Journal of Memory and Language 62 (2010) 392–406

Contents lists available at ScienceDirect

Journal of Memory and Language

journal homepage: www.elsevier.com/locate/jml

Working memory capacity: Attention control, secondary memory, or both? A direct test of the dual-component model

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ARTICLE INFO

Article history:
Received 27 March 2009
revision received 28 January 2010
Available online 24 February 2010

Keywords:
Working memory capacity
Attention control
Secondary memory
Fluid intelligence

ABSTRACT

The current study examined the extent to which attention control abilities, secondary memory abilities, or both accounted for variation in working memory capacity (WMC) and its relation to fluid intelligence. Participants performed various attention control, secondary memory, WMC, and fluid intelligence measures. Confirmatory factor analyses suggested that attention control, secondary memory, and WMC were best represented as three separate, yet correlated factors, each of which was correlated with fluid intelligence. Structural equation modeling suggested that both attention control and secondary memory accounted for unique variance in WMC. Furthermore, structural equation modeling and variance partitioning analyses suggested that a substantial part of the shared variance between WMC and fluid intelligence was due to both attention control and secondary memory abilities. Working memory capacity also accounted for variance in fluid intelligence independently of what was accounted for by the other two factors. The results are interpreted within a dual-component model of WMC which suggests that both attention control and secondary memory abilities (as well as other abilities) are important components of WMC.

Introduction

Measures of working memory capacity (WMC) such as operation and reading span have consistently been shown to be one of the best predictors of higher-order cognition. In particular, several studies have demonstrated moderate to strong correlations between WMC and higher-order cognitive abilities such as fluid intelligence (Ackerman, Beier, & Boyle, 2002; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004; Kyllonen & Christal, 1990), reading comprehension (e.g., Daneman & Carpenter, 1980; Daneman & Merikle, 1996), and scholastic aptitude performance (Engle et al., 1999; Turner & Engle, 1989). It is clear from these large scale latent variable studies as well meta-analytic reviews (Ackerman, Beier, & Boyle, 2005; Daneman & Merikle, 1996) that WMC has substantial predictive power in terms of predicting performance on a number of measures. However, the reason for this predictive power remains elusive. Recently, two main types of theories have been put forth to explain the predictive power of WMC. One type of theory suggests that attentional abilities are at the heart of WMC predictive power, while another type of theory suggests that WMC predictive power derives from basic memory abilities. The current study examines the extent to which attention abilities, memory abilities, or both account for WMC's predictive power.

Attention and memory based theories of working memory capacity

The notion that attention and working memory are intimately related has long been a core component of a

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doi:10.1016/j.jml.2010.02.001

number of working memory models. These include the notion that both attention control (e.g., Engle & Kane, 2004) and the scope or size of the focus of attention (e.g., Cowan, Fristoe, Elliot, Brunner, & Saults, 2006; Cowan et al., 2005) are important components of working memory and WMC. That is, Engle, Kane, Conway and colleagues (e.g., Engle & Kane, 2004; Kane, Conway, Hambrick, & Engle, 2007) argue that the ability to control attention is an important component of working memory, whereas Cowan and colleagues (e.g., Cowan et al., 2005, 2006) argue that the scope of attention is also an important component of working memory. In particular, Cowan and colleagues argue that the scope of attention is an important determinant of the number of items that can be held in the focus and thus act as a storage component. In the current study we primarily focus on attention control abilities, but will we discuss the importance of Cowan and colleagues' scope of attention view again in the Discussion.

According to attention control based theories of WMC, the primary determinant of individual differences in WMC and the reason why WMC predicts performance on so many tasks is attention control abilities (e.g., Engle & Kane, 2004; Hasher, Lustig, & Zack, 2007; Kane & conway et al., 2007). This corresponds to Baddeley's (1986) concept of the central executive and suggests that the primary underlying construct of interest is attention control capabilities. Indeed, Baddeley (1993) noted that "the central executive component of working memory does not itself involve storage, which produces the apparently paradoxical conclusion that not all working memory studies need involve memory" (p. 167). Thus, attention control, and not memory per se, is the primary component of WMC in these attention based theories. Specifically, Engle, Kane, Conway and colleagues (Engle & Kane, 2004; Kane & conway et al., 2007) have suggested that domain-general attention control abilities are needed to actively maintain task relevant information in the presence of potent internal and external distraction. Attention control is needed to ensure that task goals are maintained in an active state and to prevent attentional capture from other distracting stimuli. According to this attention control theory of WMC, high WMC individuals have greater attention control capabilities than low WMC individuals, and thus are better at actively maintaining information in the presence of distraction. Specifically, Engle and Kane (2004) noted that "when we refer to individual differences in WMC, we really mean the capability of just one element of the system: executive attention. Thus, we assume that individual differences in WMC are not really about memory storage per se, but about executive control in maintaining goal-relevant information in a highly active accessible state under conditions of interference or competition" (p. 149). Thus, these views suggest that although WMC is a multifaceted construct, the primary component in terms of the predictive power of WMC is attention control.

Important evidence for the attention control view comes from numerous studies demonstrating differences between high and low WMC individuals on low-level attention tasks that make little demands on memory. For instance, recent work has demonstrated WMC differences in selective and divided focus in dichotic listening (Colflesh & Conway, 2007; Conway, Cowan, & Bunting, 2001), Stroop interference (Kane & Engle, 2003; Long & Prat, 2002), flanker interference (Heitz & Engle, 2007; Redick & Engle, 2006), voluntary saccade control in antisaccade paradigms (Kane, Bleckley, Conway, & Engle, 2001; Unsworth, Schrock, & Engle, 2004), as well as differences in flexible visual attention allocation (Bleckley, Durso, Crutchfield, Engle, & Khanna, 2004; Poole & Kane, 2009; Sobel, Gerrie, Poole, & Kane, 2007). In each case, high WMC individuals were better at controlling aspects of their attention than low WMC individuals even though demands on memory were low. As such, these studies provide important evidence for attention control theories of WMC and suggest that one major difference between high and low WMC individuals is the ability to control attention.

Additionally, it should be noted that the attention control view of WMC also predicts differences in memory tasks when interference and competition is high (Conway & Engle, 1994; Kane & Engle, 2000; Rosen & Engle, 1997, 1998). According to the attention control view, WMC differences that arise in memory tasks do so because of basic differences in attention control. That is, attention control (or executive attention) is needed to combat interference and engage in a strategic search of memory in these memory tasks. Thus, in this view of WMC, memory differences arise because of differences in attention control. This suggests that a unitary domain-general factor accounts for differences found in both low-level attention tasks and in basic memory tasks (e.g., Engle & Kane, 2004).

Furthermore, attention control theories of WMC suggest that the main reason that WMC correlates with aspects of higher-order cognition (such as fluid reasoning) is because of this variation in attention control. That is, as noted by Engle et al. (1999), "the primary factor contributing to the relationship between measures of WM and gF is controlled attention" (p. 326). Engle et al. (1999) went onto note that in that particular study there were no measures of attention control and thus, the conclusion that attention control was the common factor between WMC and gF was "at best, an educated conjecture" (p. 326). Additionally, Kane, Hambrick, and Conway (2005) noted that "What the field needs now, then, is a latent variable approach to the problem, in which many subjects complete many marker tests of WMC, gF, and attention control. These studies should report the magnitude of the WMC-attention correlation and examine whether the shared variance between WMC and attention accounts for substantial gF variance (and more gF variance than is accounted for by residual variance from WMC or attention constructs" (p. 70). One aim of the current study was to examine this "educated conjecture" and to provide a test of the attention control view as suggested by Engle et al. (1999) and Kane et al. (2005).

In contrast to attention control views of WMC, recent work has suggested that individual differences in WMC and the reason that WMC is related to higher-order cognition is because of basic memory abilities (e.g., Mogle, Lovett, Stawski, & Sliwinski, 2008; see also Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008 for an account based on short-term memory abilities). That is, these theories suggest that attention control and active maintenance abilities are not needed to explain variation in WMC, nor are they needed to explain the relation between WMC and higher-order cognition. Rather, these memory based theories suggest that variation in WMC is due to differences in basic memory abilities such as the ability to access information from secondary (or long-term) memory (Mogle et al., 2008). Evidence for this view comes from latent variable studies demonstrating that memory latent variables are strongly related to a WMC latent variable and that the memory latent variable accounts for (mediates) the relation between WMC and intelligence.

For instance, Mogle et al. (2008) demonstrated a fairly strong correlation (.76) between a secondary memory (SM) latent variable and a WMC latent variable. Furthermore, Mogle et al. examined several structural equation models and found that SM accounted for variance in a single measure of fluid intelligence, but WMC did not account for any variance in fluid intelligence over and above what was accounted for by SM. Mogle et al. concluded that "The major novel result of this study was that SM was a stronger predictor of fluid intelligence than was WMC, which did not account for ANY variance in fluid intelligence over above SM" (p. 1075; emphasis added). Mogle et al. went onto note that "SM processes (e.g., search and retrieval), rather than maintenance of information in the face of distraction, drive the relationship between the memory constructs and fluid intelligence" (p. 1075). Additionally, Colom et al. (2008) also argued that attention control abilities do not account for the relation between WMC and intelligence.

Recently, we (Unsworth & Engle, 2007a) have suggested that both attention control and memory based abilities (such as controlled search and retrieval) are important determinants of WMC and part of the reason for WMC's predictive power. Specifically, in this framework, the attentional component serves to actively maintain a few distinct representations for on-line processing in primary memory. These representations include things such as goal states for the current task, action plans, and item representations in list memory tasks. In this view, as long as attention is allocated to these representations they will be actively maintained in primary memory (see also Craik & Levy, 1976). This continued allocation of attention serves to protect these representations from interfering internal and external distraction similar to the attention control view espoused by Engle and Kane (2004). However, if attention is removed from the representations due to internal or external distraction or due to the processing of incoming information, these representations will no longer be actively maintained in primary memory and therefore, will have to be retrieved from secondary memory if needed. Accordingly, secondary memory relies on a cue-dependent search mechanism to retrieve items (e.g., Raaijmakers & Shiffrin, 1981). Additionally, the extent to which items can be retrieved from secondary memory will be dependent on overall encoding abilities, the ability to reinstate the encoding context at retrieval, and the ability to focus the search on target items and exclude interfering items. We (Unsworth & Engle, 2007a) argued that individuals will differ in both attention control abilities that are needed to actively maintain items in primary memory and in the ability to retrieve items from secondary memory. Thus, individual differences in WMC are indexed by both attention control differences and retrieval differences. Importantly, although control processes are needed for both active maintenance and retrieval, these control processes are likely distinct. That is, similar control processes likely operate in both active maintenance and retrieval, but importantly there are also likely distinct control processes that are needed to actively maintain information and distinct control processes that are needed to strategically retrieve information from secondary memory. Thus, unlike both attention control and secondary memory views, this suggests that a single unitary construct does not uniquely account for variation in WMC.

This view accounts for previous work demonstrating differences between high and low WMC individuals on low-level attention tasks, and predicts that high and low WMC individuals should differ on secondary memory measures where active maintenance is hampered by a significant distractor filled delay or the need to remember more items than the focus of attention can handle. For instance, recent work has found high and low WMC differences on various delayed free recall tasks (Unsworth, 2007) as well as differences in cued recall (Unsworth, 2009) in which it is very unlikely that participants could maintain a large number of items over a significant distractor filled delay. Thus, this dual-component model of WMC suggests that at least two components (attention control/active maintenance and controlled retrieval) are needed to explain variation in WMC and the relation between WMC and higher-order cognitive constructs like intelligence. As noted by Colom et al. (2008), however, this model has not yet been fully tested. Therefore, the present investigation seeks to provide a direct test of this model.

Additionally, it should be noted that given that the dual-component model is an outgrowth of the attention control (executive attention; Engle & Kane, 2004) view, the two naturally account for many of the same effects with a similar explanation. That is, there are likely many similarities between the views. What we see as the major difference is that the attention control view suggests that a single unitary construct (attention control) accounts for variance in both attention tasks and memory tasks, and this shared variance is what is important for the relation with gF. We agree that there is likely a substantial amount of variance shared among these constructs, but we also think that this common variance can be further broken down into multiple sub-components, some of which are uniquely important for attention control and active maintenance in primary memory and some which are uniquely important for controlled retrieval and other memory processes that act to recover information from secondary memory. Thus, we suggest that there is a finer delineation of control processes than has been specified previously.

The present study

The goal of the present study was to examine whether WMC is best explained by attention control, secondary memory processes, or some combination of both.

Specifically, a latent variable approach was used to examine the relations among WMC, attention control (AC), secondary memory (SM) abilities, and fluid intelligence (gF). In order to derive latent variables for the constructs of interest, multiple indicators of each construct were used. This was done because previous results may be due to the fact that only a single task was used and therefore, may not provide the best evidence for more general constructs. The WMC measures were operation span, symmetry span, and reading span, all of which have been used extensively in previous work on WMC and vary across numerical, spatial, and verbal processing domains.

The attention control (AC) measures were antisaccade, arrow flankers, Stroop, and the psychomotor vigilance task. Previous work has suggested that each of these tasks measures some aspect of attention control and is related to variation in WMC. Furthermore, Poole and Kane (2009; see also Kane, Poole, Tuholski, & Engle, 2006) have recently suggested that each of these tasks represent important attention control components which are related to WMC. Specifically, Poole and Kane (2009) suggested that attention control is needed to restrain attention and prevent attentional capture from prepotent responses as is found in the antisaccade and Stroop tasks. Poole and Kane (2009) also suggested that attention control is needed to constrain attention in the presence of distractors as is found in flanker tasks. Finally, Poole and Kane (2009) suggested that attention control is needed to sustain attention on task and prevent lapses of attention that could hinder task performance (e.g., Kane et al., 2007; McVay & Kane, 2009). Importantly each of these components represents broader attention control abilities and should all load on the same factor.

The secondary memory (SM) measures were delayed free recall with unrelated words, delayed free recall with semantically related words (allowing for a build-up of proactive interference), a picture source recognition task, continual distractor free recall, and two measures of verbal fluency (animal and F letter). Each of these measures required that participants remember some information after a significant delay or from semantic memory. As such they should be relatively strong indicators of controlled retrieval abilities in the absence of active maintenance. Furthermore, each task can be considered as a measure of controlled or strategic retrieval (mediated primarily by frontal functioning) rather than merely relying on purely associative or automatic retrieval (mediated primarily by medial temporal lobe functioning; Moscovitch, 1992). This is important because prior work has suggested that individual differences in WMC should be related to memory performance when controlled/strategic processes are needed (e.g., Mogle et al., 2008; Rosen & Engle, 1997; Unsworth & Engle, 2007a). Thus, WMC should be related to delayed free recall with unrelated words (Unsworth, 2007), delayed free recall with semantically related words in which proactive interference is high (Kane & Engle, 2000), continual distractor free recall (Unsworth, 2007), and verbal fluency tasks (Rosen & Engle, 1997).

It should be noted that all of the memory measures in the current study are putative measures of secondary memory and not the capacity of primary memory (or the focus of attention) or short-term memory. We did not include primary memory capacity or scope of attention (e.g., Cowan et al., 2005) measures in the current study because we were primarily concerned with current theoretical claims that suggest that secondary memory abilities are important for WMC and account for some (or all) of the variance that is shared between WMC and gF (e.g., Mogle et al., 2008; Unsworth & Engle, 2007a). This is discussed further in the Discussion section.

We also did not include short-term memory measures, as indexed by simple span tasks, given the ambiguous nature of these tasks. Previous work has suggested that simple spans provide putative measures of short-term or primary memory, are distinguishable from WMC, and are differentially related to gF (e.g., Engle et al., 1999; Mogle et al., 2008). However, other work has suggested that simple span tasks index both primary and secondary memory (Craik, 1971; Unsworth & Engle, 2007b) and are influenced by a number of secondary memory variables (e.g., Hulme et al., 1997; Watkins, 1977). Furthermore, recent reanalyses have suggested that WMC tasks (as measured by complex spans) and short-term memory tasks (as measured by simple spans) largely measure the same processes and account for the same variance in gF (Colom, Rebollo, Abad, & Shih, 2006; Unsworth & Engle, 2007b). This is especially true for long simple span set sizes when different scoring methods are taken into account (Unsworth & Engle, 2007b). Thus, it is not at all clear that WMC and STM can be considered as distinct constructs to the extent that complex and simple span tasks are used as the measures of interest. Therefore, given that simple spans do not exclusively measure short-term memory and the fact that we were primarily concerned with secondary (or long-term) memory abilities, we did not examine putative measures of short-term memory in the current study.

Finally, the gF measures were the Raven Advanced Progressive Matrices (Raven, Raven, & Court, 1998), number series, and verbal analogies. We included these measures of gF because prior work has suggested that WMC does not account for variance in gF over and above that accounted for by secondary memory (Mogle et al., 2008) relied on a single measure of gF (i.e., Raven) and thus it is not clear to what extent this finding is due to possible problems with using a single indicator to represent gF. Thus, we had participants perform three gF measures with each measure being primarily spatial (i.e., Raven), numerical (number series), or verbal (verbal analogies) in nature. This should provide a much broader gF factor.

Using these putative measures of WMC, AC, SM, and gF, several different latent variable models can be constructed to test the extent to which the data is represented by various constructs. For instance, shown in Fig. 1 are three possibilities for what accounts for variation in WMC. Possibility 1 shown in Fig. 1a represents the attention control view of WMC suggesting that AC should have a direct effect on WMC (indicated by the solid path from AC to WMC), but SM should not have a direct effect on WMC (indicated by the dotted path from SM to WMC). This is consistent with attention control views that suggest previous research which has shown WMC differences in SM are actually due to basic attention control differences (e.g.,

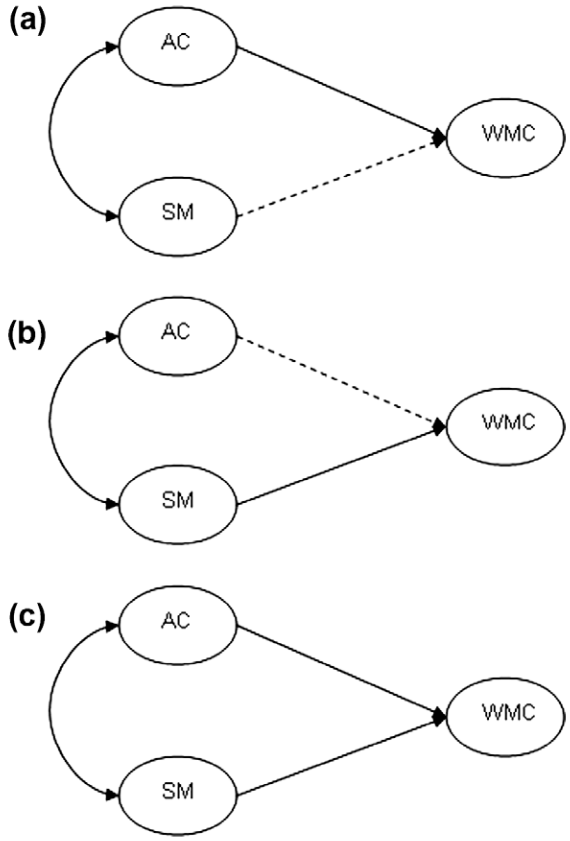

Fig. 1. Three alternative models for the relation among attention control (AC), secondary memory (SM), and working memory capacity (WMC). See text for more details.

Kane & Engle, 2000). That is, as noted previously, attention control views of WMC, suggest that covariation between WMC and memory measures is really due to (mediated by) variation in attention control. Possibility 1 tests this notion. Possibility 2, shown in Fig. 1b, represents the opposite situation in which SM has a direct effect on WMC, but AC does not. This possibility is consistent with recent claims that memory abilities, but not attention control abilities, are the primary determinant of WMC (e.g., Mogle et al., 2008; see Colom et al., 2008 for a similar claim based on short-term storage abilities). Finally, Possibility 3 shown in Fig. 1c represents the dual-component model of WMC (Unsworth & Engle, 2007a) in which both AC and SM have direct effects on WMC and, therefore, make independent contributions to WMC. If Possibility 3 is consistent with the data, then both the AC and SM paths to WMC should be significant and constraining either path to zero should lead to a significant reduction in model fit. However, if either of the other two possibilities are correct, then only one path to WMC should be significant and constraining the other path to zero should not lead to a reduction in model fit.

Additionally, given that each of the three views makes claims regarding the relation between WMC and gF, the shared variance among AC, SM, WMC and gF will be examined to determine if either AC or SM completely accounts for the relation between WMC and gF. Specifically, strong versions of the AC view of WMC suggest that the predictive power of WMC is due to AC abilities and thus, partialling out AC from the WMC–gF relation should lead to a substantial reduction in the relation between WMC and gF to the point that WMC is no longer related to gF. This position represents what has traditionally been the stance of attention control views, but we note that Kane et al. (2006) recently acknowledged the possibility that attention control may not fully mediate the relation between WMC and gF. Nonetheless we thought it prudent to test the strong version of this view in the current study. Conversely, the SM based theories of WMC suggest that SM abilities account for the shared variance between WMC and gF, thus partialling SM out of the relation should result in WMC no longer accounting for variance in gF (e.g., Mogle et al., 2008). However, the dual-component model of WMC suggests that both AC and SM are needed to provide a fuller account of the relation between WMC and gF, and thus partialling out only one component (either AC or SM) will not fully account for the relation between WMC and gF. Rather, simultaneously partialling out both components should lead to a substantial reduction in the amount of remaining shared variance between WMC and gF. Thus, all three theories make different predictions in terms of what is the primary determinant of variation in WMC and the relation between WMC and gF.

Method

Participants

A total of 181 participants (60% female) were recruited from the subject-pool at the University of Georgia. Participants were between the ages of 18 and 35 ($M = 18.74$, $SD = 1.06$) and received course credit for their participation. Each participant was tested individually in two laboratory sessions lasting approximately two hours each.

Materials and procedure

After signing informed consent, all participants completed operation span, symmetry span, reading span, delayed free recall with unrelated words, picture source recognition, animal fluency, and number series in Session 1. In Session 2, all participants completed a continual distractor free recall task, delayed free recall with semantically related words, antisaccade, arrow flanker, psychomotor vigilance, Stroop, F letter fluency, verbal analogies and Raven Advanced Progressive Matrices. All tasks were administered in the order listed above.

Tasks

Working memory capacity (WMC) tasks

Operation Span (Ospan). Participants solved a series of math operations while trying to remember a set of unrelated letters (F, H, J, K, L, N, P, Q, R, S, T, Y). Participants were required to solve a math operation and after solving the operation they were presented with a letter for 1 s. Immediately after the letter was presented the next operation was presented. Three trials of each list-length (3–7) were presented for a total possible of 75. The order of list-length varied randomly. At recall, letters from the current set were recalled in the correct order by clicking on the appropriate letters (see Unsworth, Heitz, Schrock, & Engle, 2005 for more details). Participants received three sets (of list-length two) of practice. For all of the span measures, items were scored if the item was correct and in the correct position. The score was the proportion of correct items in the correct position.

Symmetry Span (Symspan). In this task participants were required to recall sequences of red-squares within a matrix while performing a symmetry-judgment task. In the symmetry-judgment task participants were shown an 8×8 matrix with some squares filled in black. Participants decided whether the design was symmetrical about its vertical axis. The pattern was symmetrical half of the time. Immediately after determining whether the pattern was symmetrical, participants were presented with a 4×4 matrix with one of the cells filled in red for 650 ms. At recall, participants recalled the sequence of red-square locations in the preceding displays, in the order they appeared by clicking on the cells of an empty matrix. There were three trials of each list-length with list-length ranging from 2 to 5 for a total possible of 42. The same scoring procedure as Ospan was used.

Reading Span (Rspan). Participants were required to read sentences while trying to remember the same set of unrelated letters as Ospan. For this task, participants read a sentence and determined whether the sentence made sense or not (e.g. "The prosecutor's dish was lost because it was not based on fact. ?"). Half of the sentences made sense while the other half did not. Nonsense sentences were made by simply changing one word (e.g. "dish" from "case") from an otherwise normal sentence. Participants were required to read the sentence and to indicate whether it made sense or not. After participants gave their response they were presented with a letter for 1 s. At recall, letters from the current set were recalled in the correct order by clicking on the appropriate letters. There were three trials of each list-length with list-length ranging from 3 to 7 for a total possible of 75. The same scoring procedure as Ospan was used.

Attention control (AC) tasks

Antisaccade. In this task (Kane et al., 2001) participants were instructed to stare at a fixation point which was onscreen for a variable amount of time (200–2200 ms). A flashing white "=" was then flashed either to the left or right of fixation (11.33° of visual angle) for 100 ms. This was followed by the target stimulus (a B, P, or R) onscreen for 100 ms. This was followed by masking stimuli (an H for 50 ms and an eight which remained onscreen until a response was given). The participants' task was to identify the target letter by pressing a key for B, P, or R (the keys 1, 2, or 3) as quickly and accurately as possible. In the prosaccade condition the flashing cue (=) and the target appeared in the same location. In the antisaccade condition the target appeared in the opposite location as the flashing cue. Participants received, in order, 10 practice trials to learn the response mapping, 15 trials of the prosaccade condition, and 60 trials of the antisaccade condition. The dependent variable was proportion correct on the antisaccade trials.

Arrow flankers. Participants were presented with a fixation point for 400 ms. This was followed by an arrow directly above the fixation point for 1700 ms. The participants' task was to indicate the direction the arrow was pointing (pressing the F for left pointing arrows and pressing J for right pointing arrows) as quickly and accurately as possible. On 50 neutral trials the arrow was flanked by two horizontal lines on each side. On 50 congruent trials the arrow was flanked by two arrows pointing in the same direction as the target arrow on each side. Finally, on 50 incongruent trials the target arrow was flanked by two arrows pointing in the opposite direction as the target arrow on each side. All trial types were randomly intermixed. The dependent variable was the reaction time difference between incongruent and congruent trials.[1]

Stroop. Participants were presented with a color word (red, green, or blue) presented in one of three different font colors (red, green, or blue). The participants' task was to indicate the font color via key press (red = 1, green = 2, blue = 3). Participants were told to press the corresponding key as quickly and accurately as possible. Participants received 15 trials of response mapping practice, and 6 trials of practice with the real task. Participants then received 75 total real trials. Of these trials 67% were congruent such that the word and font color matched (i.e., red printed in red) and the other 33% were incongruent (i.e., red printed in green). The dependent variable was the reaction time difference between incongruent and congruent trials.

Psychomotor vigilance task (PVT). The psychomotor vigilance task (Dinges & Powell, 1985) was used as the primary measure of sustained attention. Participants were presented with a row of zeros on screen and after a variable amount of time the zeros began to count up in 1 ms intervals from 0 ms. The participants' task was to press the spacebar as quickly as possible once the numbers started counting up. After pressing the spacebar the RT was left on screen for 1 s to provide feedback to the participants. Interstimulus intervals were randomly distributed and ranged from 1 s to 10 s. The entire task lasted for 10 min for each individual (roughly 75 total trials). The dependent variable was the average reaction time for the slowest 20% of trials (Dinges & Powell, 1985).

Secondary memory (SM) tasks

Delayed free recall unrelated words. Participants were given six lists of 10 words each. All words were common

[1] Given concerns that absolute reaction time difference scores in the flanker and Stroop tasks could be due overall individual differences in processing speed, we also computed proportional interference effects in both the flanker and Stroop tasks. These proportional interference effects lead to nearly identical results at all levels of analysis as the absolute difference interference effects. This is perhaps not surprising given that the absolute and proportional effects were highly correlated for both the flanker (r = .97) and the Stroop (r = .99) tasks. Given that most prior work has relied on absolute reaction time difference scores, all analyses reported in the current paper are based on the absolute interference effects in order to remain consistent with prior work.

nouns that were presented for 1 s each. After list presentation, participants engaged in a 16 s distractor task before recall: participants saw 8 three-digit numbers appear for 2 s each, and were required to write the digits in ascending order. After the distractor task participants saw ???, which indicated that they should type as many words as they could remember from the current list in any order they wished. Participants had 45 s for recall. A participant's score was the total number of items recalled correctly.

Delayed free recall semantically related words. Participants received 6 lists of 10 words each broken down into two blocks (three lists per block). All words in each block came from the same semantic category (e.g., professions and fruits). The first three lists allowed for proactive interference to accrue and the first list in the next block allowed for a release from proactive interference. Following the last word in a list participants were required to count backwards by three's as quickly and accurately as possible from a three-digit number onscreen for 15 s and to write the numbers down as they go. After the distractor task participants saw ???, which indicated that they should type as many words as they could remember from the current list in any order they wished. Participants had 45 s for recall. A participant's score was the total number of items recalled correctly.

Picture source-recognition. Participants were presented with a picture (30 total pictures) in one of four different quadrants onscreen for 1 s. Participants were explicitly instructed to pay attention to both the picture as well as the quadrant it was located in. At test participants were presented with 30 old and 30 new pictures individually in the center of the screen. Participants indicated if the picture was new or old and, if old, what quadrant it was presented in via key press. Participants had 5 s to press the appropriate key to enter their response. A participant's score was proportion correct.

Continual distractor free recall. Participants were given 3 lists of 10 words each. All words were common nouns that were presented for 2.5 s each. Before and after each item presentation, participants were required to arrange four separate three-digit numbers (presented for 2 s each) in descending order on a sheet of paper. After list presentation, participants engaged in an additional 30 s distractor activity (e.g., 15 three-digit numbers instead of four) before recall. After the distractor task participants saw ???, which indicated that they should type as many words as they could remember from the current list in any order they wished. Participants had 45 s for recall. A participant's score was the total number of items recalled correctly.

Verbal fluency. The verbal fluency measure represented composite of the animal and F letter fluency tasks. In the animal fluency task, participants were given 1 min to type as many exemplars from the category of animals as possible. In the F letter fluency task, participants were given 1 min to type as many words that began with the letter F as possible. The dependent variable was the total number of unique instances for both fluency tasks.

Fluid intelligence (gF) tasks

Raven advanced progressive matrices. The Raven is a measure of abstract reasoning (Raven et al., 1998). The test consists of 36 items presented in ascending order of difficulty (i.e. easiest–hardest). Each item consists of a display of 3×3 matrices of geometric patterns with the bottom right pattern missing. The task for the participant is to select among eight alternatives, the one that correctly completes the overall series of patterns. Participants had 10 min to complete the 18 odd-numbered items. A participant's score was the total number of correct solutions. Participants received two practice problems.

Number series. In this task participants saw a series of numbers and were required to determine what the next number in the series should be (Thurstone, 1962). That is, the series follows some unstated rule which participants are required to figure out in order to determine which the next number in the series should be. Participants selected their answer out of five possible numbers that were presented. Following five practice items, participants had 4.5 min to complete 15 test items. A participant's score was the total number of items solved correctly.

Verbal analogies. In this task participants read an incomplete analogy and were required to select the one word out of five possible words that best completed the analogy. After one practice item, participants had 5 min to complete 18 test items. These items were originally selected from the air force officer qualifying test (AFOQT; Berger, Gupta, Berger, & Skinner, 1990), and we used the same subset of items used in Kane et al. (2004). A participant's score was the total number of items solved correctly.

Results

Descriptive statistics

Descriptive statistics for all of the measures are shown in Table 1. As can be seen in Table 1, the measures had generally acceptable values of internal consistency and most of the measures were approximately normally distributed with values of skewness and kurtosis under the generally accepted values (i.e., skewness <2 and kurtosis <4; see Kline, 1998). Correlations, shown in Table 2, were weak to moderate in magnitude with measures of the same construct generally correlating stronger with one another than with measures of other constructs, indicating both convergent and discriminant validity within the data.

Confirmatory factor analyses

Next, confirmatory factor analysis was used to test several measurement models to determine the structure of the data. Specifically, three measurement models were specified to determine how WMC, AC, and SM were related to one another. Measurement Model 1 tested the notion that WMC, AC, and SM are best conceptualized as a single unitary construct. This could be due to a single controlled attention factor that is needed in all (e.g., Engle et al., 1999). Thus, in this model all of the WMC, AC, and SM tasks loaded onto a single factor. Measurement Model 2 tested the notion that WMC and AC were best thought of as a single factor, but this factor was separate from the SM factor. This could be due to the fact that WMC and AC both reflect

Table 1
Descriptive statistics and reliability estimates for all measures.

Measure	M	SD	Range	Skew	Kurtosis	Reliability
Ospan	59.54	12.49	13–75	−1.71	1.97	.80
Symspan	29.95	7.60	7–42	−.95	.71	.76
Rspan	57.33	13.17	11–75	−1.13	1.48	.78
Anti	.53	.14	.33–.90	.25	−.43	.70
Flanker	126.18	64.92	19–385	1.07	1.79	NA
Stroop	160.70	102.41	−8–715	1.47	4.77	NA
PVT	484.84	114.49	322–1050	1.59	3.56	.97
DFRU	31.71	9.04	7–60	.29	.67	.82
DFRS	36.85	6.17	16–52	−.22	.48	.75
PicSour	.77	.14	.25–.98	−1.25	2.18	.80
CDT	11.65	3.63	2–19	−.39	−.38	.63
Fluency	38.77	8.14	17–58	.01	−.12	.60
Raven	10.79	2.49	4–17	−.09	−.20	.70
NS	9.46	2.41	4–17	.22	−.17	.67
Analogy	10.97	2.77	4–17	.06	−.67	.63

Note: Ospan = operation span; Symspan = symmetry span; Rspan = reading span; Anti = antisaccade; Flanker = arrow flankers; Stroop = Stroop; PVT = psychomotor vigilance task; DFRU = delayed free recall unrelated words; DFRS = delayed free recall semantically related words; PicSour = picture source recognition; CDT = continual distractor free recall; Fluency = verbal fluency; Raven = Raven Advanced Progressive Matrices; NS = number series; Analogy = verbal analogies.

Table 2
Correlations for all measures.

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
WMC															
1. Ospan	–														
2. Symspan	.46	–													
3. Rspan	.64	.42	–												
AC															
4. Anti	.22	.22	.34	–											
5. Flanker	−.20	−.16	−.14	−.35	–										
6. Stroop	−.20	−.16	−.12	−.15	.17	–									
7. PVT	−.21	−.21	−.23	−.24	.17	.16	–								
SM															
8. DFRU	.20	.23	.26	.17	−.11	−.15	−.19	–							
9. DFRS	.29	.23	.31	.17	−.13	−.02	−.14	.34	–						
10. PicSour	.21	.21	.30	.23	−.21	−.18	−.07	.33	.27	–					
11. CDT	.29	.21	.32	.24	−.21	−.09	−.23	.41	.33	.22	–				
12. Fluency	.18	.25	.23	.17	.06	−.09	−.05	.00	.21	.16	.12	–			
gF															
13. Raven	.20	.21	.19	.14	−.13	−.12	−.06	.13	.11	.37	.14	.06	–		
14. NS	.19	.20	.23	.16	−.16	−.10	−.16	.12	.09	.17	.18	.25	.30	–	
15. Analogy	.25	.18	.37	.15	−.11	−.12	−.14	.11	.07	.21	.12	.09	.32	.40	–

Note: WMC = working memory capacity; AC = attention control; SM = secondary memory; gF = fluid intelligence; Ospan = operation span; Symspan = symmetry span; Rspan = reading span; Anti = antisaccade; Flanker = arrow flankers; Stroop = Stroop; PVT = psychomotor vigilance task; DFRU = delayed free recall unrelated words; DFRS = delayed free recall semantically related words; PicSour = picture source recognition; CDT = continual distractor free recall; Fluency = verbal fluency; Raven = Raven Advanced Progressive Matrices; NS = number series; Analogy = verbal analogies. Correlations >.15 are significant at the $p < .05$ level.

attention control abilities which are distinct from more basic memory abilities. Thus, in this model all of the WMC and AC measures loaded onto a single factor and the SM measures loaded onto a separate factor. These two factors were allowed to correlate. Measurement Model 3 tested the notion that WMC and SM were best thought of as a single factor that was separate from AC. This could be due to the fact that WMC and SM reflect the same controlled retrieval abilities which are distinct from attention control abilities. Thus, all the WMC measures and all of the SM measures loaded onto a single factor, while all of the AC factors loaded onto another factor. The two factors were allowed to correlate. Finally, Measurement Model 4 suggested that WMC, AC, and SM were best thought of as three distinct factors that are related. Thus, in this model all of the WMC measures loaded onto a WMC factor, all of the AC measures loaded onto an AC factor, and all of the SM measures loaded onto a SM factor. The three factors were allowed to correlate.

For each model, model fits were assessed via the combination of several fit statistics. These include chi-square, root mean square error of approximation, standardized root mean square residual, the non-normed fit index, the comparative fit index, and the Akaike information crite-

Table 3
Fit indices for all models.

Model	χ^2	*df*	*p*	χ^2/df	RMSEA	NNFI	CFI	SRMR	AIC
Measurement Model 1	110.41	54	.00	2.04	.08	.89	.91	.07	158.41
Measurement Model 2	82.75	53	.01	1.56	.06	.94	.95	.06	132.75
Measurement Model 3	94.49	53	.00	1.78	.07	.92	.93	.06	144.49
Measurement Model 4	57.33	51	.26	1.12	.03	.98	.98	.05	111.33
Measurement Model 4gF	93.61	84	.22	1.11	.03	.98	.98	.05	165.61
SEM AC	63.67	52	.13	1.22	.04	.97	.97	.06	115.41
SEM SM	61.73	52	.19	1.19	.03	.97	.98	.06	113.73
SEM Both	57.33	51	.26	1.12	.03	.98	.98	.05	111.33
SEM gF	93.61	84	.22	1.11	.03	.98	.98	.05	165.61

Note: RMSEA = root mean square error of approximation; NNFI = non-normed fit index; CFI = comparative fit index; SRMR = standardized root mean square residual; AIC = Akaike information criterion.

rion. The chi-square statistic reflects whether there is a significant difference between the observed and reproduced covariance matrices. Therefore, nonsignificant values are desirable. However, with large sample sizes even slight deviations can result in a significant value, therefore the ratio of chi-square to the number of degrees of freedom is also reported. Ratios of two or less usually indicate acceptable fit. Test between nested models are examined via a chi-square difference test. We also report the root mean square error of approximation (RMSEA) which is an index of model misfit due to model misspecification and the standardized root mean square residual (SRMR) which reflects the average squared deviation between the observed and reproduced covariances. In addition, the non-normed fit index (NNFI) and the comparative fit index (CFI) which compare the fit of the specified model to a baseline null model are reported. NNFI, and CFI values >.90 and RMSEA and SRMR values <.08 are indicative of acceptable fit (Kline, 1998). Finally, the Akaike information criterion (AIC) examines the relative fit between models in which the model with the smallest AIC is preferred.

Shown in Table 3 is the fit of the four different measurement models. As can be seen, Measurement Model 4 that specified three separate, yet correlated, factors provided the best fit. Specifically, Measurement Model 4 fit significantly better than the other three models (all $\Delta\chi^2$'s > 25, p's < .01), and had the lowest AIC value.[2] Next, a gF latent variable composed of the three gF tasks was added to Measurement Model 4 to determine how all four factors were related. As shown in Table 3 the fit of this model (labeled Measurement Model 4gF) was good. As can be seen in Fig. 2, all of the measures loaded significantly onto their construct of interest and all of the factors were moderately interrelated. Thus, these results suggest that WMC, AC, and SM are best thought of as separate, yet correlated, factors, each of which is related to gF. Note, given the low loading of fluency onto the SM factor, as well as the fact that fluency can be considered as an executive function task; we tested the same models with fluency excluded from the analyses. In all cases, the results were qualitatively identical to those reported. Thus, although we feel that fluency represents, in part, SM abilities, it did not have a large influence on the overall pattern of results. For completeness we have left the fluency task in all models.

Structural equation models

Given that the measurement model suggested that WMC, AC, and SM could be considered as three distinct factors, structural equation modeling was used to examine the question of primary interest. Specifically, as noted previously, according to a strong version of AC models of WMC, AC should predict WMC, but SM should not (Possibility 1 in Fig. 1). Conversely, SM models of WMC suggest that SM should predict WMC, but AC should not (Possibility 2 in Fig. 1). Finally, according to the dual-component model of WMC, both AC and SM should predict WMC. To test this, three separate structural equation models (SEMs) were specified. In the first model (labeled SEM AC in Table 3) AC and SM were allowed to correlate with one another, but only the path from AC to WMC was freed (the path from SM to WMC was fixed to zero). This model tests the notion that AC, but not SM, accounts for WMC. In the second model (labeled SEM SM in Table 3) AC and SM were allowed to correlate with one another, but only the path from SM to WMC was free (the path from AC to WMC was fixed to zero). This model tests the notion that SM, but not AC, accounts for WMC. Finally, in the third model (labeled SEM Both in Table 3), AC and SM were allowed to correlate and both paths to WMC were freed. This model tests the notion that both AC and SM are needed to account for WMC.

As shown in Table 3, allowing both AC and SM to predict WMC led to better fit than either of the other two models, $\Delta\chi^2$'s > 4.5, p's < .05, and both paths were significant. Thus, consistent with the dual-component model and generally inconsistent with both purely attention control or secondary memory based models of WMC, both attention control and secondary memory abilities accounted for unique variance in WMC. Specifically, the path coefficient from AC to WMC was .30 and the path coefficient from SM to WMC was .46. Furthermore, both constructs combined to account for 52% of the variance in WMC. Thus, although either component alone would account for a good deal of variance in WMC, both are needed for a fuller account of WMC within the specified models.

The above analyses suggest that both AC and SM are important components of WMC, but are both needed to

[2] An exploratory factor analysis demonstrated a similar structure to the data with separate, yet correlated, working memory capacity, attention control, and memory factors.

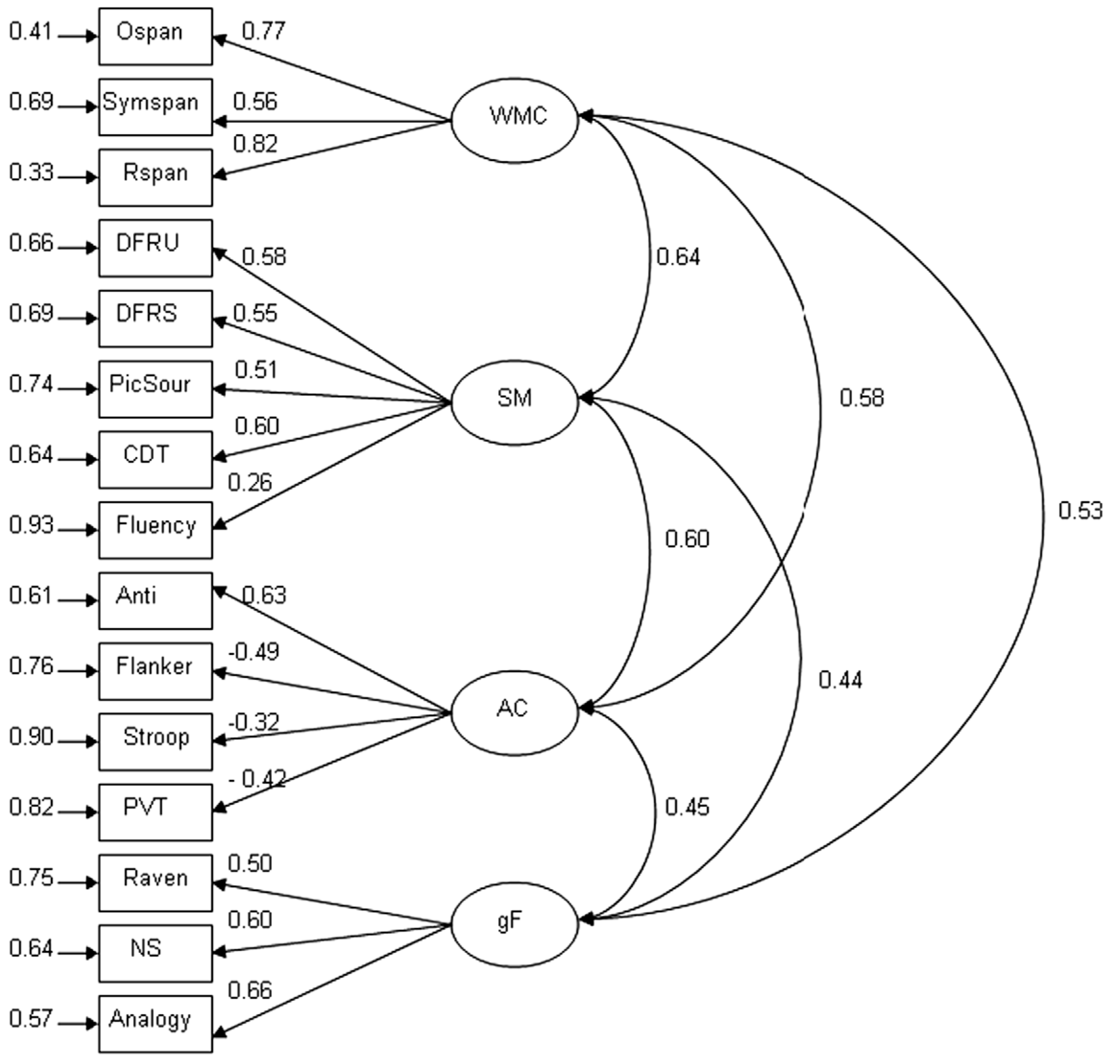

Fig. 2. Model for working memory capacity (WMC), secondary memory (SM), attention control (AC), and general fluid intelligence (gF). Paths connecting latent variables (circles) to each other represent the correlations between the constructs, the numbers from the latent variables to the manifest variables (squares) represent the loadings of each task onto the latent variable, and numbers appearing next to each manifest variable represent error variance associated with each task. Ospan = operation span; Symspan = symmetry span; Rspan = reading span; Anti = antisaccade; Flanker = arrow flankers; Stroop = Stroop; PVT = psychomotor vigilance task; DFRU = delayed free recall unrelated words; DFRS = delayed free recall semantically related words; PicSour = picture source recognition; CDT = continual distractor free recall; Fluency = verbal fluency; Raven = Raven Advanced Progressive Matrices; NS = number series; Analogy = verbal analogies. All loadings and paths are significant at the $p < .05$ level.

account for the relation between WMC and gF? That is, what will happen to the above SEM when gF is included? To examine this, the gF latent variable from the previous measurement model was added to the SEM in which both AC and SM predicted WMC. In this new SEM (labeled SEM gF in Table 3) AC, SM, and WMC all had direct links to gF. As shown in Table 3, the fit of the model was good. As can be seen in Fig. 3, the direct effect from WMC to gF was significant, but the direct effects from AC and SM to gF were not. Thus, although all three constructs accounted for approximately 32% of the variance in gF, only WMC accounted for unique variance in gF. The variance that both AC and SM accounted for in gF was likely shared with the variance accounted for by WMC.

Variance partitioning

To explore the shared and unique contribution of each latent component with gF further, we utilized variance partitioning methods that have been used previously (e.g., Chuah & Maybery, 1999; Cowan et al., 2005). Variance partitioning attempts to allocate the overall R^2 of a particular criterion variable (here gF) into portions that are shared and unique to a set of predictor variables (here WMC, SM, and AC). A series of regression analyses was carried out to obtain R^2 values from different combinations of the predictor variables (see Table 4) in order to partition the variance. For each variable entering into the regression, the latent correlations from the previous confirmatory factor analysis (i.e., Measurement Model 4gF) were used.

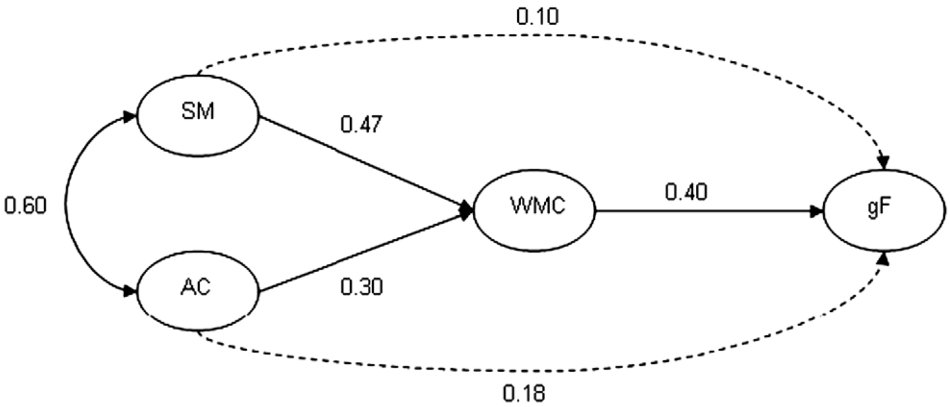

Fig. 3. Structural equation model for secondary memory (SM), attention control (AC) and working memory capacity (WMC) predicting fluid intelligence (gF). Single-headed arrows connecting latent variables (circles) to each other represent standardized path coefficients indicating the unique contribution of the latent variable. The double headed arrow connecting Mem and AC represents the correlation between the two factors. Solid paths are significant at the $p < .05$ level, whereas dashed paths are not significant.

As shown in Fig. 4, the results suggested that a total of 32% of the variance in gF was accounted for by the three constructs. Of this variance, 13% was shared by all three of the constructs (WMC, AC, and SM), whereas the remaining 19% was accounted for by both unique and shared variance across the three constructs. Specifically, 4% was uniquely shared by WMC and SM, 4% was uniquely shared by WMC and AC, but SM and AC only uniquely shared about 1%. Thus, the shared variance between WMC and gF was accounted for by both shared variance with SM and AC, but these two constructs did not account for much variance outside of what was accounted for by WMC. Indeed, both SM and AC only accounted for 1–2% unique variance in gF. WMC, on the other hand, accounted for 7% of the variance in gF independently of what was shared with both SM and AC. Similar to the SEM presented in Fig. 3, only WMC accounted for unique variance in gF. Importantly, partialling out either AC or SM would drastically reduce the amount of shared variance between WMC and gF. If both AC and SM abilities are partialled out, then WMC would only account for 7% of the variance in gF. Thus, both AC and SM are needed to account for variation in WMC, and to account for the shared variance between WMC and gF.

Table 4
R^2 values for regression analyses predicting gF for various predictor variables.

Predictor variables	R^2	F
1. WMC, SM, AC	.32	27.35
2. WMC, SM	.30	37.80
3. WMC, AC	.31	40.28
4. SM, AC	.25	29.30
5. WMC	.28	69.92
6. SM	.19	42.97
7. AC	.20	45.45

Note: All R^2 values are significant at $p < .01$. gF = fluid intelligence; WMC = working memory capacity; SM = secondary memory; AC = attention control.

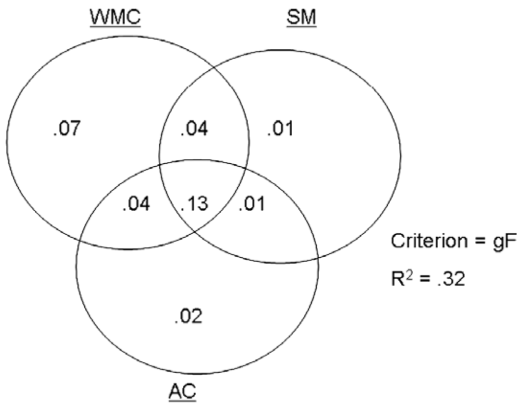

Fig. 4. Venn diagrams indicating the shared and unique variance accounted for in fluid intelligence (gF) working memory capacity (WMC), secondary memory (SM), and attention control (AC). Numbers are based on regressions from Table 4.

Discussion

The current study examined whether WMC is best explained by attention control abilities (AC), secondary memory abilities (SM), or both. Latent variables of WMC, AC, and SM were constructed based on multiple measures of each construct. Confirmatory factor analyses suggested that WMC, AC, and SM represented distinct constructs, each of which was related to fluid intelligence (gF). Examining the question of primary interest, structural equation modeling suggested that both AC and SM had direct effects on WMC. That is, WMC was accounted for by both AC and SM as specified in the current models. These results are consistent with attention control (e.g., Engle & Kane, 2004) theories of WMC which suggest that attention control is an important component of WMC and a major source of individual variation in WMC. These results are also consistent with secondary memory based (Mogle et al., 2008) theories of WMC which suggest that differences in controlled retrieval processes are an important component of WMC and for individual differences in WMC. Thus, the results are consistent with both attention control and secondary memory based theories of WMC. However, we believe that the results are most consistent with the dual-component model of WMC (Unsworth & Engle, 2007a) which suggests that WMC is composed of both attention control abilities (active maintenance in the face of distraction) and secondary memory abilities (controlled search). That is, although both attention control and secondary memory based theories individually explain a large chunk of the variance in WMC, we showed that combining these two components provides a fuller account of WMC and of individual variation in WMC.

Note, that with all models of this type, other possible configurations of the data are possible that could lead to identical fits to the data. Specifically, given the correlational nature of the study, one should be cautious is assuming causality in the models that are specified. That is, the models portrayed in Fig. 1 suggest that attention control, secondary memory, or both predict working memory capacity. Of course, the opposite model in which working memory capacity predicts both attention control and secondary memory is also likely and technically is equivalent to the models presented. However, we feel justified in presenting the models the way we have given that we were interested in the extent to which attention control and secondary memory constructs would account for unique variance in working memory capacity, and thus working memory capacity is portrayed as the criterion variable. Therefore, based on the theoretical differences described previously, our analytic technique was to examine working memory capacity as a criterion variable, rather than examine working memory capacity as a predictor. The extent to which working memory capacity is considered as a predictor variable or a criterion variable likely depends on one's particular theoretical viewpoint as well as the questions that are being asked in a given study. Thus, although the data support a prediction of the dual-component model, other alternatives not explored in the current study are possible and should be examined in the future.

In terms of the relation between WMC and gF, adding gF into the models suggested that only WMC had a direct effect on gF. The effects from AC and SM to gF were mediated through WMC. Thus, contrary to prior claims that secondary memory abilities solely account for the relation between WMC and gF (Mogle et al., 2008), the current results suggested that WMC was still related to gF even after taking both AC and SM into account. These results argue against pure secondary memory based views of WMC, in that it is clear that AC abilities are also important for the relation between WMC and gF as suggested by attention control theories of WMC (Engle & Kane, 2004; Kane & Brown et al., 2007). Likewise, the results also argue against pure attention control views of WMC, in that SM abilities accounted for unique variance in WMC and this variance is important for the relation between WMC and gF. Thus, strong versions of the attention control view of WMC, which suggest that AC should fully mediate the relation between WMC and gF are inconsistent with the current data (although see Kane et al., 2006). That is, the results are certainly consistent with the AC view in suggesting that AC is an important part of WMC and its relation to gF, but AC is not the whole story, SM processes are also important.

Furthermore, the variance partitioning analyses suggested that partialling out either AC or SM led to a substantial reduction in the amount of shared variance between WMC and gF. Specifically, the variance partitioning analyses suggested that all three constructs (WMC, AC, and SM) together shared 13% of the variance with gF. This variance likely reflects domain-general control processes that are needed not only on low-level attention tasks, but also on memory tasks where proactive interference and retrieval competition make it difficult to retrieve the correct target items (e.g., Engle & Kane, 2004; Unsworth & Engle, 2007a). That is, there is likely shared variance due to control processes that are common to both AC and SM tasks given that no task is necessarily process pure. An additional 4% of the variance was uniquely shared among WMC, SM, and gF which likely reflect specific memory abilities (encoding, retrieval, and monitoring) which are needed on all of the secondary memory tasks, but are not needed on the attention tasks. Likewise, 4% of the variance was uniquely shared among WMC, AC, and gF which might reflect specific attention control abilities such as restrained, constrained, and sustained attention (Kane et al., 2006; Poole & Kane, 2009), which are not necessarily needed on the more basic memory tasks. Collectively, AC and SM accounted for 75% of the shared variance between WMC and gF and thus, it would seem that both SM and AC are needed to provide a fuller account for the predictive power of WMC.

Multifaceted nature of working memory capacity

The results of the current study point to the multifaceted nature of WMC. In particular the results suggest that both attention control and secondary memory are important components of WMC and are important for the predictive power of WMC. In terms of attention control abilities, the current results are consistent with prior work suggesting that domain-general attention control abilities are an important component of WMC (e.g., Engle & Kane, 2004; Unsworth & Engle, 2007a). In these views, attention control is needed to actively maintain task relevant representations in the face of distraction, prevent attentional capture from irrelevant information, sustain attention on a task in order to avoid lapses of attention, as well as constrain the focus of attention to relevant target items. Thus, although attention control (AC) was represented as a single unitary construct in the current study, it is possible that this construct can be broken down into sub-components, each of which is important for WMC and its relation to higher-order cognitive constructs like intelligence.

In terms of secondary memory abilities, the current results are also consistent with prior work suggesting that the ability to engage in a controlled search of secondary memory is an important component of WMC (Mogle et al., 2008; Unsworth & Engle, 2007a). Specifically, in these views it has been suggested that controlled search is needed to access relevant target information from secondary memory in the presence of irrelevant information in tasks such as free recall, cued recall, source recognition, as well as item recognition when recollection and not familiarity is needed (e.g., Unsworth & Engle, 2007a). Similar to attention control abilities, these secondary memory abilities can also be broken down into sub-components such as setting up a retrieval plan, specifying cues needed for search, monitoring the products of the search process, as well as deciding whether to continue searching. Each of these sub-components are likely important for WMC and its predictive power.

At the same time, it should be noted that attention control and secondary memory abilities in the current study only accounted for 52% of the variance in WMC. Thus, it is clear that although both are important components of WMC, other processes are also important to fully account for variation in WMC. Furthermore, although both attention control and secondary memory abilities accounted for the majority of the variance that was shared between WMC and gF, WMC still accounted for unique variance in gF independently of what was shared with attention control and secondary memory abilities. Thus, not only are other processes needed to fully account for variation in WMC, but other processes are needed to fully account for the relationship between WMC and gF.

One likely component that accounts for additional variation in WMC and may account for the unique variation between WMC and gF not accounted for by the other factors is the scope of attention (Cowan et al., 2005, 2006; Vogel, McCollough, & Machizawa, 2005) or the capacity of primary memory (Unsworth & Engle, 2006). Recently, Cowan and colleagues (Cowan et al., 2005) suggested that the size or scope of the focus of attention was an important predictor of individual variation in intellectual abilities. Furthermore, Cowan et al. (2006) suggested that attention control and the scope of attention reflect both overlapping and distinct constructs. Cowan et al. (2006) demonstrated that measures of attention control and scope of attention accounted for both unique and shared variance in intellectual functioning similar to the current study. Thus, it seems likely that the 7% of variance that was uniquely shared between WMC and gF independently of attention control and memory constructs is due to variation in the scope or size of the focus of attention.

Similarly, we have previously suggested that individual variation in the capacity of primary memory (which we see as analogous to the focus of attention) contributes to variation in overall WMC and the relation between WMC and gF (Unsworth & Engle, 2006, 2007a). However, in our previous work we had suggested that the capacity of primary memory and the ability to actively maintain information in primary memory (attention control) reflected largely the same thing. Given Cowan and colleagues (2006) recent work, this characterization was clearly an oversimplification. Thus, it seems clear that the amount of information that can be maintained in primary memory (or the focus) and the ability to maintain that information in the presence of distraction likely reflect partially distinct constructs, each of which is needed for a fuller account for WMC and its predictive power. As noted previously, we did not include any measures of short-term memory (simple span tasks), the capacity of primary memory, or the scope of attention and so future work should be aimed at examining all of these constructs (WMC, attention control, scope of attention, and secondary memory) in the same study.

Furthermore it would be remiss not to point out that other processes could be important as well. These include integration and coordination processes that are specifically needed in complex span tasks where processing and storage operations are combined (Bayliss, Jarrold, Gunn, & Baddeley, 2003; Oberauer, Süß, Wilhelm, & Wittmann, 2003), updating and attention switching operations that are more likely needed in dynamic tasks like complex span tasks than in more basic attention and memory tasks (Oberauer, 2002; Unsworth & Engle, 2008; Verhaeghen & Basak, 2005), as well as binding operations that are needed to momentarily bind items (Halford, Cowan, & Andrews, 2007; Oberauer, 2005). Each of these operations has been linked to WMC in the past and each has been suggested as possible reasons for the strong relationship between WMC and gF. Clearly more work is needed to determine the extent to which these processes (as well as other likely processes) are needed to fully account for variation in WMC and the relation between WMC and gF. At any rate it is clear that although the dual-component model accounts for a substantial amount of the variation in WMC, this view (as well as others) needs to be augmented to include other important processes that better capture the multifaceted nature of WMC. Speculatively, we suggest that variation in WMC, and the relation between WMC and gF, reflects variation in the ability to actively maintain information in primary memory (attention control), variation in the size or capacity of primary memory (or scope of attention), variation in the ability to strategically search and retrieve information form secondary memory, as well as possibly variation in other processes. This points to the multifaceted nature of WMC and suggests that in order to understand WMC and the relation between WMC and gF, we should not be satisfied with a single source of variance, but rather must look for multiple sources of variance.

Conclusion

Overall, the results of the current study are consistent with the dual-component model of WMC (Unsworth & Engle, 2007a) which suggests that WMC is jointly determined by both attention control and memory abilities rather than either alone. Relying on only attention control or secondary memory constructs as the sole mechanism of WMC, would not fully explain the relation between WMC and gF, and would not account for the explanatory power of WMC. Furthermore, although both of these constructs (attention control and secondary memory) accounted for a substantial amount of the variance in WMC and the shared relation between WMC and gF, they did not fully account for all of the variation. Thus, other important constructs are needed to fully explain WMC and its predictive power.

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