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The mechanisms of working memory capacity: Primary memory, secondary memory, and attention control

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ABSTRACT

Working memory capacity is traditionally treated as a unitary construct that can be explained using one cognitive mechanism (e.g., storage, attention control). Several recent studies have, however, demonstrated that multiple mechanisms are needed to explain individual differences in working memory capacity. The present study focuses on three such mechanisms: Maintenance/disengagement in primary memory, retrieval from secondary memory, and attention control. Structural equation modeling reveals that each of these mechanisms is important to explaining individual differences in working memory capacity. Further analyses reveal that the degree to which these mechanisms are apparent may be driven by the type of task used to operationalize working memory capacity. Specifically, complex span (processing and storage) and visual arrays (change detection) performance is strongly related to a person's attention control, while running memory span (memory for last n items on a list) performance has a relationship to primary memory that is apparent above-and-beyond other working memory tasks. Finally, regardless of the working memory task that is used, it is found that primary and secondary memory fully explain the relationship of working memory capacity to general fluid intelligence.

> *....working memory is not a memory system in itself, but a system for attention to memory....*
>
> Oberauer et al. (2007)

Introduction

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. Critically, individual differences in working memory capacity are associated with performance in diverse aspects of cognition, such as multi-tasking (Hambrick, Oswald, Darowski, Rench, & Brou, 2010), emotion regulation (Kleider, Parrott, & King, 2009), hindsight bias (Calvillo, 2012), and susceptibility to stereotype threat (Hutchison, Smith, & Ferris, 2012). Perhaps most famously, working memory capacity shares at least half its statistical variance with general fluid intelligence (the ability to reason with novel information; Kane, Hambrick, & Conway, 2005). Thus, exploring the mechanisms of working memory capacity may provide the most straightforward method of clarifying the processes involved in human reasoning (Conway, Getz, Macnamara, & Engel de Abreu, 2010; Oberauer, Schulze, Wilhelm, & Süß, 2005). We highlight three broadly

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defined mechanisms that are prevalent in the literature: Primary memory, attention control, and retrieval from secondary memory.

Primary memory

As it relates to working memory, primary memory is typically construed as a type of limited capacity storage that can maintain 3–5 items at any one point in time (Cowan, 2001; Luck & Vogel, 1997; Rouder, Morey, Morey, & Cowan, 2011; Unsworth & Engle, 2007b). In effect, it represents the size of a person's attentional focus (e.g., Cowan et al., 2005; Unsworth & Engle, 2007b). The function of this system is to protect relevant information from proactive interference (Cowan, 2001) and allow novel connections to be formed between disparate units of information (Oberauer et al., 2007).

While most theories of working memory capacity postulate that primary memory is a critical component, the assumption that this system strictly reflects multi-item storage is not universal. For instance, focal attention has also been researched as a serial process (e.g., Garavan, 1998; McElree, 2001; Verhaeghen & Basak, 2005), leading some to conclude that the primary memory aspects of working memory are better construed as a binding-function, than as a storage system. Specifically, the 3–5 item maintenance capacity is sometimes interpreted as a person's ability to form and break temporary associations between disparate memory units (Oberauer, 2002; Oberauer et al., 2007). These *bindings* provide facilitated access between contextually relevant units of memory. From this perspective, the size of a person's primary memory is determined by the efficacy with which new bindings are created and dissolved as the context of a situation changes. The present study was not designed to test between absolute-maintenance or binding-capacity theories; however, both perspectives will be examined when considering the implications of our results.

Attention control

Working memory capacity is typically operationalized via information that is either in conscious awareness, or can be readily recalled into awareness. Thus, it is parsimonious to equate working memory capacity with primary memory. However, the environment in which working memory operates may contain any number of distractions to which attention is drawn. The ability to select goal-relevant information and responses is therefore critical when the environment (or a memory search) activates conflicting information or prepotent responses.

In contrast to strict maintenance-related perspectives of working memory capacity (e.g., Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008), the executive attention account (Engle, 2002) equates working memory capacity with the ability to use attention to select relevant information from the environment and to retain access to memories that reside outside of conscious awareness (Kane, Conway, Hambrick, & Engle, 2007). That is, working memory capacity is seen to be driven by ability to focus on critical information and resist having one's attention captured by distraction. Indeed, individual differences in working memory capacity are positively correlated to performance on a variety of attention capture tasks (Engle, 2002; Fukuda & Vogel, 2009, 2011; Hutchison, 2007; Kane, Conway, et al., 2007; Unsworth & Spillers, 2010). These tasks require test takers to make goal-relevant responses (e.g., look away from a peripheral flash) in the face of prepotent tendencies (e.g., the reflexive inclination to orient toward peripheral events; Engle, 2002). Critically, the information load for attention capture tasks is typically low (Roberts, Hager, & Heron, 1994), implying that the relationship between working memory capacity and resistance to attention capture is not readily explained by individual differences in temporary storage capacity.

Secondary memory

The previously discussed perspectives of working memory capacity focus on mechanisms of maintenance. Yet, it is noteworthy that many working memory tasks require test-takers to manage more information than the 3–5 units to which immediate awareness is constrained. Thus, regardless of the scope of a person's primary memory, or attention control abilities, some to-be-remembered information is likely to be displaced and therefore require retrieval from longer-term storage (Unsworth & Engle, 2007b).

For instance, Unsworth and Engle's (2007) dual-component model defines working memory capacity as a combination of limited-capacity maintenance in primary memory, as well as retrieval from *secondary memory*. Specifically, secondary memory is contextually-relevant information that is not currently maintained by primary memory. The critical variable is the specificity with which this information is searched. People who can constrain their searches of secondary memory on the basis of highly relevant cues (e.g., time periods, associated information) generate relatively few irrelevant retrieval candidates. In other words, little proactive interference is produced and critical information is recalled with a higher probability. In contrast, people who have difficulty selecting relevant cues will conduct relatively diffuse searches of secondary memory and thus will generate many irrelevant retrieval candidates. In other words they will contend with a high level of proactive interference and thus have a reduced likelihood of recalling critical information (see also Watkins, 1979; Wixted & Rohrer, 1994).

Working memory tasks

Working memory capacity can be measured through a variety of tasks that make a variety of demands on the system. It is therefore understandable if different working memory tasks reflect different mechanisms of working memory, and thus provide slightly different perspectives on the cognitive processes that define this construct. The present study focuses on working memory capacity as it is reflected in complex span, running memory span and visual arrays performance. Of particular importance, these tasks differ greatly in their demands, yet they predict reasonably similar variation in working memory capacity (Broadway & Engle, 2010; Cowan et al., 2005; Shipstead

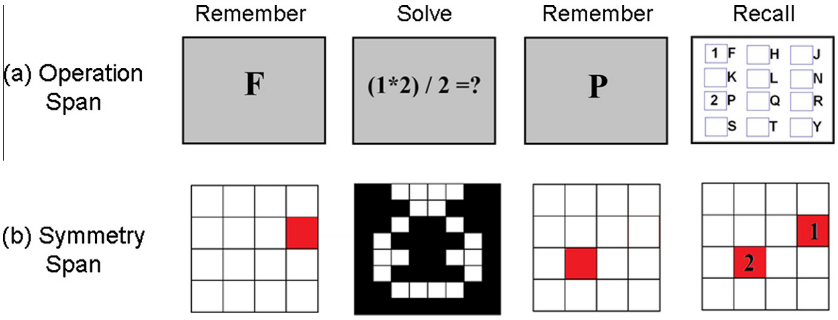


Fig. 1. Examples of complex span tasks. Operation span (a) presents a letter, then requires a participant to solve a simple mathematical equation. After several such pairings, the test-taker uses the "recall" screen to indicate the letters that had been presented, in the order that they were originally 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.

& Engle, 2013; Shipstead, Redick, Hicks, & Engle, 2012). Thus, understanding the shared and unique mechanisms that explain performance of these tasks will provide a more complete understating of the system as a whole.

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 (see Engle & Oransky, 1999). Two variations, known as the operation and symmetry span, are depicted in Fig. 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 (Fig. 1a), this is a mathematical equation that must be solved. For the symmetry span task (Fig. 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.

Performance on complex span tasks is strongly predictive of a person's attention control abilities (Hutchison, 2007; Unsworth & Spillers, 2010; Unsworth, Spillers, & Brewer, 2009). This association is interpreted as a reflection of the need to engage controlled attention to maintain the activation of to-be-remembered information while the processing task is being performed (Barrouillet, Bernardin, & Camos, 2004; Engle, 2002; Kane, Brown, et al., 2007; Kane, Conway, 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 (Friedman & Miyake, 2004; Kane & Engle, 2000; see also May, Hasher, & Kane, 1999). More importantly, complex span tasks best predict performance on complex cognition tasks (e.g., fluid intelligence, verbal ability) when proactive interference is high (Bunting, 2006; Lustig, May, & Hasher, 2001).[1] In other words, the predictive powers of complex span tasks seem to be at least partially related to the ability to perform searches of secondary memory; particularly when the need to minimize proactive interference is at a premium (Unsworth & Engle, 2007b).

One might argue that attention control is responsible for guiding these searches (e.g., Healey & Miyake, 2009), however, Unsworth and Spillers (2010) found that attention control and secondary memory are dissociable, and each separately 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. The residual relationship was attributed to primary memory (which was not directly measured by Unsworth & Spillers, 2010). Indeed, separate studies (Unsworth & Engle, 2007b; Unsworth, Spillers, & Brewer, 2010) have found that both the primary- and secondary memory components of free recall tasks (see Methods) independently predict complex span performance and contribute to explaining its relationship to higher cognition. Thus, present evidence indicates that complex span performance reflects all of the mechanisms discussed above.

Running memory span

Unlike the complex span task, the running span does not include an interpolated processing task (Fig. 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, several studies have concluded that running memory span performance largely reflects the same processes as tapped by the complex span tasks. For instance, a confirmatory factor analysis, performed by Shipstead et al. (2012), revealed that these tasks load on the same latent factor. Furthermore, several studies have found that running span performance accounts for the same (if not more) variance in fluid

[1] At least within younger populations. See Emery et al. (2008).

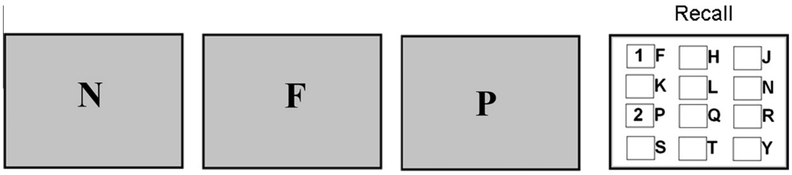


Fig. 2. Example of the running memory span task. In this task as series of to-be-remembered items are displayed, one at a time. In this case, it is three letters. After the last item, the recall screen cues the test-taker to remember a subset of these letters. In this case it is the last 2 items.

intelligence as the complex span tasks (Broadway & Engle, 2007; Cowan et al., 2005; Shipstead et al., 2012).

Thus, the interpolated processing task of the complex spans is not critical to measuring working memory capacity (Broadway & Engle, 2010). Moreover, if running span does indeed measure fluid intelligence above-and-beyond complex span (Broadway & Engle, 2007; Shipstead et al., 2012), it implies that this seemingly simpler task taps into components of working memory capacity that are not reflected in performance of the more classic complex span.

Unlike the complex span, the running memory span does not contain an attention-demanding secondary component. Thus, this task likely provides a more direct measure of certain aspects of primary memory, such as its absolute capacity (Broadway & Engle, 2010; Bunting, Cowan, & Saults, 2006), or the ability to update its contents in real-time (Bunting et al., 2006; Dahlin, Stigsdotter Neely, Larsson, Bäckman, & Nyberg, 2008; Miyake et al., 2000). This type of component may account for the observation that running memory span predicts variance in fluid intelligence above-and-beyond complex span (Broadway & Engle, 2007; Shipstead et al., 2012).

Visual arrays

While the complex span task is often assumed to provide a strong reflection of the executive attention aspects of working memory (Engle, 2002; Kane, Brown, et al., 2007; Kane, Conway, et al., 2007), the visual arrays task is almost universally treated as a process-pure reflection of primary memory capacity (Awh, Barton, & Vogel, 2007; Chuderski, Taraday, Nęcka, & Smoleń, 2012; Cowan et al., 2005; Fukuda, Vogel, Mayr, & Awh, 2010; Luck & Vogel, 1997; McNab and Klingberg, 2008; Rouder et al., 2011; Saults & Cowan, 2007). In the classic example of this task (Fig. 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 circled. 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 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 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. In other words, despite the lack of any obvious component of selection or distraction (in the basic task, all information is relevant; Fig. 3a and b), visual arrays performance predicts at least some aspects of attention control. This perspective is also supported by the work of Cowan, Fristoe, Elliot, Brunner, and Saults (2006), who found that a significant portion of the relationship between visual arrays performance and I.Q. was explained by performance on a selective attention task.

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 and Luck, in press). More directly, Shipstead and Engle (2013) demonstrated that when two trials are presented close to one another in time (relative to previous trials), estimates of storage capacity shrink. In contrast, 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 be-

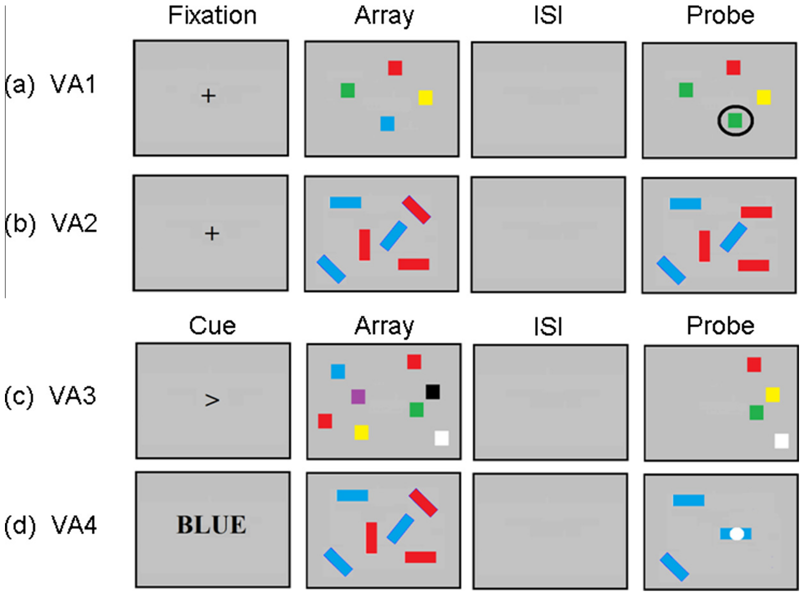


Fig. 3. Examples of visual arrays tasks used in the present study. VA1–VA4 = visual arrays, version 1–4. (a and b) Begin with fixation, which is followed by a target array of to-be-remembered items, then an inter-stimulus interval (ISI). For (a) the test-taker must indicate whether the encircled box 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

lieved to function in the seemingly disparate complex span and running span tasks.

The present study

The present study examines the cognitive mechanisms of working memory capacity via structural equation modeling. Several measures of primary memory, attention control, and retrieval from secondary memory will be used to form factors that correspond to these aspects of cognition. We will test the direct and indirect relationship of these mechanisms to working memory capacity as it is reflected in the performance of complex span, running memory span and visual arrays tasks.

In order to simplify these analyses, complex- and running span will be examined separately from visual arrays tasks. To preview our results, we find that while complex and running span tasks do indeed reflect many of the same underlying processes, running span performance reflects primary memory above-and-beyond complex span performance. This accounts for the task's particularly strong relationship to fluid intelligence.

Fig. 3 displays four types of visual arrays tasks that will be used in the present study. One reason for the variety of tasks is to increase the diversity of demands, and thus refine our measurement of the central aspects of visual arrays performance. However, examination of Fig. 3 reveals that tasks VA1 and VA2 (3a and 3b) require simple maintenance of all information, while VA3 and VA4 (3c and 3d) include irrelevant information. These latter tasks thus introduce an attention filtering component. The goal is to examine whether this filtering requirement introduces attention control processes that are not apparent in the standard tasks.

Briefly, we do find that selective filtering requirements introduce certain attention control demands that are not reflected in standard visual arrays performance. Nonetheless, all visual arrays tasks have a particularly strong relationship to attention control, regardless of specific demands.

Finally, on the assumption that examination of the mechanisms of working memory capacity simultaneously clarifies the processes involved in human reasoning, we perform mediational analyses in which primary memory, attention control, and secondary memory are allowed to account for the correlation between working memory capacity and fluid intelligence. We find that while attention control is critical to maintaining the contents of primary memory, it is the memory-related factors that relate working memory capacity to fluid intelligence.

Method

Participants

The data were collected as part of a general screening procedure. All participants were residents of the general community of Atlanta and between the ages of 18–30. Participants were compensated with $30 per session, or credit toward course requirements (Georgia Tech students only). In total, 273 people consented to participate in a two session study. Fifty six either did not complete both sessions or were removed for reasons including disruptive behavior, copying of to-be-remembered items, not following instructions, or because they did not meet our inclusion criteria (age; 20/50 vision). In the final sample of 215 participants, the mean age was 22.31 years (*SD* = 3.70). 48% were female. 60% were either attending or had graduated from college. Sessions included 1–5 participants working individually at computers.

Procedure

The study was conducted in two 2-h 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. All tasks were administered via computer. 18″ CRT monitors were used.

Table 1 provides the order in which tasks were administered. Because this study doubled as a screening procedure, two tasks (i.e., ReasoningMix and Beauty Contest) were part of separate projects and are not discussed further.

Working memory tasks (span tasks)

In all working memory span tasks, participants provided responses via mouse-click. Items were presented visually. In all tasks the dependent variable was the number of items recalled in their correct serial positions.

Operation span (OSpan; Fig. 1c). The automated operation span (Unsworth, Heitz, Schrock, & Engle, 2005) required participants to remember a series of letters while alternately solving simple mathematical equations. Lists lengths ranged between 3 and 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 and 5 items. Each list length occurred 3 times.

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.

Running letter span (RunLett; Fig. 1b). 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.

Rapid Running digit span (RunDigit). The automated running 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 (Fig. 3). 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 *single probe* 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 display* 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; Fig. 2a). 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 circled item had changed color. 28 trials of each set size were included. 14 were no-change, 14 were change.

VA2 (orientation judgment; Fig. 2b). 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; Fig. 2c). This task was based on Experiment 2 of Vogel, Woodman, and 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 on the left and right sides of the screen.

VA4 (selective orientation task; Fig. 2d). This task was based on the first experiment of Vogel, McCollough, and Machizawa (2005). Single probe report was used. Each trial began with an instruction to attend to either the red or blue items (200 ms), 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. The critical item was identified at test by a superimposed white dot. Test takers judged whether the orientation of this item had changed, relative to the initial presentation. No other changes could occur within the display. 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 s) 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. This was done to regulate recall strategies across participants. 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.

One concern regarding the Tulving-Colotla method is that it is based on Miller's (1956) "magical number 7". Unlike traditional measures of the magical number, such as digit span, the Tulving-Colotla method is unlikely to produce primary memory scores in the range of 7, since it assumes input and output of items are equally interfering actions. Thus, this method assumes that the effective size of primary memory is smaller than seven, and thus produces estimates that correspond to modern notions of primary memory. Specifically, the dependent variable is rarely larger than 3–4 items, and is not susceptible to buildups of proactive interference (Craik & Birtwistle, 1971). There are benefits to favoring this method over simply using the size of a person's recency effect as a measure of primary memory (e.g., Tulving & Patterson, 1968). First, the Tulving-Colotla method is more reliable on a trial-by-trial basis (Watkins, 1974). Second, it allows for the assumption that people sometimes maintain items in primary memory other than those from the final part of the list (Unsworth et al., 2010).

Free recall of three-digit numbers (PM_Numb; SM_Numb). This task was the same as word free recall, 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.

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. On this point, instructions further 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 dependent variable was the number of lists correctly recalled. Responses were entered via mouse-click.

The intent of this all-or-none scoring method (rather than the method used with the above WM span tasks) was to minimize retrieval from secondary memory (see Unsworth & Engle, 2007a). That is, once test-takers need to retrieve information from outside of primary memory, erroneous responses become more common, due to increased proactive interference. Under these circumstances, correct responses also begin to reflect a stronger component of accurate retrieval from secondary memory. These types of responses are minimized by ending testing when errors become prevalent. This is not to say that absolute scoring of digit span will create a process-pure measure of primary memory. Rather, we expected the role of retrieval from secondary memory to be greatly reduced.

Continuous Paired Associates (CPA). This task included two types of trial. On *study* trials participants first saw the word "STUDY" outlined in blue for 500 ms. Next, a two-digit number paired with an upper case letter (e.g., "18 – Q") appeared in a box below the word "STUDY" for 3000 ms. Finally, the number–letter pair disappeared for 3000 ms. On *test* trials participants saw the word "TEST" outlined in red for 500 ms. Next, a previously presented two-digit number was presented in a box, with 5 upper case letters (B, N, Q, T, X) in individual boxes below. Participants used the mouse to click on the letter that had been paired with the given number. 3000 ms were allowed for responding. After a response was made, the probe and letters disappeared for 3000 ms, plus any remaining time that was allotted for responding (to control for effects of temporal discriminability; see Baddeley, 1976).

The order of presentation of all items and trials was fixed. Numbers were not reused within a session. Old pairings of a given letter with a number were not reused once a letter reappeared 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). This assumption was not based upon a supposed capacity of primary memory. Indeed, it is difficult to know, a priori, what primary memory capacity would be in this task. For instance, what is the effect of a test trial on the contents of primary memory? Is all of the information lost? Does the letter–number of a study trail begin as a pair and then become chunked into a unit? Would this not remove information from primary memory, before freeing space?

Instead we looked at separate studies with the question of when secondary memory begins to become the more important mechanism of performance in this task. Rowe and Smith (1973) used the Waugh and Norman (1965) method of estimating the probability that an item was recalled from either primary or secondary method. They concluded that, when memoranda were highly imageable words, probability of recall from primary memory was still high with a lag of 1. But they also argue that the role of primary memory decreases precipitously at lags 2 and 3 and is absent at lag 4.

More recently, Unsworth et al. (2011) demonstrated that when pairs of unrelated words are used, significant interference is present at all lags other than 0. Furthermore, the largest accuracy drop occurred between lag 0 and lag 1. One test-trial causes a significant amount of forgetting, but subsequent study- and test-trails follow a smoother pattern. Sudden drops of accuracy are often interpreted as a transition between primary and secondary memory (e.g., Luck & Vogel, 1997; Unsworth & Engle, 2006). Nonetheless, we did not predict that one or two interruptions would lead to process-pure measurement of secondary memory. We did, however, assume that the role of primary memory would be minimized at lags 2–5.

Attention control tasks

Antisaccade task (AntiSacc). The antisaccade task (Hallett, 1978) was a modified version of the one used by Hutchison (2007). Each trial began with a "+" fixation that lasted for either 1000 or 2000 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 5000 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 (1935) 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. A total of 72 congruent, 72 incongruent and 72 neutral trials were evenly distributed throughout three blocks. 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, French, Harman, & Dermen, 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 Selst 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 4700 observations, 12 met this criterion. These scores were replaced with the cutoff value. Multivariate normality was tested using Mardia'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.

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 comparisons were made using change in χ^2 and change in Akaike's (1987) information criterion (AIC). AIC is a measure of model parsimony which takes into account both goodness-of-fit and number of to-be-estimated parameters. If a path is added and this results in a smaller AIC value, then it can be said that the loss of parsimony is offset by improved explanatory power.

Results and discussion

Descriptives are presented in Table 2. Intercorrelations among the tasks are presented in Table 3. Note that the score listed for digit span is the total number of lists correctly recalled, not the average list length at which test takers were unable to properly recall information. For the interested reader, this statistic was 6.6 (*SD* = 1.40).

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, for each participant, was entered into the analysis. Across tasks, internal consistency was generally good, with the exception of VA3 (Table 2). However, the simple correlations between VA3 and all other tasks were generally similar to the other three visual arrays tasks (Table 3). Moreover, a consistency score was generated across all four visual arrays tasks, which produced a Cronbach's alpha of .83. Thus, while one task is somewhat unstable, all four visual arrays tasks are united by a stable factor. VA3 was therefore retained for further analysis.

One 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 misunderstood instructions and reversed the response keys. These participants would 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 et al., 2012).

Model of memory and attention

The present model of memory and attention is displayed in Fig. 4 (Fit statistics on Table 4 – No Split Span).

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; 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, LetterSet = Letter Sets; NumSer = Number Series.

This model differs from our hypothesized model in that the split span tasks have been excluded and continuous paired associates is allowed to load on both primary and secondary memory. As can be seen, continuous paired associates had equivalent loadings on PM[2] (primary memory) and SM (secondary memory). This is curious, given that continuous paired associates only included lags of 2–5, which we assumed would minimize the presence of primary memory

[2] From this point on, abbreviations (e.g., PM) will refer to observed factors in our models. The constructs that these factors represent will continue to be referred to by their proper names (e.g., primary memory).

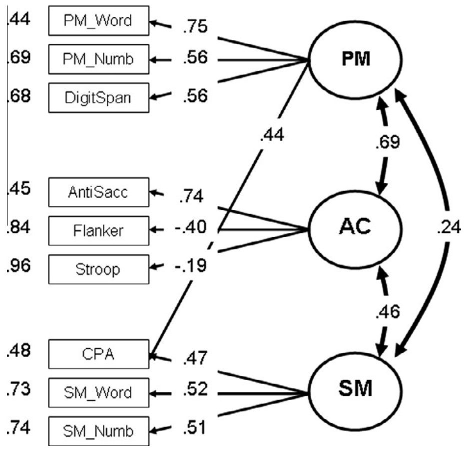


Fig. 4. Confirmatory factor analysis describing primary memory (PM), attention control (AC), secondary memory (SM). PM_Word = Primary Memory – words; PM_Numb = Primary Memory – numbers; AntiSacc = Antisaccade; CPA = Continuous Paired Associates; SM_Word = Secondary Memory – words; SM_Numb = Secondary Memory – Numbers.

(Rowe & Smith, 1973; Unsworth et al., 2011). This loading may indicate that CPA lags of 5 are not sufficient to overrun PM storage. It might also indicate that primary memory is not strictly limited-capacity storage. In hindsight, the requirement that test-takers continually create associations between letters and number likely introduced a component of contextual binding, similar to that proposed in the focal attention model of Oberauer et al. (2007). The efficacy with which this process is carried out may have had a lasting influence on memory of the letter–number pairs. Regardless, CPA loads equivalently on PM and SM and thus cannot be assumed to be solely reflecting retrieval from secondary memory. Finally, as we will explain, the split span tasks had an unexpectedly strong relationship to attention control, and were thus excluded from further analyses.

Based on previous studies (Mogle, Lovett, Stawski, & Sliwinski, 2008; Unsworth et al., 2010) it was expected that a theoretically accurate model would require the primary and secondary memory components of the free recall tasks to load on separate factors that have little-to-no correlation. In the initial model split span-blue was loaded on the primary memory factor (see Fig. 4). Split span-red and continuous paired associates were only loaded onto the secondary memory factor. While this grouping of tasks was seemingly coherent, the fit for this model was poor (Table 4; Initial Model).

Although we predicted that split span-blue would load on primary memory and both split span-red and continuous paired associates would load on secondary memory, this was based upon pre-experimental assumptions regarding the nature of primary and secondary memory. The memory and attention tasks were thus examined via exploratory factor analysis, which allowed for an examination of these tasks, independent of our pre-experimental assumptions.

As can be seen in Table 5, the predicted three-factor solution obtained. Factor 1 is defined by the primary memory tasks, factor 2 by the secondary memory tasks and factor 3 by the attention control tasks. However, both of the split span tasks had strong loadings on the attention factor, and continuous paired associates had loadings on both primary and secondary memory.

We thus allowed the split span tasks to cross load on the attention factor (Table 4; Split Span Cross Loads). While this improved the fit of the model, a strong correlation was apparent between the primary and secondary memory factors ($r = .63$). This observation is contrary to other studies that found a substantially smaller (sometimes non-existent) relationship between these factors (Mogle et al., 2008; Unsworth et al., 2010). Consistent with the exploratory factor analysis we cross loaded CPA on primary memory (CPA Cross Load). This reduced the correlation between primary and secondary memory to a non-significant .21, thus bringing the model in line with other studies.

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 Memory Number; CPA = Continuous Paired Associates; SSred = Split span red squares.
Bold values load on a given factor at .3 or higher.

Table 4
Fit statistics for confirmatory factor analyses.

	χ^2	*df*	χ^2/df	RMSEA	SRMR	NNFI	CFI	AIC
Memory and attention tasks								
Initial model	88.56	41	2.16	.07	.06	.92	.94	138.56
Split span cross load	71.35	39	1.83	.06	.06	.94	.96	125.35
CPA cross load	48.28	38	1.27	.04	.05	.98	.99	104.28
No split span	**32.96**	**23**	**1.43**	**.05**	**.05**	**.96**	**.97**	**76.96**
Full confirmatory factor analysis								
Full model	**199.69**	**139**	**1.44**	**.05**	**.05**	**.98**	**.98**	**341.69**

Note: Preferred models appear in bold type. CPA = Continuous Paired Associates.

While this model provides a good fit to the data, problems were apparent with the split span tasks, which had an unexpectedly strong relationship to the attention control factor. More problematic, split span red did not significantly load on secondary memory in the model labeled "Split Span Cross load" (Table 4), while split span blue did not have a significant loading on the primary memory factor in the model labeled "CPA Cross Load". Due to this inconsistent relationship between these tasks and the constructs they were designed to measure, split span was removed from the analysis.

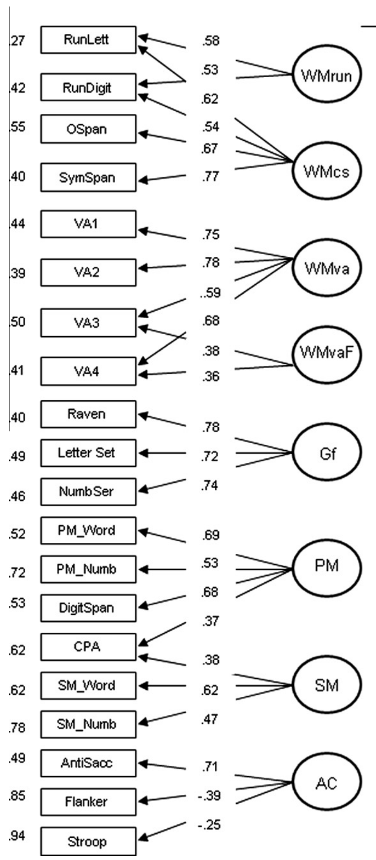
Full confirmatory factor analysis

The confirmatory factor analysis, in which all hypothesized factors were included, is displayed in Fig. 5. The fit to the data was strong (Table 4; Full Model).

Two sets of factors are noteworthy. First, the factor labeled WMcs is composed of complex span variance that is shared with running span tasks. However, as we have noted, some studies have reported that running memory span substantially predicts fluid intelligence above-and-beyond complex span (Broadway & Engle, 2007; Shipstead et al., 2012), thus implying the presence of additional processes.

We confirmed this observation in the present data by forming *z*-score composites of complex span tasks (CSz), running memory span tasks (RSz) and fluid intelligence tasks (GFz). The working memory composites were entered into a regression as predictors of fluid intelligence. Fig. 6 displays that, while CSz and running memory span (RSz) largely share in prediction of GFz (.22), RSz adds substantially to the model (.19).

This trend is represented in Fig. 5 through the factor labeled WMrun. This factor is composed of running memory span variance that is not shared with complex span tasks. WMrun has strong correlations to Gf and PM, but no relationship to AC or SM. This indicates that the strong relationship of running span to fluid intelligence is due to a component of primary memory that is absent from complex span tasks.



	WMrun	WMcs	WMva	WMvaF	Gf	PM	SM	AC
WMrun	-							
WMcs	X	-						
WMva	.11	.61	-					
WMvaF	.29	.03	X	-				
Gf	.43	.71	.68	.16	-			
PM	.69	.66	.61	.28	.80	-		
SM	.08	.52	.52	.13	.59	.35	-	
AC	.09	.68	.74	.41	.69	.70	.51	-

Fig. 5. Full confirmatory factor analysis. For clarity, latent correlations between factors are represented as a matrix. "X" indicates a relationship that is constrained to 0. Signs for attention factor have been reversed to positive. WMrun = working memory variance that is unique to the running memory span task; WMcs = working memory as reflected by complex span tasks; WMva = working memory as reflected by visual arrays tasks; WMvaf = working memory variance that is unique to visual arrays tasks with an attention filtering component; Gf = general fluid intelligence; PM = primary memory; SM = Secondary Memory; AC = attention control; RunLett = Running Letter Span; RunDigit = Running Digit Span; Ospan = operation span; SymSpan = Symmetry Span; ; VA1 = visual arrays – color change; VA2 = visual arrays – orientation change; VA3 = visual array – selective color change; VA4 = visual arrays – selective orientation change; NumSer = Number Series; LetterSet = Letter Sets; PM_Word = Primary Memory, Free Recall, Words; PM_Numb = Primary Memory, Free Recall, Numbers; SM_Word = Secondary Memory, Free Recall, Words; CPA = Continuous Paired Associate; SM_Numb = Secondary Memory, Free Recall, Numbers; AntiSacc = antisaccade task.

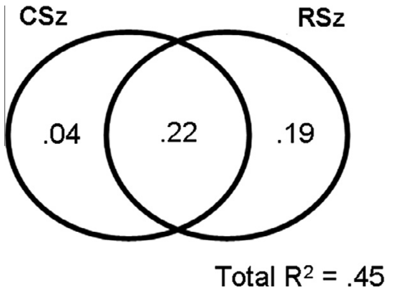


Fig. 6. *Z*-score composites of complex and running memory span predicting a *z*-score composite of fluid intelligence.

The second noteworthy observation pertains to the visual arrays factors. All visual arrays tasks were loaded onto factor WMva (working memory, as measured by visual arrays). This factor represents components that are common to all visual arrays tasks, regardless of task demands. Turning to WMvaF (visual arrays – attention filtering), this factor was formed by cross-loading the visual arrays tasks that included a filtering component onto a separate factor. Consistent with our predictions, WMvaF has a significant relationship to the attention control factor (AC) above-and-beyond the basic visual arrays factor. Nonetheless, it is noteworthy that the relationship between WMva and AC is strong.

Common mechanisms of working memory capacity and fluid intelligence

The first structural analysis articulates our theoretical perspective regarding causality among the factors. Specifically, the correlation between working memory capacity and fluid intelligence is expressed as the common influence of primary memory, attention control, and secondary memory. As such, the model in Fig. 7 treated PM, AC, and SM as common causes of WMC (working memory capacity) and of Gf (fluid intelligence). In this initial model WMC was defined using complex span and non-filtering visual arrays tasks. The specific reasons for selecting these, rather than all, working memory tasks are detailed in the subsequent section. In short, this definition of WMC was preferred, as these tasks accounted for the variance that was common to all working memory capacity tasks. The fit was good (Table 6; CS and VA).

Examining Fig. 7, regression paths extend from PM, AC, and SM to both WMC and Gf. The direction of the arrows in this model is motivated by our theoretical perspective that PM, AC, and SM can be treated as mechanisms of WMC and Gf. As such, a significant path is interpreted as an indication that a given predictor has a causal effect on either WMC or Gf. To summarize our interpretation of this model, Fig. 7 indicates that secondary memory is the only factor that directly explains the correlation between working memory capacity and fluid intelligence. The rest of this correlation is explained by the relationship between primary memory and attention control. Two points are critical to this interpretation.

First, non-significant paths between the factors should not be interpreted as a lack of correlation. For example, the path from AC to Gf is non-significant. The confirmatory factor analysis revealed that these factors are strongly correlated (.69; Fig. 5), but the structural analysis in Fig. 7 (which is a latent regression) indicated that the correlation is better construed as being mediated by PM and SM. In other words, attention control contributes to fluid intelligence to the extent that attention control is correlated with primary and secondary memory.

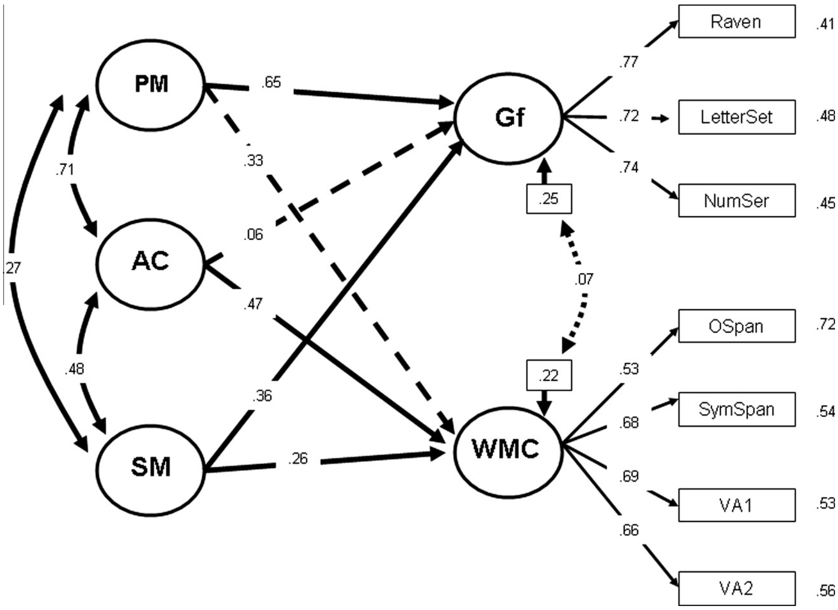


Fig. 7. Structural equation model in which primary memory, attention control, and secondary memory serves as explanations for the correlation between fluid intelligence and working memory capacity. Note that the tasks that compose Gf and WMC have been included for clarity. The tasks that compose PM, AC, and SM can be found in Fig. 3. Dashed paths are non-significant at the .05 level. PM = primary memory; AC = attention control; SM = Secondary Memory; Gf = fluid intelligence; WMC = working memory capacity; Raven = Raven's Advanced Progressive Matrices; LetterSet = Letter Sets; NumSer = Number Series; OSpan = operation span; SymSpan = Symmetry Span; VA1 = visual arrays – color change; VA2 = visual arrays – orientation change.

Table 6
Fit statistics for model of correlation between working memory capacity and fluid intelligence.

Model	χ^2	*df*	χ^2/df	RMSEA	SRMR	NNFI	CFI	AIC
CS and VA	**127.43**	**93**	**1.37**	**.04**	**.05**	**.98**	**.99**	**213.43**
All WMC tasks	410.28	159	2.58	.09	.06	.94	.95	512.28

Note: Preferred models appear in bold. CS = complex span; VA = visual arrays; WMC = working memory capacity.

Second, if significant paths extend from any predictor to both WMC and to Gf, then this predictor can be interpreted as a common cause. That is, it directly expresses a portion of the correlation between WMC and Gf (obtainable by multiplying these two paths together; see Loehlin, 2004). The model in Fig. 7 indicated that only SM meets this criterion. While the path from PM to Gf was significant, this was not the case for the path between PM and WMC. Conversely, the direct relationship between AC and WMC was significant, but this was not the case for AC and Gf.

Thus, of the presently included predictors, only retrieval from secondary memory provided a direct explanation of the correlation between fluid intelligence and working memory capacity. This is not to say that retrieval from secondary memory explains the full correlation between working memory capacity and fluid intelligence (cf. Mogle et al., 2008). SM only directly accounted for a small portion of the total correlation ($r = .09$). Yet examination of the full model reveals that the entire correlation between WMC and Gf was accounted.

This latter statement is confirmed by examining the disturbance terms, which are the boxes next to WMC and Gf. These terms represent the portion of each of these factors that is not explained by the model. The correlation between the disturbance terms was not significant. That is, the portions of WMC and Gf that were not predicted by the model were also not related. Thus, the bulk of the relationship between WMC and Gf was expressed in the correlation between AC and PM, which was quite strong (.71).

On this latter point, although the path from PM to WMC was numerically larger than the path from SM to WMC, it was non-significant. One interpretation of this issue is that, because PM and AC were strongly correlated, the model could not properly portion the variance that these factors shared with WMC to one path or the other. Thus, the next set of analyses will treat PM, AC, and SM as direct mediators of the relationship between WMC and Gf. This will allow for greater control over manner in which variance is portioned to different factors.

The definition of WMC in Fig. 7

Regarding the composition of WMC, this factor was defined by complex span and the non-selective visual arrays tasks. A second version of this factor was also created in which all working memory tasks were loaded onto WMC, however, the fit for this model was poor (Table 6, All-WMC-Tasks). It is worth noting that we favored the restricted factor that is presented in Fig. 7 for reasons beyond fit statistics.

First, the confirmatory factor analysis (Fig. 5) revealed that all variance that was common to the working memory tasks was expressed in the two factors that were defined by complex span and basic visual arrays tasks (WMcs and WMva). Variance that was specific to running memory span (WMrun) and visual arrays filtering (WMvaF) tasks was uncorrelated to either WMcs or WMva. Thus, all common aspects of working memory capacity should be captured by WMC in Fig. 7.

Second, a more complex model that included WMrun and WMvaF could be created. However, in models such as the one in Fig. 7, the correlations between factors on the right hand side are expressed through factors on the left hand side (see Loehlin, 2004). Thus, including factors that are uncorrelated to WMC (i.e., WMrun and WMvaF) can result in misleading or uninterpretable solutions. That is, it is undisciplined to assume that uncorrelated factors have a common cause (e.g., arrows from PM to both WMC and WMrun). WMrun and WMvaF are best handled in the next set of analyses that specifically allow them to have independent relationships to PM, AC, and SM.

Fractionating the correlation between working memory span and fluid intelligence

The next set of structural equation models focused on relating performance on different types of working memory tasks to memory and attention control, with the goal of building a model of the relationship between working memory capacity and fluid intelligence. Note that the direction of arrows between all working memory factors and PM, SM, and AC will be reversed (see Fig. 8). This does not denote a change in theory from the model in Fig. 7. Rather, it was done to allow WMrun and WMvaF to be related to the predictor variables, independent of either WMspan or WMva. Such changes are allowable, since structural equation models are correlational, and thus not sensitive to causality. Importantly, these models allow us to portion variance in a more specific manner than the model in Fig. 7.

The basic model in each analysis is displayed in Fig. 8a. A technical reading of this model implies that PM, AC, and SM are all related to the extent that they are components of the working memory system. However, our use of this model is not to contradict Fig. 7, which treats PM, AC, and SM as common causes of WMC and Gf. Instead, the models in Fig. 8 allow us to use mediational techniques to decompose the relationship between WMC and Gf with finer precision than in Fig. 7. Moreover, WMrun and WMvaF can be added to these models such that they will have relationships to PM, AC, and SM that are independent of WMcs or WMva.[3]

[3] That is, structural equation models express correlations by tracing arrows backward then forward, but not forward then backward. Thus, two working memory variables can be represented as having fully independent relationships to the same factor (see Loehlin, 2004).

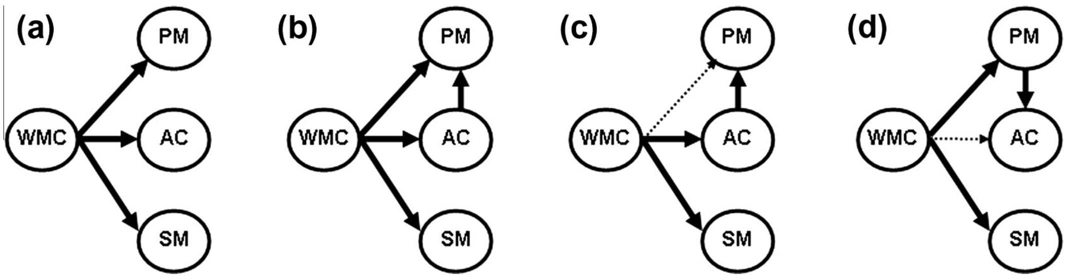


Fig. 8. Diagram of meditational tests performed to test direct and indirect relationship between working memory capacity and the memory and attention factors. WMC = working memory capacity (as measured by a given set of tasks); PM = primary memory; AC = attention control; SM = Secondary Memory.

Fig. 8b adds a regression path between two latent variables. If this path is significant, it can be stated that PM and AC have a relationship beyond being components of WMC.

Since structural equation modeling is not sensitive to causality, the arrow between PM and AC could point in either direction and produce the same fit. However, reversing the direction of the arrow allows us to use mediational techniques to reduce model complexity. Fig. 8c displays a case in which the relationship between WMC and PM can be explained by variance that these factors share with AC. This relationship was implied by the model in Fig. 7. In this case, the path from WMC to PM becomes non-significant and can be removed from the model without reducing the fit. Fig. 8d displays a contrasting case in which PM fully accounts for the relationship between WMC and attention control. Due to the strong correlation between PM and AC, as well as the relatively large path between PM and WMC, this model remains tenable. It would indicate that the relationship between WMC and AC can be fully explained by variance that both share with PM.

Analysis of complex span tasks

Although complex- and running memory span tasks reflect many of the same processes (Cowan, 2005; Broadway & Engle, 2010; Shipstead et al., 2012), the confirmatory factor analysis (Fig. 5) indicated that the running memory span includes cognitive mechanisms that are not reflected in complex span performance. Thus, the first step was to create a simple model that related complex span performance to PM, AC, and SM. Running memory span was included in a subsequent model.

The best fitting model (Table 7; PM Removed) is displayed in Fig. 9 (critical intermediate models can be found in Appendix A). The data are consistent with the position that processing tasks in complex span tasks cause the contents to primary memory to be lost (Unsworth & Engle, 2006) and controlled attention is engaged to maintain this information (e.g., Barrouillet et al., 2004; Engle, 2002; Kane, Brown, et al., 2007; Kane, Conway, et al., 2007). Also noteworthy, we replicated the findings of Unsworth and Spillers (2010) in which the relationship between WMcs and SM was not mediated by AC. Complex span performance does not simply reflect a person's ability to use attention to manage the contents of primary memory, but also a person's ability to engage searches of secondary memory to retrieve relevant information that has been displaced from primary memory (Unsworth & Engle, 2007b; Unsworth & Spillers, 2010).

Although the model from Fig. 8a provided a reasonable fit to the data (Table 7; Basic Model), the fit improved significantly when a path was added from AC to PM (Table 7; AC to PM; $\chi^2_{\text{difference}} = 9.49$; $p < .05$; additional path reduced AIC). Moreover, the path from WMcs to PM became non-significant. Removing this path did not reduce the model fit ($\chi^2_{\text{difference}} = .78$; $p > .10$). In contrast, removal of the path from WMcs to AC resulted in a poor fit across all measures (Table 7; AC Removed; $\chi^2_{\text{difference}} = 38.33$; $p < .05$). No other test of mediation approached significance.

Table 7
Mediational analysis of working memory span tasks.

Model	χ^2	*df*	χ^2/df	RMSEA	SRMR	NNFI	CFI	AIC
Complex span only								
Basic model	68.46	40	1.71	.06	.06	.95	.96	120.46
AC to PM	58.97	39	1.51	.05	.05	.96	.97	112.97
PM removed	**59.75**	**40**	**1.49**	**.05**	**.05**	**.96**	**.97**	**111.75**
AC removed	97.19	40	2.43	.08	.11	.87	.91	149.19
AC to SM	67.96	39	1.74	.06	.05	.95	.96	121.96
PM to SM	68.1	39	1.75	.06	.05	.95	.96	240.11
Complex and running span								
RSpan to PM	**109.62**	**58**	**1.89**	**.06**	**.05**	**.95**	**.97**	**175.62**
AC added	109.28	57	1.92	.07	.05	.95	.96	177.28
SM added	109.82	57	1.93	.07	.05	.95	.96	177.82
Relationship to fluid intelligence								
Span tasks to Gf	**145.90**	**93**	**1.57**	**.05**	**.05**	**.97**	**.98**	**231.90**

Note: Preferred models appear in bold. AC = attention control; PM = primary memory; SM = Secondary Memory; Rspan = running memory span; Gf = fluid intelligence.

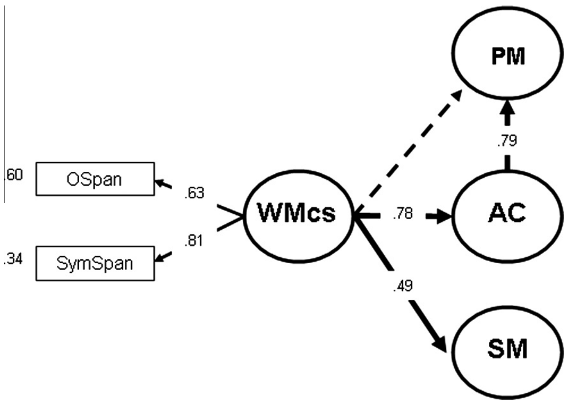


Fig. 9. Final model of the relationship of complex span to memory and attention. Dashed paths have been constrained to 0. Note that the tasks used to measure WMcs have been included for clarity. The tasks that compose PM, AC, and SM are displayed in Fig. 3. WMcs = working memory as measured by complex span tasks; PM = primary memory; AC = attention control; SM = Secondary Memory; OSpan = operation span; SymSpan = Symmetry span.

The unique aspects of running memory span

The next step of the analysis expanded the model to include running memory span (Fig. 10). Consistent with the confirmatory factor analysis (Fig. 5), the running memory span was loaded on the same factor as complex span (WMcs) as well as a separate, independent, factor (WMrun). Consistent with the confirmatory factor analysis, WMrun was allowed to predict PM.

This model provided a good fit to the data (Table 7; Rspan to PM). Importantly, it also provides a good fit to theory regarding the similarities and differences between complex span and running memory span performance. Complex span performance contains interpolated distraction which displaces information from primary memory (Unsworth & Engle, 2006). This information can either be maintained by engaging controlled attention when distraction is high (Kane, Brown, et al., 2007; Kane, Conway, et al., 2007), or retrieved when maintenance fails (Unsworth & Engle, 2007b). Both of these processes are critical to complex span performance.

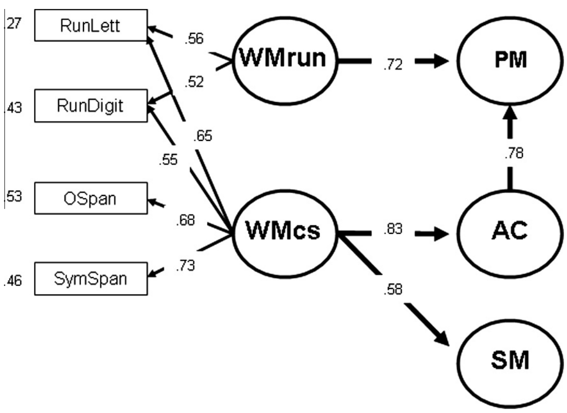


Fig. 10. Final model of unique components of running memory span and components that are shared with complex span. Note that the tasks used to measure WMcs and WMrun have been included for clarity. The tasks that compose PM, AC, and SM are displayed in Fig. 3. WMrun = variance that is unique to the running memory span task. WMcs = working memory as measured by complex span tasks; PM = primary memory; AC = attention control; SM = Secondary Memory; RunLett = Running Letter Span task; RunDigit = Running Digit Span task; OSpan = operation span; SymSpan = Symmetry span.

As indicated by the cross loading of the running memory span tasks on WMcs, the ability to resist failures of attention and to retrieve forgotten information aids a person's performance on these tasks. That said, running memory span does not include a component of overt distraction. This is key to understanding WMrun. In the absence of an interpolated processing task, running memory span tasks likely provide a cleaner measurement of the storage capacity of primary memory on a moment-to-moment basis (Bunting et al., 2006).

Additional tests allowed paths between WMrun and AC (Table 7; AC Added; $\chi^2_{\text{difference}} = .34$; $p > .10$; AIC increased) and WMrun and SM (SM Added; $\chi^2_{\text{difference}} = .2$; $p > .10$; AIC increased). Neither resulted in improved the fit. Thus, running memory span reflects the same processes as complex span, along with an additional component of primary memory.

The relationship of span tasks to fluid intelligence

Finally, fluid intelligence was added to the model such that primary memory, secondary memory and attention control served as mediators of its relationship to working memory capacity (Fig. 11), the fit was good (Table 7; Span Tasks to Gf).[4] Several observations are noteworthy. First the relationship of complex- and running memory span tasks to fluid intelligence was fully explained by primary and secondary memory. Second, although the raw correlation between AC and Gf was strong (see Fig. 5), the model in Fig. 11 revealed that it is fully explained by PM and, to a lesser extent, SM. That is, the effect that attention control has on reasoning is not direct, but realized through its effect on memory processes.

The model in Fig. 11 further clarifies the relatively strong relationship between running memory span and fluid intelligence. Running memory span measures primary memory in a more direct manner than does complex span. This relationship is likely attributable to running memory span providing a fairly direct measure of moment-to-moment storage capacity of focal attention (Bunting et al., 2006), apart from the influence of interruption.

Fractionating the correlation between visual arrays and fluid intelligence

Next the visual arrays tasks were subjected to the same meditational analysis (e.g., Fig. 8). As with complex- and running memory span tasks, this analysis was carried out in two steps. First, a model of basic visual arrays performance was constructed, then filtering tasks were added.

The model that relates WMva to the three mechanisms is displayed in Fig. 12 (critical intermediate models are avail-

[4] In an initial model the path between PM and Gf was non-significant, despite the numerically large relationship. On the assumption that this was attributable to multicollinearity between WMrun, PM, and Gf, a starting value from the initial model was provided for the direct path between PM and Gf. This resolved the issue.

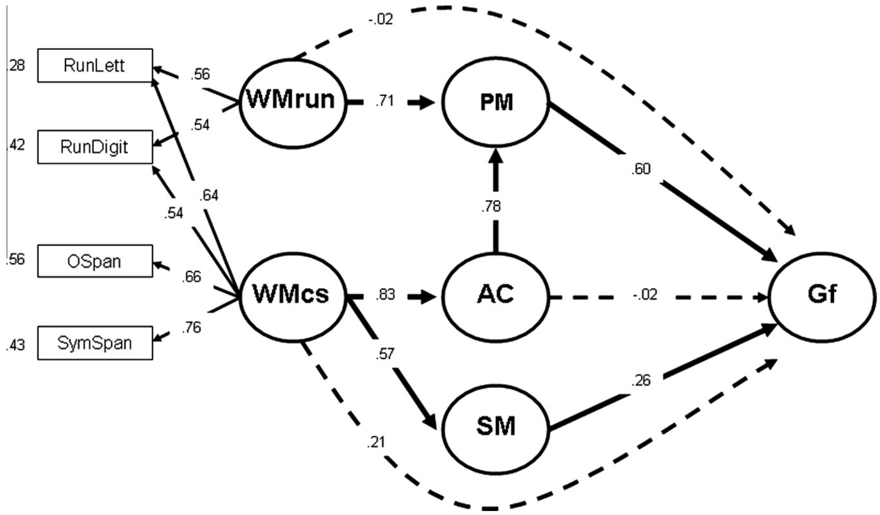


Fig. 11. The relationship of working memory capacity (as reflected in complex and running memory span tasks) to fluid intelligence, as mediated by primary memory, attention control, and secondary memory. Note that the tasks used to measure WMcs and WMrun have been included for clarity. The tasks that compose PM, AC, SM, and Gf are displayed in Fig. 4. WMrun = variance that is unique to the running memory span task. WMcs = working memory as measured by complex span tasks; PM = primary memory; AC = attention control; SM = Secondary Memory; Gf = general fluid intelligence RunLett = Running Letter Span task; RunDigit = Running Digit Span task; OSpan = operation span; SymSpan = Symmetry span.

able in Appendix B). It indicates that visual arrays performance (WMva) is directly related to attention control and secondary memory and indirectly related to primary memory, via attention control. Despite task-specific differences, the processes involved in visual arrays performance are similar to those reflected in complex span performance.

Similar to complex span tasks, Fig. 8b (in which no direct relationship exists between working memory and primary memory) provided the best explanation of visual arrays performance (Table 8; PM Removed). Relative to Basic Model, fit improved when a path was added between PM and AC (Table 8; AC to PM; $\chi^2_{\text{difference}} = 7.56;\ p < .05$; AIC decreased). Relative to model AC to PM, removing the direct path from WMva to PM did not reduce the fit of the model (PM removed; $\chi^2_{\text{difference}} = 1.00;\ p > .10$). In contrast, removing the direct path from WMva to AC did reduce the fit (AC removed; $\chi^2_{\text{difference}} = 12.26;\ p < .05$).

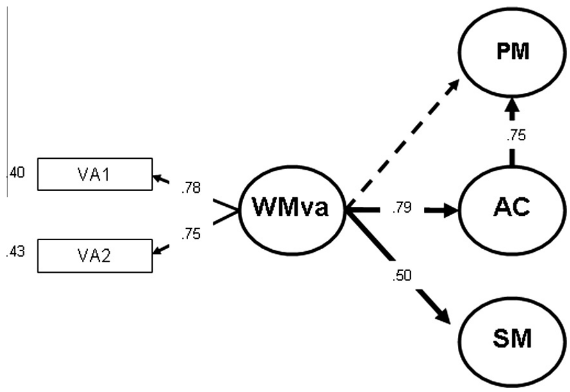


Fig. 12. Final model of the relationship of visual arrays to memory and attention. Dashed paths have been fixed to 0. Note that the tasks used to measure WMva have been included for clarity. The tasks that compose PM, AC, and SM are displayed in Fig. 3. WMva = working memory as measured by visual arrays tasks; PM = primary memory; AC = attention control; SM = Secondary Memory; VA1 = visual arrays – color change; VA2 = visual arrays – orientation change.

Visual arrays and attention filtering

Next, the visual arrays filtering tasks were added to the model. As can be seen in Fig. 13, the requirement that participants engage attention to filter inappropriate information (WMvaF) from a display predicts aspects of attention control that are not apparent in the basic visual arrays task. That is, the relationships of WMva and WMvaF to AC are independent. Contrary to storage-based accounts of visual arrays performance, visual arrays also had a strong relationship to attention control, regardless of which type of task is used.

The preferred model from Fig. 13 was based on the confirmatory factor analysis and only related WMvaF to AC (Table 8; WMvaF to AC). Attempts to relate WMvaF to PM (PM added; $\chi^2_{\text{difference}} = .20; p > .10$; AIC increased) and to SM (SM added; $\chi^2_{\text{difference}} = .96; p > .10$; AIC increased) did not result in improvements to model fit.

The relationship of visual arrays tasks to fluid intelligence

Finally, as seen in Fig. 14, fluid intelligence was added to the model. Similar to span-based measures of working memory capacity, the relationship was fully explained by PM, AC, and SM and the fit was excellent (Table 8; Visual Arrays to Gf). Consistent with the results of our initial structural equation model (Fig. 7), visual arrays shows the same structure of relationships to primary memory, attention control, secondary memory, and fluid intelligence as does complex span. Thus the results of our initial structural equation model cannot be attributed to an excessive influence of one type of working memory task on the composition of that overall factor (WMC in Fig. 7).

The finding that complex span and visual arrays reflect the same underlying structure of latent variables has important implications for the study of working memory

Table 8
Mediational analysis of visual arrays tasks.

Model	χ^2	*df*	χ^2/df	RMSEA	SRMR	NNFI	CFI	AIC
Visual arrays – basic only								
Basic model	48.97	40	1.22	.03	.05	.98	.99	100.97
AC to PM	40.41	39	1.04	.01	.04	1.00	1.00	94.41
PM removed	**41.41**	**40**	**1.04**	**.01**	**.05**	**1.00**	**1.00**	**93.11**
AC removed	52.67	40	1.32	.04	.05	.98	.99	104.67
AC to SM	47.99	39	1.23	.03	.05	.98	.99	101.99
PM to SM	47.99	39	1.23	.03	.05	.98	.99	101.99
Visual arrays – basic and filter								
WMvaF to AC	**76.02**	**58**	**1.31**	**.04**	**.05**	**.98**	**.98**	**142.02**
PM added	75.82	57	1.33	.04	.05	.98	.98	143.82
SM added	75.06	57	1.32	.04	.05	.98	.98	143.06
Relationship to fluid intelligence								
Visual arrays to Gf	**100.83**	**92**	**1.10**	**.02**	**.04**	**.99**	**.99**	**188.83**

Note: Preferred models appear in bold. AC = attention control; PM = primary memory; SM = Secondary Memory; WMvaF = visual arrays tasks that include a filtering component; Gf = fluid intelligence.

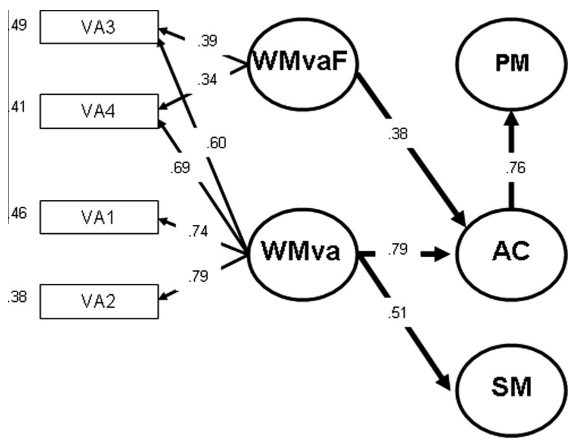


Fig. 13. Final model of the relationship of visual arrays (with and without a filtering component) to memory and attention. Note that the tasks used to measure WMva and WMvaF have been included for clarity. The tasks that compose PM, AC, and SM are displayed in Fig. 3. WMva = working memory as measured by visual arrays tasks; WMvaF = variance that is unique to visual arrays tasks that include a filtering component; PM = primary memory; AC = attention control; SM = Secondary Memory; VA1 = visual arrays – color change; VA2 = visual arrays – orientation change; VA3 = visual array – selective color change; VA4 = visual arrays – selective orientation change.

capacity. Foremost, it increases confidence that, at least at the latent level, the results of studies that are conducted using one of these types of task are applicable to the theories that are based on research that was conducted using the other. That said, research conducted using one type of task is not automatically applicable to research conducted using the other. Indeed, the confirmatory factor analysis indicated that these tasks can be loaded onto separate factors, and this observation is supported in separate data sets (Shipstead et al., 2012, submitted for publication). Moreover, complex span and visual arrays differ in terms of memoranda, report type, and serial versus parallel presentation of information. And when visual arrays includes a filtering component, this adds a component of attention control that is not related to the factor that underlies complex span performance (see Fig. 5). Thus, due to task-specific demands, researchers may, in certain cases, find differences in the predictive utility of these tasks.

General discussion

The present study demonstrates that working memory capacity and its relationship to fluid intelligence can be largely described as primary memory, attention control, and secondary memory functioning in concert to facilitate complex cognition. All working memory tasks had strong, direct, relationships to both attention control and secondary memory. But in the cases of complex span and visual arrays, the relationship to primary memory was explained by a common relationship to attention control.

With respect to complex span, the relationship is readily interpreted within the perspective of Engle, Kane, and colleagues (Engle, 2002; Kane, Brown, et al., 2007; Kane, Conway, et al., 2007; Unsworth & Engle, 2006). It is difficult to maintain to-be-remembered items while alternately performing secondary processing tasks. Attention control is engaged in the service of organizing the contents of primary memory (e.g., Engle, 2002; Kane, Brown, et al., 2007; Kane, Conway, et al., 2007). For visual arrays, the relationship is a bit more vexing, as this task is typically assumed to reflect the amount of information a person can store in immediate awareness (Chuderski et al., 2012; Luck & Vogel, 1997; Saults & Cowan, 2007). One obvious difference between the way primary memory and visual arrays were defined is that the primary memory tasks were verbal, while visual arrays were visuo-spatial. Thus, a different outcome may have been reached had our primary memory factor been differently defined.

Although we cannot eliminate this conclusion, we note that visual arrays had a strong, direct, relationship to secondary memory, which was composed of the same verbal materials used in the primary memory tasks. Moreover, in terms of the relationship of visual arrays to fluid intelligence, there was no need to assume the presence of a separate visuo-spatial primary memory. The correlation is fully explained by the present memory factors, with no evidence of a residual relationship.

In light of these observations, we contend that an important component of visual arrays performance is a

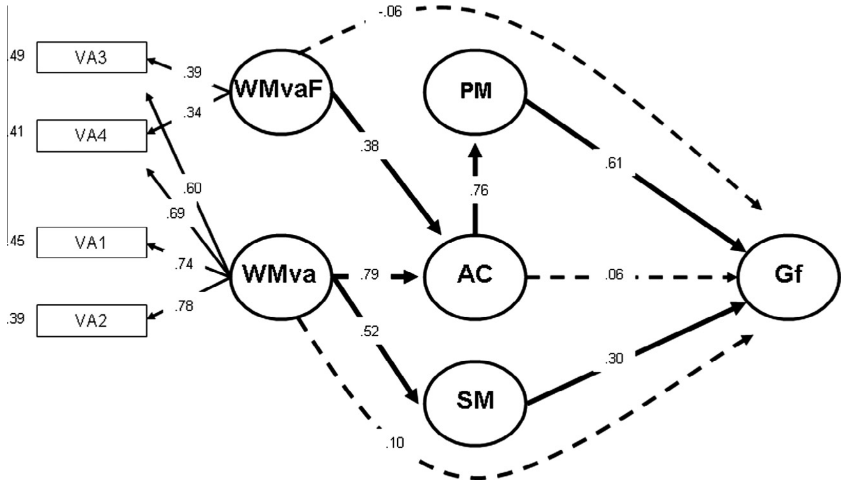


Fig. 14. The relationship of visual arrays (simple change detection and attention filtering tasks) to general fluid intelligence, as mediated by primary memory, attention control and secondary memory. Note that the tasks used to measure WMva and WMvaF have been included for clarity. The tasks that compose PM, AC, SM, and Gf are displayed in Fig. 4. WMva = working memory as measured by visual arrays tasks; WMvaF = variance that is unique to visual arrays tasks that include a filtering component; PM = primary memory; AC = attention control; SM = Secondary Memory; Gf = general fluid intelligence; VA1 = visual arrays – color change; VA2 = visual arrays – orientation change; VA3 = visual array – selective color change; VA4 = visual arrays – selective orientation change.

person's ability to remain focused on the task. Loss of focus may disrupt the initial encoding of the array, or cause the test-taker to lose contact with the memory of the array during the delay period, or both. In other words, our results are consistent with the perspective of Fukuda and Vogel (2009, 2011) that visual arrays performance strongly reflects a person's ability to resist being drawn into distraction. Although the basic visual arrays task does not include an overt component of distraction, people with poor attention control will be prone to losing focus in this task, due to events in the testing environment, or cognitive events (for instance, mind-wandering; Kane, Brown, Neath, & Chater, 2007; McVay & Kane, 2011). The success or failure of attention control processes (as well as retrieval processes; Hartshorne, 2008; Makovski & Jiang, 2008; Shipstead & Engle, 2013) thus contributes to a person's effective maintenance capacity.

Turning to running memory span, this variety of task had a direct relationship to primary memory above-and-beyond any relationship to attention control. This finding clarifies the relatively strong relationship between running span and fluid intelligence. Running span provides a more direct index of primary memory capacity that do other working memory tasks. Importantly, and unlike attention control, primary memory capacity is directly related to fluid intelligence.

What is primary memory?

From a theoretical perspective, we initially equated primary memory with Cowan (2001, Cowan et al., 2005) and Oberauer's (2002, Oberauer et al., 2007) models of focal attention. Cowan (2001) conceives of focal attention as a storage system, in which 3–5 units of information can be protected from proactive interference. Oberauer's (2002) position on this topic is similar (Oberauer et al., 2007), but assumes that the structurally-fixed portion of focal attention is limited to one item. Individual differences in maintenance capacity are explained through the ability to form and break temporary associations between attention and relevant units of memory, thus expanding the size of primary memory beyond one item. The critical divergences from Cowan's perspective are that (1) the 3–5 item limit is not fixed capacity storage, but the result of effective processing (Oberauer et al., 2007) and (2) these items are subject to proactive interference (Oberauer, 2001).

Aspects of both perspectives are apparent in the present data. For instance, the central tenet of Cowan's (2001) theory is that focal attention can protect multiple items from proactive interference. As we have noted, Craik and Birtwistle (1971) report that the secondary memory component of free recall is subject to buildups of proactive interference, while the primary memory component is not. We reexamined our data and found a replication of this trend. Mean recall for SM_Word was 2.43 (sd = 1.47) on the first trial, but 1.65 (sd = 1.51) on the last trial ($t = 6.51$, $p < .001$). In contrast, average PM_Word recall was 2.67 (sd = 1.08) on the first trial and 2.68 (sd = 1.16) on the last trial ($t = -.05$; $p = .96$). Only the secondary memory portion of free recall decreased in response to the buildup of proactive interference. This is consistent with Cowan's (2001) position that focal attention provides multi-item maintenance that protects information from proactive interference.

At the same time, our models indicated that the capacity of primary memory is subject to two major influences. The first was represented by WMrun and second by AC. Each of these factors accounted for roughly half of the variance in PM (obtained by squaring the direct paths between these factors; ~.7 squared is .49). Thus, while multi-item storage may be apparent in our data, the relationship between PM and AC indicates that the effective capacity of primary memory capacity is partially determined by attention control, which keeps memory and attention organized around relevant information.

On this point, it is relevant to note that, although we have treated the AC factor as reflecting a person's ability to resist distraction, similarly-defined factors are typically found to have a strong relationship to memory updating (Friedman et al., 2006, 2008; Miyake et al., 2000; Shipstead et al., submitted for publication). Distraction-avoidance may be a narrow interpretation AC. In all likelihood processes that are critical to keeping immediate memory up-to-date provide at least a secondary influence in our AC factor. The strong relationship between PM and AC indicates that primary memory capacity represents more than the amount of information a person can maintain. Primary memory also reflects processes that function to ensure that attended-and-maintained information is appropriate. This perspective bears a closer resemblance to the theory of Oberauer et al. (2007) in which the capacity of primary memory capacity is limited, not by fixed capacity storage, but by a process that ensures only relevant information is bound to focal attention.

Primary memory capacity as it relates to running memory span

Of our working memory-related factors, only WMrun had a direct relationship to PM. The implication is that running memory span performance includes a component of absolute primary memory capacity that is independent of the influence of attention control or retrieval from secondary memory.

In their analysis of the running memory span task, Bunting et al. (2006) argue that, when faster presentation rates are used (which was the case in this study), the contents of focal attention cannot be accurately updated. Test-takers thus adopt a passive approach in which they wait until the entire list has been presented, then recall relevant items from short-term memory. Critical to this perspective, short-term memory is assumed to decay rapidly (see Cowan, 1988, 1999). Thus, the amount of information a person can immediately report is directly related to the amount that can be instantly captured in focal attention. Applying this perspective to the present data, WMrun represents the portion of recall in running memory span performance that is related to the size of focal attention, and WMcs represents attention control and secondary memory processes that facilitate further retrieval of information.

The passive-processing position is apparent in the results of other studies. For instance Hockey (1973) demonstrated that, when presentation rate is greater than one item per second, passive strategies result in more items being recalled, relative to when test-takers actively rehearse items. More recently, Palladino and Jarrold (2008) reported that test-takers generally recall fewer to-be-maintained items in the running memory span than in simple span tasks, even when the number of to-be-remembered items is consistent between-tasks. This supports the idea that, when left to their own devices, test-takers do not attempt to actively maintain all relevant information, but rather adopt a passive strategy for performing running memory span. Finally, Broadway and Engle (2010) report that running memory span performance does not vary on the basis of whether test-takers are told how many items they should report either at the beginning, or at the conclusion of a trial. As with Palladino and Jarrold (2008), these data are readily explained by assuming that test-takers are inclined to retrieve as much information as possible as soon as a trial ends, rather than engage in active rehearsal of relevant items.

Although confidence in Bunting et al.'s (2006) passive-strategy explanation is bolstered by the above studies, there are shortcomings. Foremost, this explanation relies on an assumption of time-based decay of information, which has a tenuous history as a mechanism of forgetting (Capaldi & Neath, 1995; Keppel & Underwood, 1962; Shipstead & Engle, 2013; Turvey, Brick, & Osborn, 1970; Unsworth, Heitz, & Parks, 2008). Moreover, the previously discussed studies tend to equate active maintenance with rehearsal-based strategies. These studies may thus be interpreted as specifically invalidating the position that running memory span performance represents strategic updating of (or rehearsal in) the articulatory loop (Ruiz et al., 2005). This is a different concept than assuming that primary memory capacity represents maintenance of the most recently perceived events, in real time and regardless of strategic rehearsal.

In order to understand primary memory capacity without recourse to decay or rehearsal, we consider a form of proactive interference that is unique to the running memory span task. For both complex span and visual arrays, relevant information is defined on a trial-by-trial basis. All information that was relevant at the beginning of a trial remains relevant until a response is required. The only source of proactive interference is information from previous trials.

In the running memory span task relevant information is defined in a less discrete manner. Each item begins as relevant, but may become irrelevant after enough intervening items are presented. It follows that performance of this task has a strong potential to be limited by inter-list interference. The susceptibility of an individual to such interference may contribute to the size of primary memory.

One way of conceptualizing this issue comes from temporal-ratio perspectives of memory (Baddeley, 1976; Bjork & Whitten, 1974; Brown et al., 2007; Crowder, 1976). These perspectives assume that primary and secondary memory represent separate memory phenomena, rather than separate cognitive systems. The classic example equates inter-item interference with telephone poles receding to the horizon (Crowder, 1976). Nearby poles are easily discriminated from one another. More distant poles become progressively harder to discriminate from their *neighbors*. More directly, time has a compressing effect on memory: Inter-item interference increases as the temporal distance between a given item and its neighbors decreases, relative to temporal distance between that item and a retrieval attempt (see Brown et al., 2007).

Assuming this rate of compression is constant across trials, it would explain the present observation that the primary memory portion of free recall was not subject to buildup of proactive interference (see also Craik & Birtwistle, 1971), without recourse to a specific storage system. Primary memory represents a region of high inter-item discriminability and its capacity is limited by the rate at which interference becomes great enough to prevent accurate discrimination of events in memory.

When applied to the present data, an important consequence of this explanation of primary memory is that the rate at which inter-item interference builds is not simply the ratio of presentation-rate to retention-interval, but also subject to individual differences. People with smaller primary memory scores are overrun by inter-item interference sooner than people with larger primary memory scores. However, the mechanisms that would account for this difference are unclear, since temporal-ratio studies are generally focused on explaining mean performance (e.g., Bjork & Whitten, 1974; Brown et al., 2007; Unsworth et al., 2008), rather than individual differences.

Examining Figs. 11 and 14, individual differences in attention control provide one source of individual differences. People who can focus on a task and resist having attention drawn to other events or cognitions will effectively have larger primary memories, as they are encoding and maintaining appropriate information. A question for future research thus regards the processes that are represented by WMrun, and their contribution to individual differences in sensitivity to temporal-context.

Our current perspective on this issue is that the flip-side of remembering relevant information is forgetting no-longer-relevant information. If attention control facilitates binding of information to temporal-context, then one potential mechanism of WMrun is the unbinding process of Oberauer's (2002, Oberauer et al., 2007) focal attention model. Within a single running memory span trial, test takers not only need to report relevant information, but also distinguish relevant from no-longer-relevant information. Information can become irrelevant inside of a single trial. Successful disengagement reduces inter-item interference by removing associations between primary memory and no-longer-relevant information. This action increases the functional size of primary memory by allowing appropriate encodings to be more effectively utilized (see Oberauer et al., 2007).

This position also reflects the sentiment that the correlation between memory and fluid intelligence is not limited to processes associated with intentional remembering, but also represents disengagement from no-longer-relevant information (Ecker, Lewandowsky, & Oberauer, in press; Friedman et al., 2006; Shipstead & Engle, 2013; Wiley, Jarosz, Cushen, & Colflesh, 2011). Specifically, although intuition suggests that a large maintenance capacity will facilitate the production of novel combinations of information (e.g., Cowan et al., 2005; Oberauer et al., 2007), novel combinations do not necessarily equate to correct puzzle solutions. When a solution proves untenable, maintenance capacity will only be effective in further problem solving to the extent that a person can disengage from inappropriate information. Properly conducting this action allows a new, potentially more appropriate, combination to be generated (Wiley et al., 2011). People who cannot carry out such functions are likely to perseverate on inappropriate information (Azuma, 2004; Rosen & Engle, 1997; Shipstead et al., submitted), thus preventing the discovery of the correct solution (Wiley et al., 2011). In essence, while the factor labeled WMrun likely represents the ultimate capacity of focal attention (Bunting et al., 2006), the ability to disengage from no-longer-relevant information provides a mechanism through which this capacity may be reached.

To date, evidence linking complex span performance to disengagement has been inconsistently obtained (Ecker, Lewandowsky, Oberauer, & Chee, 2010; Ecker et al., in press; Harrison et al., 2013; Shipstead & Engle, 2013; but see Rosen & Engle, 1997; Wiley et al., 2011). Whether this ability specifically applies to the running memory span task (and by extension WMrun, primary memory and fluid intelligence) is an important topic for further study.

What does visual arrays performance represent?

The present study is not the first to conclude that attention control is important to visual arrays performance (Cusack, Lehman, Veldsman, & Mitchell, 2009; Fukuda & Vogel, 2009, 2011). In particular, Fukuda and Vogel (2009, 2011) have repeatedly demonstrated that individual differences in visual arrays performance predict a person's ability to recover from attention capture. It is noteworthy that, in the present models, antisaccade was the task with the strongest loading on AC. 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 inhibiting a word's semantic representation) would not plausibly improve antisaccade performance: Early inhibition of distracting information would preclude any behavior in the antisaccade task. Therefore, the present attention factor is particularly well suited to the view of Fukuda and Vogel (2009, 2011), in which individual differences in visual arrays performance predict peoples' ability to quickly recover from attention capture. Essentially, strong attention control allows people to remain focused on the memory of the array over the inter-stimulus interval, rather than being drawn into distraction by random events (either cognitive or physical).

Does report-type matter?

Another attention-related account of visual arrays performance to which the present analyses can speak is that of Cusack et al. (2009). They report that visual arrays tasks that require test-takers to recognize changes to cued items (single probe) predict fluid intelligence, while tasks that require memory for all items (whole display) do not. They hypothesize that this trend reflects test-takers' ability to constrain their memories of single probe displays: When single probe is used, people with strong executive control strategically create stable memories for a few items. People with weak executive control tend to create ephemeral memories for several items. Whole display methods, in contrast, require attending to all information and thus eliminate these differences. Under these circumstances, everybody creates ephemeral memories.

The present study refutes this hypothesis in two ways. First, VA1 and VA4 used single probe and VA2 and VA3 used whole display (see Fig. 3). Nonetheless, all tasks had roughly equivalent correlations to the fluid intelligence and attention capture tasks (Table 2). Second, the factor these tasks formed was predictive of both AC and Gf. Thus, visual arrays performance reflects mechanisms of executive 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 display tasks were change-detection based, while Cusack et al. (2009) required participants to report letters that had been displayed in the array. This aspect likely accounts for the differences in between-study findings. Nonetheless, the current results found a strong relationship between whole display tasks and attention control. This indicates that attention does not function in visual arrays by limiting the number of items that are encoded into memory.

The relationship of memory, attention, and fluid intelligence

One interesting aspect of the present models is the relationship between attention control and fluid intelligence. Although a person's attention control abilities represent an important component of working memory, this resistance to distraction was not shown to directly affect fluid intelligence. Rather, any effect that attention control has on novel reasoning is realized through an effect on memory.

To clarify this point, Fig. 15 presents an alternate model in which all memory tasks have been cross-loaded on the attention capture factor to form three independent factors (χ^2 = 52.16; χ^2/df = 1.19; RMSEA = .03; SRMR = .04; NNFI = .96; CFI = .99). This serves two purposes. First, it creates a latent variable that approximates the definition of working memory capacity offered by Engle and colleagues (e.g., working memory = attention control + short term memory; Engle, Tuholski, Laughlin, & Conway, 1999). Second, it allows for examination of memory that is both related to and independent of the attention control.

Both PM and SM retain significant relationships to Gf after AC is removed. However, it is also clear that the portion of memory that is associated with attention control is critical to reasoning abilities, as AC now has the strongest relationship to Gf of all variables.

This observation is not entirely novel. The factor we call "attention control" approximates an executive function that Miyake and Friedman (2012) term "inhibition". Similar to the present study, Friedman et al. (2006) found that inhibition had no direct relationship to intelligence. Our reading of their data, however, is that a mediated relationship does exist in the form of variance shared with a memory-related factor (memory updating; see Fig. 1 of Friedman et al., 2006). Consistent with this interpretation, a subsequent study (Friedman et al., 2008) allowed several memory tasks to cross-load onto the inhibition factor (similar to Fig. 15). In this case, inhibition had a relationship to intelligence that was equivalent to that of memory. This is the same phenomenon that is apparent in Fig. 15.

It is clear that a person's ability to resist attention capture explains a large portion of both working memory capacity and its relationship to higher cognitive abilities. At the same time, this relationship is realized through an interaction with memory.

Whether the causal flow of this relationship represents an effect of attention on memory (e.g., Kane, Conway, et al., 2007), or of memory on attention (e.g., Chuderski et al., 2012), is unknown. On the basis of the low memory load imposed by attention control tasks we interpreted our results from the perspective in which attention control has a causal influence on primary memory, rather than the reverse. That is, attention control ensures appropriate information is attended or maintained. A large maintenance capacity, on the other hand, is unlikely to explain performance of most attention control tasks, since these tasks ostensibly only require maintenance of a single goal (e.g., look away from a flash; see Roberts et al., 1994).

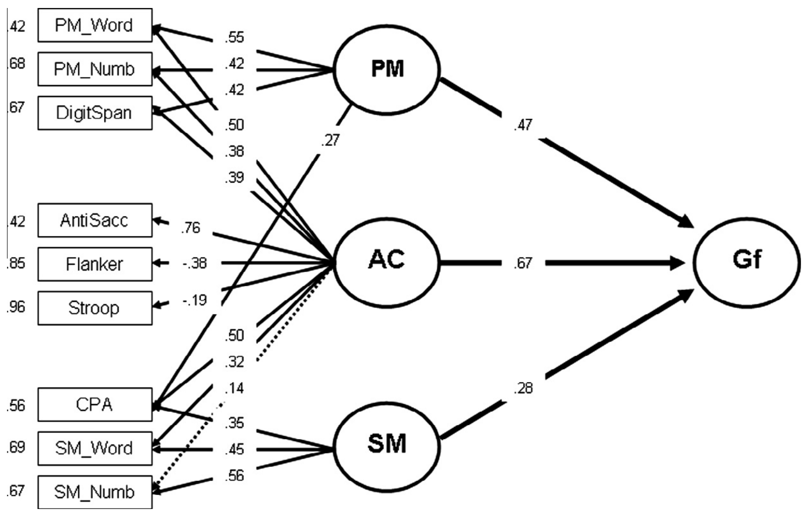


Fig. 15. The relationship of primary memory, attention control and secondary memory to general fluid intelligence when variance in primary and secondary memory is allowed to load on the attention control factor. Note that the tasks that load on the general fluid intelligence factor are the same as displayed in Fig. 4. PM = primary memory; AC = attention control; SM = Secondary Memory; Gf = general fluid intelligence; PM_Word = Primary Memory, Free Recall, Words; PM_Numb = Primary Memory, Free Recall, Numbers; SM_Word = Secondary Memory, Free Recall, Words; AntiSacc = antisaccade task; CPA = Continuous Paired Associate; SM_Numb = Secondary Memory, Free Recall, Numbers.

The critical point, however, is not one of causality. The critical point is that the qualitative interaction of attention control and memory is a significant component of both working memory capacity and fluid intelligence. The present results indicate that working memory capacity is most strongly associated with attention control aspects of this relationship (at least as working memory capacity is measured by most tasks). Conversely, fluid intelligence was found to be more strongly associated with the primary memory component of this relationship.

Conclusions

Across these analyses, it is clear that primary memory, secondary memory, and attention control are all critical components of working memory capacity. However, these mechanisms are not similarly represented by all working memory tasks. Running memory span performance reflects primary memory more strongly than either complex span or visual arrays tasks. The performance of these latter tasks is more closely associated with a person's attention control and retrieval abilities.

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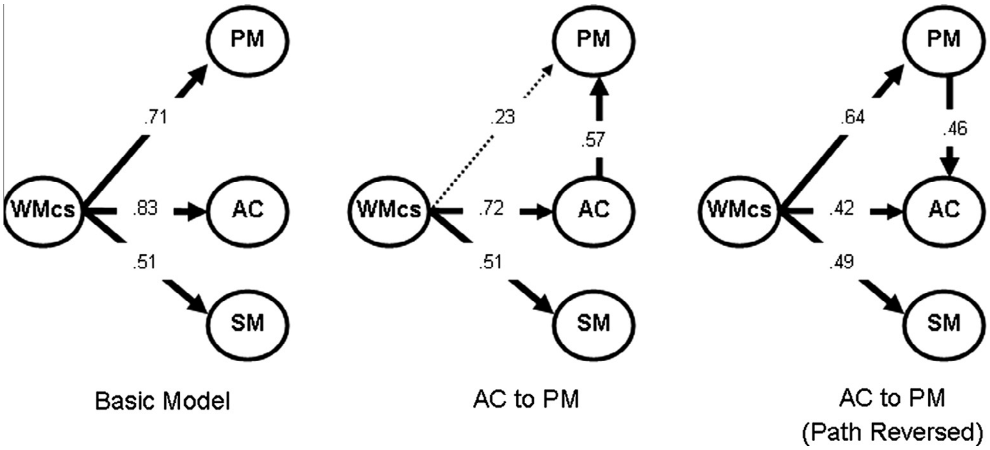
Appendix A

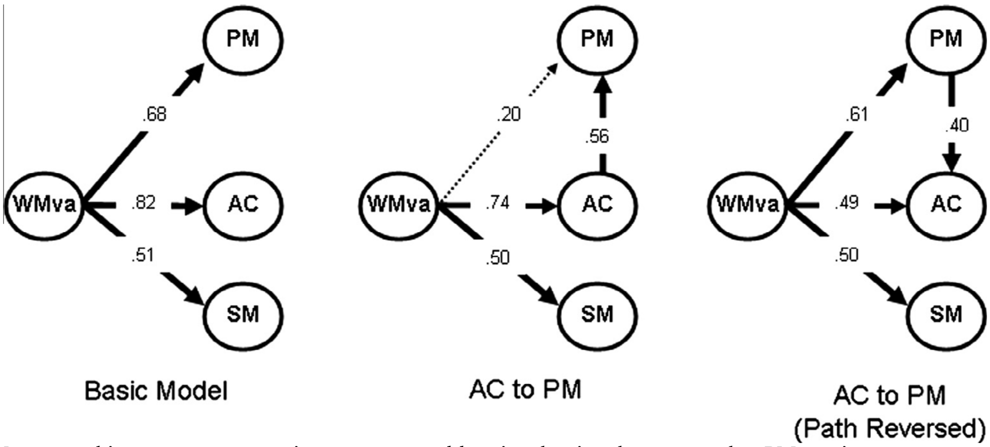
Critical Intermediate Solutions from Table 6.



Note: WMcs = working memory capacity as measured by complex span tasks; PM = primary memory; AC = attention control; SM = secondary memory.

Appendix B

Critical Intermediate Solutions from Table 7.



Note: WMva = working memory capacity as measured by simple visual arrays tasks; PM = primary memory; AC = attention control; SM = secondary memory.

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