor-referenced cognitive tests*. Princeton, NJ: Educational Testing Service.

Engle, R. W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science, 11*, 19-23.

Engle, R. W. & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. In B. Ross (Ed.), *The Psychology of Learning and Motivation, Vol. 44* (pp. 145-199). NY: Elsevier.

Engle, R. W., & Oransky, N. (1999). Multi-store versus dynamic models of temporary storage in memory. In R. Sternberg (Ed.), *The Nature of Cognition* (pp. 514-555). Cambridge, MA: MIT Press.

Engle, R.W., Tuholski, S.W., Laughlin, J.E., & Conway, A.R.A. (1999). Working memory, short-term memory and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General, 128*, 309-331.

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology: General, 133*, 101-135.

Friedman, N. P., Miyake, A., Young, S. E., DeFries, J. C., Corley, R. P., & Hewitt, J. K. (2008). Individual differences in executive functions are almost entirely genetic in origin. *Journal of Experimental Psychology: General, 137*, 201-225. doi:10.1037/0096-3445.137.2.201

Fukuda, K., & Vogel, E. K. (2009). Human variation in overriding attentional capture. *The Journal of Neuroscience, 29*, 8726-8733.

Fukuda, K., & Vogel, E. K. (2011). Individual differences in recovery time from attentional capture. *Psychological Science, 22*, 361-368.

Fukuda, K., Vogel, E., Mayr, U., Awh, E. (2010). Quantity, not quality: The relationship between fluid intelligence and working memory capacity. *Psychonomic Bulletin & Review, 17*, 673-679.

Garavan, H. (1998). Serial attention within working memory. *Memory & Cognition, 26*, 263-267.

Gray, J. R., Chabris, C. F., and Braver, T. S. (2003). Neural mechanisms of general fluid intelligence. *Nature Neuroscience, 6*, 316-322.

Hallett, P. E. (1978). Primary and secondary saccades to goals defined by instructions. *Vision Research, 18*, 1279-1296.

Hartshorne, J. K. (2008). Visual working memory capacity and proactive interference. PLoS ONE 3(7): e2716. doi:10.1371/journal.pone.0002716

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. In D. Gropher, & A. Koriat (Eds.), *Attention and Performance XVII* (pp. 653-675). Cambridge, MA: MIT Press.

Healy, M. K., & Miyake, A. (2009). The role of attention during retrieval in working-memory span: A dual-task study. *The Quarterly Journal of Experimental Psychology, 62*, 733-745.

Heitz, R. P. & Engle, R. W. (2007). Focusing the spotlight: Individual differences in visual attention control. *Journal of Experimental Psychology: General, 136*, 217-240.

Hu, L., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling, 6*, 1–55.

Hutchison, K. A. (2007). Attentional control and the relatedness proportion effect in semantic priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition. 33*, 645-662.

Jaeggi, S. M., Buschkuehl, M., Jonidas, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences of the United States of America, 105*, 6829-6833. doi:10.1073/pnas.0801268105

Jaeggi, S. M., Buschkuehl, M., Perrig, W. J., & Meier, B. (2010). The concurrent validity of the N-back task as a working memory measure. *Memory, 18*, 392-412. doi:10.1080/09658211003702171

Jaeggi, S. M., Studer-Luethi, B., Buschkuehl, M., Su, Y. -F., Jonides, J., & Perrig, W. J. (2010). The relationship between n-back performance and matrix reasoning – Implications for training and transfer. *Intelligence, 38,* 625-635. doi:10.1016/j.intell.2010.09.001

Kane, M. J., Bleckley, K. M., Conway, A. R. A., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General, 130*, 169-183.

Kane, M. J., Conway, A. R. A., Miura, T. K., & Colflesh, G. J. (2007). Working memory, attention control, and the N-back task: A question of construct validity. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33*, 615-622. doi:10.1037/0278-7393.33.3.615

Kane, M. J., Conway, A. R. A., Hambrick, D. Z., & Engle, R. W. (2007). Variation in working memory capacity as variation in executive attention and control. In A.R.A. Conway, C. Jarrold, M.J. Kane, A. Miyake, and J.N. Towse (Eds.), *Variation in Working Memory* (pp. 21 - 48). NY: Oxford University Press.

Kane, M., & Engle, R. (2000). Working-memory capacity, proactive interference, and divided attention: Limits on long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 26*, 336.

Kane, M. J. & Engle, R. W. (2003). Working memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General, 132*, 47-70.

Kane, M. J., Hambrick, D. Z., & Conway, A. R. A. (2005). Working memory capacity and fluid intelligence are strongly related constructs: Comment on Ackerman, Beier, and Boyle (2005). *Psychological Bulletin, 131*, 66-71. doi:10.1037/0033-2909.131.1.66

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: A latent-variable approach to verbal and visuo-spatial memory span and reasoning. *Journal of Experimental Psychology: General, 133*, 189–217.

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. *Journal of Experimental Psychology, 55*, 352-358. doi:10.1037/h0043688

Kline, R. B. (1998). *Principles and practice of structural equation modeling*. New York: Guilford Press.

Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability is (little more than) working memory capacity? *Intelligence, 14*, 389-433. doi:10.1016/S0160-2896(05)80012-1

Lavie, N., Hirst, A., de Fockert, J. W., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General, 133*, 339-354.

Li. S. -C., Schmiedeck, F., Huxhold, O., Röcke, C., Smith, J., & Lindenberger, U. (2008). Working memory plasticity in old age: Practice gain, transfer, and maintenance. *Psychology and Aging, 23*, 731-742. doi:10.1037/a0014343

Lin, P-H, & Luck, S. J. (in press). Proactive interference does not meaningfully distort visual working memory capacity estimates in the canonical change detection task. *Frontiers in Cognition*.

Loehlin, J. C. (2004). Latent variable models: *An introduction to factor, path, and structural equation analysis* (4th ed.). New York: Psychology Press.

Luck, S.J. & Vercera, S.P. (2002). Attention. In H.E. Pashler (Ed.), Steven's handbook of experimental psychology (pp. 235 – 286). New York: Wiley.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390*, 279-281.

Lustig, C., May, C. P., & Hasher, L. (2001). Working memory span and the role of proactive interference. *Journal of Experimental Psychology: General, 130*, 199-207.

Makovski, T., & Jiang, Y. V. (2008). Proactive interference from items previously stored in visual working memory. *Memory & Cognition, 36*, 43-52.

May, C. P., Hasher, L., & Kane, M. J. (1999). The role of interference in memory span. *Memory & Cognition, 27*, 759-767.

McElree, B. (2001). Working memory and focal attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*, 817-835.

McNab, F., & Klingberg, T. (2008). Prefrontal cortex and basal ganglia control access to working memory. *Nature Neuroscience, 11*, 103-107.

McVay, J. C., & Kane, M. J. (2012). Why does working memory capacity predict variation in reading comprehension? On the influence of mind wandering and executive attention. *Journal of Experimental Psychology: General, 141*, 302-320. doi:10.1037/a0025250

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

Miyake, A., & Shah, P. (1999). *Models of working memory: Mechanisms of active maintenance and executive control*. New York: Cambridge University Press.

Mogle, J. A., Lovett, B. J., Stawski, R. S., & Sliwinski, M. J. (2008). What's so special about working memory? An examination of the relationship among working memory, secondary memory, and fluid intelligence. *Psychological Science, 19*, 1071-1077.

Morey, C. C., & Cowan, N. (2004). When visual and verbal memories compete: Evidence of cross-domain limits in working memory. *Psychonomic Bulletin & Review, 11*, 296-301.

Morey, C. C. & Cowan, N. (2005). When do visual and verbal memories conflict? The importance of working-memory load and retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*, 703-713.

Norman, D. A. (1968). Toward a theory of memory and attention. *Psychological Review, 75*, 522-536.

Norman, D. A. & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R. Davidson, G. Schwartz, & D. Shapiro, (Eds.), *Consciousness and self regulation: Advances in research and theory, Vol. 4* (pp. 1-18). New York: Plenum.

Oberauer, K. (2001). Removing irrelevant information from working memory. A cognitive aging study with the modified Sternberg task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*, 948-957.

Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*, 411–421.

Oberauer, K. (2005). Binding and inhibition in working memory: Individual and age differences in short-term recognition. *Journal of Experimental Psychology: General, 134*, 368-387.

Oberauer, K., Schulze, R., Wilhelm, O., & Süß, H. M. (2005). Working memory and intelligence - their correlation and their relation: A comment on Ackerman, Beier, and Boyle (2005). *Psychological Bulletin, 131*, 61-65. doi:10.1037/0033-2909.131.1.61

Oberauer, K., Süß, H.-M., Wilhem, O., Sander, N. (2007). Individual differences in working memory capacity and reasoning ability. In A.R.A. Conway, C. Jarrold, M. H. Kane, A. Miyake, & J. N. Towse (Eds.), *Variation in working memory* (pp. 49-75). New York: Oxford University Press.

Oberauer, K., Süß, H., Wilhelm, O., & Wittmann, W. W. (2003). The multiple faces of working memory: Storage, processing, supervision, and coordination. *Intelligence, 31*, 167-193.

Pashler, H. (1988). Familiarity and visual change detection. *Perception & Psychophysics, 44*, 369-378.

Pollack, I., Johnson, L. B. & Knaff, P. R. (1959). Running memory span. J*ournal of Experimental Psychology, 57*, 137-146.

Posner, M. I., & Snyder, C. R. (1975). Facilitation and inhibition in the processing of signals. In P. M. A. Rabbitt & S. Dornic (Eds.), *Attention and performance V*. New York: Academic Press.

Raaijmakers, J. G. W. & Shiffrin, R. M. (1992). Models for recall and recognition. *Annual Review of Psychology, 43*, 205-234.

Raven, J. C. (1990). *Advanced progressive matrices*. Oxford, UK: Oxford Psychological Press.

Redick, T. S., Broadway, J. M., Meier, M. E., Kuriakose, P. S., Unsworth, N., Kane, M. J., Engle, R. W. (in press). Measuring working memory capacity with automated complex span tasks. *European Journal of Psychological Assessment*.

Redick, T. S., & Engle, R.W. (2006). Working memory capacity and Attention Network Test performance. *Applied Cognitive Psychology, 20*, 713-721.

Redick. T. S., Shipstead, Z., Harrison T., L., Hicks, K. L., Fried, D. E., Hambrick, D. Z., Kane, M. J., Engle, R. W. (in press). No evidence of intelligence improvement after working memory training: A randomized, placebo-controlled study. *Journal of Experimental Psychology, General*. doi:10.1037/a0029082

Roberts, R. J., Hager, L. D., & Heron, C. (1994). Prefrontal cognitive processes: Working memory and inhibition in the antisaccade task. *Journal of Experimental Psychology: General, 123*, 374-393.

Rouder, J. N., Morey, R. D., Moray, C. C., & Cowan, N. (2011). How to measure working memory capacity in the change detection paradigm. *Psychonomic Bulletin & Review, 18,* 324-330. DOI 10.3758/s13423-011-0055-3.

Rowe, E. J. & Smith, S. K. (1973). Imagery effects in continuous paired-associate learning. *Journal of Experimental Psychology, 99*, 290-292.

Saults, J. S., & Cowan, N. (2007). A central capacity limit to the simultaneous storage of visual and auditory arrays in working memory. *Journal of Experimental Psychology: General, 136*, 663-684.

Shipstead, Z. & Broadway, J. M. (2012). Individual differences in working memory capacity and the Stroop Effect: Do high spans block the words? *Learning and Individual Differences*. doi:10.1016/j.lindif.2012.04.003

Shipstead, Z., & Engle, R. W. (in press). Interference within the focus of attention: Working memory tasks reflect more than temporary maintenance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*.

Shipstead, Z., Harrison, T. L., & Engle, R. W. (2012). Working memory capacity and visual attention: Top-down and Bottom-up guidance. *Quarterly Journal of Experimental Psychology, 65*, 401-407.

Shipstead, Z., Redick, T. S., Hicks, K. L., & Engle, R. W. (2012). The Scope and Control of Attention as Separate Aspects of Working Memory. *Memory*. doi:10.1080/09658211.2012.691519

Shipstead, Z., Redick, T. S., & Engle, R. W. (2012). Is working memory training effective? *Psychological Bulletin*. doi: 10.1037/a0027473

Spillers, G.J. & Unsworth, N. (2011). Variation in working memory capacity and temporal-contextual retrieval from episodic memory. J*ournal of Experimental Psychology: Learning, Memory, and Cognition*, *37*, 1532-1539.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology 18*, 643-662.

Thurstone, L. L. (1938). *Primary mental abilities*. Chicago, IL: University of Chicago Press.

Tulving, E. & Colotla, V. A. (1970). Free recall of trilingual lists. *Cognitive Psychology, 1*, 86-98.

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language, 28*, 127-154.

Unsworth, N., Brewer, G. A., & Spillers, G. J. (2011). Variation in working memory capacity and forgetting over both the short and the long term: An application of the population dilution model. *Journal of Cognitive Psychology, 23*, 243-255.

Unsworth, N., & Engle, R.W. (2006). Simple and complex memory spans and their relation to fluid abilities: Evidence from list-length effects. *Journal of Memory and Language, 54*, 68-80.

Unsworth, N., & Engle, R. W. (2007a). Individual differences in working memory capacity and retrieval: A cue-dependent search approach. In J. S. Nairne (Ed*.), The Foundations of Remembering: Essays in Honor of Henery L. Roediger, III* (pp. 241-258). NY: Psychology Press.

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

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

Unsworth, N., Heitz, R.P., Schrock, J.C., & Engle, R.W. (2005). An automated version of the operation span task. *Behavior Research Methods, 37*, 498 - 505.

Unsworth, N., Miller, J. D., Lakey, C. E., Young, D. L., Meeks, J. T., Campbell, W. K., & Goodie, A. S. (2009). Exploring the relations among executive functions, fluid intelligence, and personality. *Journal of Individual Differences, 30*, 194-200.

Unsworth, N., Redick, T. S., Heitz, R. P., Broadway, J. M., & Engle, R. W. (2009). Complex working memory span tasks and higher-order cognition: A latent-variable analysis of the relationship between processing and storage. *Memory, 17*, 635 - 654.

Unsworth, N., Schrock, J. C., & Engle, R. W. (2004). Working memory capacity and the antisaccade task: Individual differences in voluntary saccade control. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 30*, 1302-1321.

Unsworth, N., & Spillers, G.J. (2010). Working memory capacity: Attention, Memory, or Both? A direct test of the dual-component model. *Journal of Memory and Language, 62*, 392-406.

Unsworth, N., Spillers, G. J., & Brewer, G. A. (2009). Examining the relations among working memory capacity, attention control, and fluid intelligence from a dual-component framework. *Psychology Science Quarterly, 4*, 388-402.

Unsworth, N., Spillers, G. J., & Brewer, G. A. (2010). The contributions of primary and secondary memory to working memory capacity: An individual differences analysis of immediate free recall. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 36*, 240-247.

Van Selst, M. & Jolicoeur, P. (1994). A solution to the effect of sample size on outlier elimination. *The Quarterly Journal of Experimental Psychology, 47A*, 631-650.

Verhaeghen, P., & Basak, C. (2005). Ageing and switching of the focus of attention in working memory: Results from a modified *N*-back task. *The Quarterly Journal of Experimental Psychology, 58A*, 134-154.

Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature, 428*, 748-751.

Vogel, E. K., McCollough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual differences in controlling access to working memory. *Nature, 438*, 500-503.

Vogel, E. K., Woodman, G. F., & Luck (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 92-114.

Vogel, E. K., Woodman, G. F., & Luck (2005). Pushing around the locus of selection: Evidence for the flexible-selection hypothesis. *Journal of Cognitive Neuroscience, 17*, 1907-1922.

Watkins, M.J. (1974). Concept and measurement of primary memory. *Psychological Bulletin, 81,* 695–711.

Watkins, M.J. (1979). Engrams as cuegrams and forgetting as cue over-load: A cueing approach to the structure of memory. In C.R. Puff (Ed.), *Memory organization and structure* (pp. 347-372). New York: Academic Press.

Watkins, O. C., & Watkins, M. J. (1975). Buildup of proactive inhibition as a cuse-overload effect. *Journal of Experimental Psychology: Human Learning and Memory, 104*, 442-452.

Waugh, N. C. & Norman, D. A. (1965). Primary memory. *Psychological Review, 72*, 89-104.

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General, 131*, 48-64. doi:10.1037/0096-3445.131.1.48

Wixted, J. T., & Rohrer, D. (1994). Analyzing the dynamics of free recall: An integrative review of empirical literature. *Psychonomic Bulletin & Review, 1*, 89-106.

VITA

Zach Shipstead

Zach Shipstead was born in Traverse City, Michigan. He obtained his undergraduate degree in psychology from Alma College. He earned his masters in applied psychology from Montana State University before pursuing his PhD in Cognition and Brain Sciences at Georgia Tech.