Working Memory and Fluid Intelligence: A Multi-Mechanism View

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"We want to understand intelligence, not only map its network of correlations with other constructs. This means to reveal the functional – and ultimately, the neural – mechanisms underlying intelligent information processing. Among the theoretical constructs within current theories of information processing, [working memory capacity] WMC is the one parameter that correlates best with measures of reasoning ability, and even with g_f and *g*. Therefore, investigating WMC, and its relationship with intelligence, is psychology's best hope to date to understand intelligence." – Oberauer, Schulze, Wilhelm, & Süß (2005)

Working memory (WM) is a construct developed by cognitive psychologists to characterize and help further investigate how human beings maintain access to goal-relevant information in the face of concurrent processing and/or distraction. For example, suppose you are fixing a cocktail for your spouse, who has just arrived home from work. You need to remember that for the perfect Manhattan, you need 2 ounces of bourbon, 1 ounce of sweet vermouth, a dash of bitters and a splash of maraschino cherry juice, and at the same time you need to listen to your spouse tell you about his or her day. WM is required to remember the ingredients without repeatedly consulting the recipe and to process the incoming information to understand the conversation. Many important cognitive behaviors, beyond cocktail-mixing, such as reading, reasoning, and problem solving require WM because for each of these activities, some information must be maintained in an accessible state while new information is processed and potentially distracting information is ignored. If you have experience preparing this particular drink then you could rely on procedural memory to perform the task. If not, however, then WM is required to simultaneously remember the ingredients and comprehend the conversation.

Working memory is a limited-capacity system. That is, there is only so much information that can be maintained in an accessible state at one time. There is also substantial variation in WM capacity (WMC) across individuals: Older children have greater capacity than younger children, the elderly tend to have lesser capacity than younger adults, and patients with certain types of neural damage or disease have lesser capacity than healthy adults. There is even a large degree of variation in WMC within healthy adult samples of subjects, such as within college-student samples.

It is important to clarify at the outset the distinction between WM and WMC. WM refers to the cognitive system required to maintain access to information in the face of concurrent processing and/or distraction (including mechanisms involved in stimulus representation, maintenance, manipulation, and retrieval), while WMC refers to the maximum amount of information an individual can maintain in a particular task that is designed to measure some aspect(s) of WM. This has caused some confusion in the literature because different researchers operationally define WM in different ways, and this has implications for the relationship between WM and intelligence. For example, two researchers may share the same exact definition of WM but they may operationalize WM differently, which could result in a different perspective on WMC and its correlates.

The focus of the current chapter is on the relationship between WMC and fluid intelligence (g_f) in healthy young adults. Recent meta-analyses, conducted by two different groups of researchers, estimate the correlation between WMC and g_f to be somewhere between $r = .72$ (Kane, Hambrick, & Conway, 2005) and $r = .85$ (Oberauer et al., 2005). Thus, according to these analyses, WMC accounts for at least half the variance in g_f. This is impressive, yet for this line of work to truly inform theoretical accounts of intelligence, we need to better understand the construct of WM and discuss the various ways in which it is measured.

The emphasis here is on fluid intelligence rather than crystallized intelligence, general intelligence (*g*) or intelligence more broadly defined because most of the research linking WM to the concept of intelligence has focused on fluid abilities and reasoning rather than acquired knowledge or skill (however see Hambrick, 2003; Hambrick & Engle, 2002; Hambrick & Oswald, 2005). This is a natural place to focus our microscope because WM is most important in situations that do not allow for the use of prior knowledge and less important in situations in which skills and strategies guide behavior (Ackerman, 1988; Engle, Tuholski, Laughlin, & Conway, 1999). That said, we acknowledge that fluid intelligence is a fuzzy concept. The goal of the current chapter and much of the research reviewed in this chapter is to move away from such nebulous constructs and towards more precisely defined cognitive mechanisms that underlie complex cognition.

The chapter begins with a brief review of the history of WM, followed by our own contemporary view of WM, which is largely shaped by Cowan's model (1988; 1995; 2001; 2005), but also incorporates ideas from individual differences research (for a review, see Unsworth and Engle, 2007), neuroimaging experiments (for a review, see Jonides et al., 2008), and computational models of WM (Ashby, Ell, Valentin, & Casale, 2005; O'Reilly & Frank, 2006). We then discuss the measurement of WMC. These initial sections allow for a more informed discussion of the empirical work that has linked WMC and g_f. We then consider various theories on the relationship between WMC and g_f, and propose a novel perspective, which we call the *multi-mechanism view*. We conclude with a discussion of a recent trend in research on WM and intelligence: WM training and its effect on g_f.

Historical perspective on WM

The *concept* of WM was first introduced by Miller, Galanter, and Pribram (1960) in their influential book, *Plans and the Structure of Behavior*. The book, which is recognized as one of the milestones of the cognitive revolution, is also known for introducing the iterative problem solving strategy known as TOTE, or Test – Operate – Test – Exit. The TOTE strategy is often implemented as people carry out plans and pursue goal-directed behavior. For example, when mixing the drink for your spouse, you could perform a *Test* (is the drink done?), and if not, then perform an *Operation* (add bourbon, which would require remembering that bourbon is one of the ingredients), and test again, and so on until the goal is achieved, at which point you *Exit* the plan. Miller et al. realized that a dynamic and flexible short-term memory system is necessary to engage the TOTE strategy and to structure and execute a plan. They referred to this short-term memory system as a type of "working memory" and speculated that it may be dependent upon the prefrontal cortex.

The *construct* WM was introduced in the seminal chapter by Baddeley and Hitch (1974). Prior to their work, the dominant theoretical construct used to explain short-term memory performance was the short-term store (STS), epitomized by the so-called "modal model" of memory popular in the late 1960s (e.g., Atkinson & Shiffrin, 1968). According to these models, the STS plays a central role in cognitive behavior, essentially serving as a gateway to further information processing. It was therefore assumed that the STS would be crucial for a range of complex cognitive behaviors, such as planning, reasoning, and problem solving. The problem with this approach, as reviewed by Baddeley and Hitch, was that disrupting the STS with a small memory load had very little impact on the performance of a range of complex cognitive tasks, particularly reasoning and planning. Moreover, patients with severe STS deficits, for example, a digit span of only two items, functioned rather normally on a wide range of complex cognitive tasks (Shallice & Warrington, 1970; Warrington & Shallice, 1969). This would not be possible if the STS were essential for information processing, as proposed by the modal model.

Baddeley and Hitch therefore proposed a more complex construct, *working memory*, that could maintain information in a readily accessible state, consistent with the STS, but also engage in concurrent processing, as well as maintain access to more information than the limited capacity STS could purportedly maintain. According to this perspective, a small amount of information can be maintained via "slave" storage systems, akin to the STS, but more information can be processed and accessed via a central executive, which was poorly described in the initial WM model but has since been refined, and will be discussed in more detail below.

Baddeley and Hitch argued that WM but not the STS plays an essential role in a range of complex cognitive tasks. According to this perspective, WMC should be more predictive of cognitive performance than the capacity of the STS. This prediction was first supported by an influential study by Daneman and Carpenter (1980), which explored the relationship between the capacity of the STS, WMC, and reading comprehension, as assessed by the Verbal Scholastic Aptitude Test (VSAT). STS capacity was assessed using a word span task, in which a series of words were presented, one per second, and at the end of a series the subject was prompted to recall all the words in correct serial order. Daneman and Carpenter developed a novel task to measure WMC. The task was designed to require short-term storage, akin to word span, but also to require the simultaneous processing of new information. Their *reading span* task required subjects to read a series of sentences aloud and remember the last word of each sentence for later recall. Thus, the storage and recall demands of reading span are the same as for the word span task, but the reading span task has the additional requirement of reading sentences aloud while trying to remember words for later recall. This type of task is thought to be an ecologically valid measure of the WM construct proposed by Baddeley and Hitch.

Consistent with the predictions of WM theory, the reading span task correlated more strongly with VSAT ($r = .59$) than the word span task ($r = .35$). This may not seem at all surprising, given that both the VSAT and reading span involve *reading*. However, subsequent work by Turner and Engle (1989) and others showed that the processing component of the WM span task does not have to involve reading for the task to be predictive of VSAT. They had subjects solve simple mathematical operations while remembering words for later recall and showed, consistent with Daneman and Carpenter (1980), that the operation span task predicted VSAT more strongly than the word span task. More recent research has shown that a variety of WM span tasks, similar in structure to reading span and operation span but with various processing and storage demands, are strongly predictive of a wide range of complex cognitive tasks, suggesting that the relationship between WM span performance and complex cognition is largely domain-general (e.g., Kane, Hambrick, Wilhelm, Payne, Tuholski, & Engle, 2004).

In sum, WM is a relatively young construct in the field of psychology. It was proposed as an alternative conception of short-term memory performance in an attempt to account for empirical evidence that was inconsistent with the modal model of memory that included a STS to explain short-term memory. Original measures of WMC, such as reading span and operation span (also known as complex span tasks, see the measurement section below), were shown to be more strongly correlated with measures of complex cognition, including intelligence tests, than are simple span tasks, such as digit span and word span. Recent work has called into question this simple distinction between complex and simple span tasks, which we will discuss later in the chapter, but here at the outset it is important to highlight that Baddeley and Hitch (1974) proposed WM as an alternative to the concept of a STS. Indeed, referring to WM as a "system" and using the digit span task as a marker of the STS, Baddeley and Hitch concluded:

> "This system [WM] appears to have something in common with the mechanism responsible for the digit span, being susceptible to disruption by a concurrent digit span task, and like the digit span showing signs of being based at least in part upon phonemic coding. It should be noted, however, that the degree of disruption observed, even with a near-span concurrent memory load, was far from massive. This suggests that although the digit span and working memory overlap, there appears to be a considerable component of working memory which is not taken up by the digit span task."

Contemporary view of WM

Delineating the exact characteristics of WM and accounting for variation in WMC continues to be an extremely active area of research. There are, therefore, several current theoretical models of WM and several explanations of WMC variation. In this section we introduce just one view of WM, simply to provide the proper language necessary to explain WM measurement and the empirical data linking WMC to intelligence. Later in the chapter we will consider alternative theoretical accounts. Our view is largely shaped by Cowan's model (1988; 1995; 2001; 2005) rather than the recent incarnation of Baddeley's model (2007) because we argue that Cowan's model is more amenable to recent findings from neuroimaging studies of WM (Jonides et al., 2008; Postle, 2006). We also prefer Cowan's model to computational modeling approaches to WM (e.g., Ashby et al., 2005; O'Reilly & Frank, 2006) because Cowan's model, while less specified mechanistically, addresses a broader range of phenomena, including the correlation between WMC and g_f.

Cowan's model (see Figure 1) assumes that WM consists of activated long-term memory representations (see also Anderson, 1983; Atkinson & Shiffrin, 1971; Hebb, 1949) and a central executive responsible for cognitive control (for work that explains cognitive control without reference to a homuncular executive, see O'Reilly and Frank, 2006). Within this activated set of representations, or "short-term store", there is a focus of attention that can maintain approximately 4 items in a readily accessible state (Cowan, 2001). In other words, we can "think of" approximately 4 mental representations at one time.

Our own view is quite similar to the model in Figure 1. However, we make three modifications. First, we prefer "unitary store" models of memory, rather than multiple store models and therefore do not think of the activated portion of LTM as a "store." The reason for this distinction is that there is very little neuroscience evidence to support the notion that there is a neurologically separate "buffer" responsible for the short-term storage of information (see Postle, 2006). We acknowledge that there are memory phenomena that differ as a function of retention interval (for a review, see Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, and Usher, 2005) but we argue that these effects do not necessitate the assumption of a short-term store (for a review see Sederberg, Howard, and Kahana, 2008). Second, recent work has shown that the focus of attention may be limited to just one item, depending on task demands (Garavan, 1998; McElree, 2001; Nee & Jonides, 2008; Oberauer, 2002). We therefore adopt Oberauer's view that there are actually 3 layers of representation in WM: (1) the focus of attention, limited to one item; (2) the region of direct access, limited to approximately 4 items; and (3) representations active above baseline but no longer in the region of direct access. To avoid confusion over Cowan and Oberauer's terminology, we will use the phrase "scope of attention" to refer to the limited number of items that are readily accessible, recognizing that one item may have privileged access. Third, and most important for the current chapter, we argue that Cowan's view of WMC is too limited to account for complex cognitive activity, such as reasoning. Complex cognitive behavior, such as reasoning, reading, and problem solving requires rapid access to more than 4 items at one time. WM therefore must also consist of a retrieval mechanism that allows for the rapid retrieval of information from LTM. This notion has been referred to as long-term WM (Ericcson & Kintsch, 1995).

Thus, we view WM as consisting of at least 3 main components: (1) cognitive control mechanisms (aka the central executive), which are most likely governed by the prefrontal cortex (PFC), anterior-cingulate cortex (ACC) and subcortical structures including the basal ganglia and thalamus (Ashby et al. 2005; Botvinick, 2007; Miller & Cohen, 2001; O'Reilly & Frank, 2006); (2) 1-4 representations in the scope of attention, which are most likely maintained via activity in a frontal-parietal network (Todd & Marois, 2004; Vogel & Machizawa, 2004); and (3) a retrieval mechanism responsible for the rapid retrieval of information from LTM. This process is most likely achieved via cortical connections from the PFC to the medial temporal lobe (MTL), including the hippocampus (Chein, Moore, & Conway, 2010; Nee & Jonides, 2008; Ranganath, 2006; O'Reilly & Norman, 2002; Unsworth & Engle, 2007).

Assuming this general architecture, consider Figure 2, from Jonides et al. (2008), which depicts the processing and neural representation of a single stimulus over the course of a few seconds in a hypothetical WM task, consisting of the presentation of 3 stimuli followed by a probe. Note that three brain regions, PFC, parietal cortex, and MTL, are integral to processing. This framework is consistent with our view and with recent individual differences research on WM proposing that variation in WMC is partly due to active maintenance of information, achieved via PFC-parietal connections, and controlled retrieval of information achieved via PFC-MTL connections (Unsworth & Engle, 2007). We further propose that WMC is partly determined by cognitive control mechanisms, such as interference control (Burgess, Braver, Conway, & Gray, 2010). We elaborate upon this multi-mechanism view later in the chapter.

Measurement of WMC

There are several different WM tasks used in contemporary research. These tasks vary in extremely important ways, which we will discuss below. As well, the extent to which WMC predicts g_f is largely dependent upon which set of tasks one uses to measure WMC. Thus, a detailed discussion of various WM tasks is essential here. We mainly consider WM tasks that have shown strong correlations with measures of g_f in a domain-general fashion, for example, a verbal WM task predicting a spatial reasoning task and vice-versa.

Complex span tasks

As discussed above, complex span tasks, such as reading span (Daneman & Carpenter, 1980), and operation span (Turner & Engle, 1989), were designed from the perspective of the original WM model. Other complex span tasks include the counting span task (Case, Kurland, & Goldberg, 1982), as well as various spatial versions (see Kane et al., 2004; Shah & Miyake, 1996). Complex span tasks require participants to engage in some sort of simple processing task (e.g., reading unrelated sentences aloud or completing a math problem, as in reading span and operation span, respectively) between the presentations of to-be-remembered items (e.g., letters, words, digits, spatial locations). After a list of items have been presented, typically between 2 and 7, the subject is prompted to recall all the to-be-remembered items in correct serial order.

For example, in the counting span task, the subject is presented with an array of items, such as blue and red circles and squares, and instructed to count a particular class of items, such as blue squares. After counting aloud the subject is required to remember the total and is then presented with another array. They again count the number of blue squares aloud and remember the total. After a series of arrays they are required to recall all the totals in correct serial order. Thus, the storage and recall demands are the same as a simple digit span task, but there is the additional requirement of counting the arrays, which demands controlled attention (Treisman & Gelade, 1980) and therefore disrupts active maintenance of the digits. Again, this is thought to be an ecologically valid measure of WM as proposed by Baddeley and Hitch (1974) because it requires access to information (the digits) in the face of concurrent processing (counting) (for more details, see Conway, Kane, Bunting, Hambrick, Wilhelm, and Engle, 2005).

As mentioned above, complex span tasks reveal strong correlations with the VSAT (*r*s approximately .5, see Daneman and Carpenter, 1980, 1983; Turner and Engle, 1989) and other measures of reading comprehension (*r*s ranging from .50 to .90 depending on the comprehension task). Complex span tasks also correlate highly with each other regardless of the processing and storage task (Turner & Engle, 1989). For example, Kane et al. (2004) administered several verbal and several spatial complex span tasks and the range of correlations among all the tasks was $r = .39$ to $r = .51$. Moreover, the correlation between latent variables representing spatial complex span and verbal complex span was $r = .84$ and the correlation between a latent variable representing all complex span tasks and g_f was $r = .76$. These results suggest that complex span tasks tap largely domain-general mechanisms, which makes them good candidates for exploring the relationship between WMC and g_f.

<u>Simple span tasks</u>

Simple span tasks (e.g., digit span, word span, letter span), in contrast to complex span, do not include an interleaved processing task between the presentation of to-be-remembered items. For example, in digit span, one digit is presented at a time, typically one per second, and after a series of digits the subject is asked to recall the digits in correct serial order. Simple span tasks are among the oldest tasks used in memory research, for example, digit span was included in the first intelligence test (Binet, 1903) and continue to be popular in standardized intelligence batteries (e.g., WAIS, WISC).

As mentioned above, simple span tasks like digit span correlate less well with measures of complex cognition than complex span tasks (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Engle et al., 1999; Kane et al., 2004). As well, simple span tasks are thought to be more domain-specific than complex span tasks, such that within-domain correlations among simple span tasks are higher than cross-domain correlations among simple span tasks (Kane et al., 2004). Moreover, this domain-specific dominance is greater in simple span tasks than in complex span tasks (Kane et al., 2004). These results would suggest that simple span tasks are not ideal candidates for exploring the relationship between WMC and g_f. However, recent research has shown that in some situations simple span tasks correlate as well with measures of g_f as complex span tasks, and in some cases tap domain-general WM processes. We discuss three of these situations here: (1) simple span with very rapid presentation of items, known as running span; (2) simple span with spatial stimuli, known as spatial simple span; and (3) simple span with long lists of items, known as long-list simple span.

In a running memory span task (Pollack, Johnson, & Knaff, 1959), subjects are rapidly presented with a very long list of to-be-remembered items, the length of which is unpredictable. At the end of the list the subject is prompted to recall as many of the last few items as possible. Cowan et al. (2005) found that running span correlates well with various measures of cognitive ability in children and adults (see also Mukunda and Hall, 1992). Cowan et al. argued that the rapid presentation (e.g., 4 items per second as compared to 1 item per second in digit span) prevents verbal rehearsal and that any WM memory task that prevents well-learned maintenance strategies, such as rehearsal and chunking, will serve as a good predictor of complex cognition, including g_f.

This same explanation may account for the fact that simple span tasks with spatial stimuli tend to show strong correlations with measures of g_f (Kane et al., 2004; Miyake et al., 2001). For example, in a computerized version of the corsi blocks task, subjects are presented with a 4x4 matrix and a series of cells in the matrix flash, one location at a time, typically at a rate of 1 location per second. At the end of a series, the subject is required to recall the flashed locations in correct serial order. Kane et al. found that a latent variable derived from 3 spatial simple span tasks correlates as well with g_f as a latent variable derived from 3 spatial complex span tasks. It is important to note, however, that the g_f variance accounted for by complex span and spatial simple span does not completely overlap, a point we will return to later in the chapter.

Simple span tasks are also strong predictors of g_f when only trials with long lists are considered. Reanalyzing data from Kane et al. (2004), Unsworth and Engle (2006) showed that the correlation between simple span and g_f increased as the number of to-be-remembered items in the span task increased. In contrast, the correlation between complex span and g_f remained stable as the number of items in the complex span task increased. Also, the correlation between simple span and g_f was equivalent to the correlation between complex span and g_f for lists of 4 or more items. Unsworth and Engle therefore argued that controlled retrieval of items is needed when the number of items exceeds the scope of attention, that is, approximately 4 items. According to this perspective, simple span tasks with long-lists require the same retrieval mechanism as complex span tasks because in each type of task, some information is lost from the scope of attention and must be recovered at the recall prompt. In the case of long-list simple span, some items are lost because the scope of attention is full and in the case of complex span items are lost because attention is shifted to the processing component of the task.

Scope of attention tasks

Running memory span and spatial simple span tasks with short lists, discussed above, might also be considered "scope of attention" tasks. Cowan (2001) reviewed evidence from a variety of tasks that prevent simple maintenance strategies such as rehearsal and chunking and found that for most of these tasks the number of items that could be maintained was about 4. As mentioned above, other researchers have shown that in some tasks one item in the focus of attention has privileged access (Garavan, 1998; McElree, 2001; Nee & Jonides, 2008; Oberauer, 2002) but according to Cowan's (2001) review the *scope* of attention is approximately 4 items. While running span and spatial simple span may be considered part of this class, they are not ideal measures of the scope (and control) of attention because the to-be-remembered items must each be recalled and therefore performance is susceptible to output interference. In other words, it's possible that more than 4 items are actively maintained but some representations are lost during recall.

For this reason, the visual array comparison task (Luck & Vogel, 1997) is considered a better measure of the scope of attention. There are several variants of the visual array comparison task but in a typical version subjects are briefly presented (e.g., 100 ms) with an array of several items that vary in shape and color. After a short retention interval (e.g., 1 s), they are then presented with another array and asked to judge whether the two arrays are the same or different. On half the trials the two arrays are the same and on the other half one item in the second array is different. Thus, if all items in the initial array are maintained then subjects will be able to detect the change. Most subjects achieve 100% accuracy on this task when the number of items is less than 4 but performance begins to drop as the number of items in the array increases beyond 4.

Tasks that are designed to measure the scope of attention, like visual array comparison tasks, have not been used in studies of WM and g_f as often as complex and simple span tasks but recent research shows that scope of attention tasks account for nearly as much variance in cognitive ability as complex span tasks (Awh, Fukuda, Vogel, & Mayr, 2009; Cowan et al., 2005; Cowan et al., 2006). This work will be discussed in more detail below.

Coordination and transformation tasks

All of the above mentioned tasks require subjects to recall or recognize information that was explicitly presented. In some WM tasks, which we label "coordination and transformation" tasks, subjects are presented with information and required to manipulate and/or transform that information to arrive at a correct response. We include in this class backward span, letter-number sequencing, alphabet recoding, as well as more complex tasks used by Kyllonen and Christal (1990) and Oberauer and colleagues (Oberauer et al., 2003; Oberauer, 2004; Süß et al., 2002).

Backward span tasks are similar to simple span tasks except that the subject is required to recall the items in reverse order. Thus, the internal representation of the list must be transformed for successful performance. In letter-number sequencing, the subject is presented with a sequence of letters and numbers and required to recall first the letters in alphabetical order and then the numbers in chronological order. In alphabet recoding the subject is required to perform addition and subtraction using the alphabet, e.g., C – 2 = A. The subject is presented with a problem and required to generate the answer. Difficulty is manipulated by varying the number of letters presented, e.g., CD – 2 = AB.

Kyllonen and Christal (1990) found very strong correlations between WMC and reasoning ability, using a variety of WM tasks that can all be considered in this "coordination and transformation" class (*r*s between .79 and .91). Also, Oberauer and colleagues showed that the correlation between WMC and g_f does not depend upon whether WM is measured using complex span tasks or these types of transformation tasks, suggesting that coordination and transformation tasks tap the same mechanisms as complex span tasks. Importantly, this suggests that the dual-task nature of complex span tasks (i.e., processing and storage) is not necessary for a WM task to be predictive of g_f, a point we return to below.

N-back tasks

In an n-back task the subject is presented with a series of stimuli, one at a time, typically one every 2-3 seconds, and must determine if the current stimulus matches the one presented n-back. The stimuli may be verbal, such as letters or words, or visual objects, or spatial locations. N-back tasks have been used extensively in fMRI experiments, and more recently in WM training experiments. Gray, Chabris, and Braver (2003) showed that a verbal n-back task was a strong predictor of a spatial reasoning task (Ravens Advanced Progressive Matrices), making n-back a class of WM tasks to consider as we discuss the relationship between WMC and g_f.

Empirical evidence linking WMC and g_f

Now that we have considered various measures of WMC, we turn to a review of the empirical evidence linking WMC and g_f. As mentioned above, two recent meta-analyses, conducted by two different groups of researchers, estimated the correlation between WMC and g_f to be somewhere between $r = .72$ (Kane et al., 2005) and $r = .85$ (Oberauer et al., 2005). Kane et al. summarized the studies included in their meta-analysis in a table, which is reproduced here (see Table 1). Each of the studies included in the meta-analysis administered several tests of

WMC and several tests of g_f and latent variable analysis was used to determine the strength of the relationship between the two constructs. A variety of WM tasks were used in these studies, including complex span, simple span, and coordination and transformation tasks. None of the studies referenced in Table 1 used tests designed to measure the scope of attention, like visual array comparison, or n-back tasks.

One finding that has emerged from these studies is that complex span tasks are a stronger predictor of g_f than simple span (Conway et al., 2002; Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Engle et al., 1999; Kane et al., 2004). However, as mentioned above, more recent research has demonstrated that this is only true for verbal simple span tasks (Kane et al., 2004; Miyake et al., 2001), and then, it is only true for verbal simple span tasks that do not include long lists (Unsworth & Engle, 2006, 2007). Unsworth and Engle have now repeatedly shown that simple span tasks with long lists correlate as strongly with measures of g_f as complex span tasks. Also, Kane et al. found that simple span tasks with spatial stimuli revealed correlations with measures of g_f as high as complex span tasks did.

These recent findings have important implications for theories of the relationship between WMC and g_f. However, it is important to note that in each of these cases, simple span with spatial stimuli, and simple span with long lists, the variance explained in g_f is not entirely the same as the variance explained by complex span. To illustrate this, we re-analyzed data from Kane et al. (2004). We conducted a series of hierarchical regression analyses to determine the variance in g_f that is either uniquely or commonly explained by complex span and simple span (cf., Chuah & Mayberry, 1999). The results of this analysis are presented in Figure 3, panel A. As the figure illustrates, simple span with spatial stimuli accounts for a substantial portion of variance in g_f, and some of that variance is shared with complex span but some of it is unique to simple span with spatial stimuli. At first glance, this finding indicates that spatial simple span is tapping a mechanism that is important to g_f but is not common to complex span. However, the battery of reasoning tasks used by Kane et al. to derive the g_f factor had a slight bias towards spatial reasoning tests. When we model g_f from only the verbal reasoning tests we observe a different result (see Figure 3, panel B). This suggests that spatial simple span does NOT account for any domain-general variance in g_f above and beyond complex span.

Unsworth and Engle (2006) conducted a similar analysis with respect to the relationship between complex span, simple span with short and long lists, and g_f. The results of their analysis are reproduced here in Figure 4. As with simple span with spatial stimuli, simple span with long lists (5-7 items) accounts for a substantial percentage of variance in g_f (22.5%). However, most of that variance is shared with complex span (79%). This suggests that simple span with long lists and complex span tap similar mechanisms.

As mentioned above, none of the studies in the meta-analyses conducted by Kane et al. (2005) included tasks specifically designed to measure the scope of attention. However, Cowan and his colleagues have conducted several recent studies to explore the relationship between scope of attention tasks, complex span, and cognitive ability in both children and adults. The results from just one of these studies are reproduced in Figure 5. Here we see that the variance in g_f accounted for by scope of attention tasks is largely shared by complex span tasks but that complex span tasks account for variance in g_f above and beyond scope of attention tasks. This result suggests that complex span and scope of attention tasks tap some overlapping mechanisms but complex span taps something that is important to g_f that is not required by scope of attention tasks.

Finally, recent studies by Jeremy Gray and colleagues have considered the relationship among complex span, g_f, and n-back. An important feature of Gray's n-back task is the inclusion of lure trials, which are trials in which the current stimulus matches a recently presented stimulus, but not the one n-back (e.g., n-1 or n+1 back). Accuracy to lure trials is lower than accuracy to non-lure foils and accuracy to lure trials correlates more strongly with complex span tasks and with tests of g_f than accuracy to non-lure trials (Burgess et al., 2010; Gray et al., 2003; Kane et al., 2007). Burgess et al. examined the relationship between lure accuracy, complex span, and g_f. The results of their analyses are reproduced in Figure 6. Here again, n-back and complex span account for much of the same variance in g_f but complex span accounts for a substantial portion of variance in g_f that is not explained by n-back (see also Kane et al., 2007). As with the scope of attention tasks, this suggests that complex span and n-back tap some mechanisms that are common and important to g_f but that they also tap some mechanisms that are unique and important to g_f.

Theoretical accounts of the link between WM and g_f

Several theoretical accounts have been offered to account for the strong relationship between WMC and g_f. It should be stated at the outset that these different accounts vary more in terms of emphasis and approach than they do in terms of the data they explain or the predictions they make. Furthermore, we believe that these various accounts can be encompassed by one theory, our multi-mechanism view, which we discuss at the end of this section.

Executive attention

The first comprehensive theoretical account of the relationship between WMC and g_f was offered by Engle and colleagues, and particularly in the work of Engle and Kane (Engle & Kane, 2004; Kane & Engle, 2002). This view has been referred to as the "controlled attention" or "executive attention" theory. According to this perspective, individuals with greater cognitive control mechanisms, such as goal maintenance, selective attention, and interference resolution (inhibition) will perform better on a variety of tasks, including measures of WMC and tests of g_f. There is a great deal of support for this theory, and an exhaustive review is not possible here. Instead, we will highlight a few important findings. First, performance on various WM tasks has been linked to mechanisms of cognitive control, such as inhibition. For example, individuals who perform better on complex span tasks do so in part because they are better at resolving proactive interference from previous trials (Bunting, 2006; Unsworth & Engle, 2007). Similarly, individuals who perform better on complex span tasks are also more accurate on lure trials in the n-back task and lure trials predict g_f better than non-lure trials (Burgess et al., 2010; Gray et al., 2003; Kane et al., 2007). As well, tasks that place heavy demands on cognitive control but little demand on memory predict g_f (Dempster & Corkill, 1999).

Perhaps most strikingly, the correlation between complex span and g_f increases as a function of the amount of proactive interference (PI) in the task (Bunting, 2006). Bunting had subjects perform a complex span task and manipulated the category from which the to-be-remembered items were drawn (words or digits). The category was repeated for 3 items (to build PI) and then switched on the fourth item (to release PI). The correlation between complex span and Ravens Progressive Matrices, a marker of g_f, increased linearly as PI increased and dropped significantly when PI was released.

While executive attention theory has enjoyed considerable support, a fair criticism is that the empirical evidence is overly reliant on studies using complex span tasks. This is problematic because complex span tasks are, as the name suggests, complex. Thus, while Engle and colleagues have argued that "executive attention" is the primary source of variation in these tasks, other researchers have emphasized the fact that other sources of variance are at play as well, such as domain-specific abilities required to perform the processing component of the task (e.g., mathematical ability, in the case of operation span; or verbal ability, in the case of reading span) (Bayliss, Jarrold, Gunn, & Baddeley, 2003; Daneman & Carpenter, 1983; Shah & Miyake, 1996). As well, performance of complex span tasks can be influenced by strategy deployment, such that a person may perform above average on a complex span task because he or she implements an effective strategy, not because the person actually has superior WMC (Dunlosky & Kane, 2007; McNamara & Scott, 2001; Turley-Ames & Whitfield, 2003).

Scope and control of attention

According to Cowan's approach, the scope of attention is limited to about 4 items and individual differences in the scope and control of attention are what drive the correlation between measures of WMC and g_f. (for a similar perspective on capacity limitations, see Drew and Vogel, 2009). The difference between Cowan's approach and that of Engle and colleagues, however, may be just one of emphasis. Cowan's recent work has emphasized the scope of attention while Engle's recent work, particularly that of Unsworth and Engle, has emphasized retrieval of information that has been lost from the focus of attention. Thus, we do not see these views as necessarily incompatible and we incorporate both into our multi-mechanism view, articulated below. One issue of debate, however, is whether scope of attention tests of WMC, like visual array comparison, account for the same variance in g_f as complex span tasks. The results of Cowan et al. (2005), reproduced here in Figure 5, suggest that complex span tasks have something in common with g_f that scope of attention tasks do not. However, Cowan et al. reported confirmatory factor analyses indicating that a two-factor model of the WM tasks, dissociating scope of attention and complex span, did NOT fit the data better than a single-factor model. Also, more recent work has demonstrated correlations between scope of attention tasks and g_f that are as strong as correlations typically observed between complex span tasks and g_f (Awh et al., 2009; Cowan et al., 2006). More research is needed to further investigate the relationship between scope of attention tasks, complex span tasks, and g_f.

Binding limits

Oberauer and colleagues characterize the relationship between WMC and g_f as one of "binding limits" rather than one of attention. Oberauer argues that memory requires the binding of features into objects and the binding of objects into episodes. There is a limit to the number of bindings that can be actively maintained at once and this causes WMC. Importantly, more complex tasks require more bindings, and Oberauer has shown that more complex WM tasks tend to show stronger correlations with tests of g_f, which themselves are complex tasks. Of particular importance is the finding, mentioned above, that WM tasks that require multiple bindings, such as coordination and transformation tasks, predict g_f just as well as complex span tasks, and account for largely the same variance in g_f as complex span tasks (Oberauer et al., 2003; Süß et al., 2002). This suggests that the dual-task nature of complex span tasks is not necessary to predict g_f and calls into question a basic tenet of executive attention theory, that is, that cognitive control mechanisms are responsible for the relationship between WMC and g_f. That said, an unresolved issue is the relationship between attention and binding. Hence, it isn't clear if Oberauer's view is incompatible with Engle and/or Cowan's view.

Active maintenance and controlled retrieval

Unsworth and Engle (2007) argue that there are two dissociable domain-general mechanisms that influence WMC: (1) a dynamic attention component that is responsible for maintaining information in an accessible state; and (2) a probabilistic cue-dependent search component, which is responsible for searching for information that has been lost from the focus of attention. For example, as a subject performs a complex span task, the dynamic attention component is necessary to coordinate the processing and storage demands of the task and to maintain the to-be-remembered items in an accessible state. The search component is necessary at the recall prompt to recover to-be-remembered items that may have been lost from the focus of attention because of the demands of the processing component of the task.

Empirical support for this theory comes from simple span tasks with long lists and from serial free recall tasks designed to assess primacy and recency effects. As mentioned above, Unsworth and Engle (2006; 2007) have shown that simple span tasks with long lists correlate as well with g_f as measures of complex span tasks and much of the variance explained by simple span with long lists is shared with complex span (see Figure 4). They argue that simple span with long lists taps the same controlled retrieval mechanism as complex span because the focus of attention is overloaded and items displaced from the focus of attention must be recovered during recall. More recent work demonstrates that individual differences in the primacy portion of free recall account for different variance in g_f than individual differences in the recency portion (Unsworth, Spillers, & Brewer, 2010). Unsworth et al. argue that variance in the primacy effect is driven by individual differences in controlled retrieval and variance in the recency effect is driven by individual differences in active maintenance via attention.

While they do not provide a neural model of their theory, the dynamic attentional processes implicated in their account are consistent with recent computational models of WM that implicate PFC, ACC, and parietal cortex as regions involved in the active maintenance, updating, and monitoring of information in WM (Botvinick et al., 2001; Frank et al., 2001; Miller & Cohen, 2001; O'Reilly & Frank, 2006). Indeed, neuroimaging studies of complex span tasks show that PFC, ACC, and parietal areas are more strongly recruited in complex span tasks than during simple span tasks (Bunge et al., 2000; Chein et al., 2010; Kondo et al., 2004; Osaka et al., 2003; Osaka et al., 2004; Smith et al., 2001).

Unsworth and Engle further speculate that the medial temporal lobes (MTL) are also important for WM performance, which is a relatively novel prediction (but see Ranganath, 2006). In particular, they argue that the cue-dependent search process implicated during recall relies on coordinated activity between PFC and MTL. This view is also consistent with computational models that examine the interaction between PFC and MTL in a variety of memory tasks (O'Reilly & Norman, 2002). Indeed, a recent fMRI study indicates greater PFC and hippocampal activity during recall in complex span tasks than during recall in simple span tasks (Chein et al., 2010).

A multi-mechanism view

We argue that there are multiple domain-general cognitive mechanisms underlying the relationship between WMC and g_f. Our view is largely shaped by Unsworth and Engle's account discussed above, but also by computational models and neuroimaging data that similarly fractionate WM into dissociable mechanisms. Most important among these are the scope and control of attention, updating and conflict monitoring, interference resolution, and controlled retrieval. These mechanisms have been linked to neural activity in specific brain regions: PFC-parietal connections for the scope and control of attention (Todd & Marois, 2004; Vogel & Machizawa, 2004); a PFC-ACC-basal ganglia-thalamus network for updating and conflict monitoring (Ashby et al. 2005; Botvinick, 2007; O'Reilly & Frank, 2006); inferior frontal cortex for interference resolution (Aron, Robbins, & Poldrack, 2004); and PFC-hippocampal connections for controlled retrieval (Chein, et al., 2010; Nee & Jonides, 2008; Ranganath, 2006).

This multi-mechanism view of the relationship between WMC and g_f is consistent with the parieto-frontal integration theory (P-FIT) of intelligence (Jung & Haier, 2007), according to which, intelligence and reasoning are particularly dependent upon connections between parietal and pre-frontal cortices. The current view is consistent with P-FIT but suggests that sub-cortical structures, such as the basal ganglia and thalamus, and medial temporal regions, such as the hippocampus, are also important. In fact, at the end of their review, Jung and Haier (2007) speculated; "there are likely other brain regions critical to intelligence and the implementation of intelligent behavior, including regions identified in studies of discrete cognitive processes, such as the basal ganglia, thalamus, hippocampus, and cerebellum".

Multi-mechanism, or multiple component theories of intelligence are not new. In fact, they date back to the beginning of the debate about the basis of Spearman's *g* (Thompson, 1916). Spearman described the underlying source of variance in *g* as a unitary construct, reflecting some sort of cognitive resource, or "mental energy". However, early critics of Spearman's work illustrated that *g* could be caused by multiple factors as long as the battery of tasks from which *g* is derived tap all of these various factors in an overlapping fashion. That is, any one individual task does not have to tap all the common factors across a battery of tasks but each task must have at least one factor in common with another task. These theories have been referred to as "sampling theories" of *g* and are best represented by the work of Thomson (1916) and Thorndike (1927). According to sampling theories, *g* will emerge from a battery of tasks that "sample" an array of "elements" that, in combination, constitute the cognitive abilities measured by the tests (Jensen, 1998). Thomson (1916) provided a mathematical proof of this by randomly sampling various sized groups of digits. In his terms, the groups represented mental tests and the digits represented elements. In our view, the "elements" are the various domain-general mechanisms tapped by the mental tests. Thomson showed that the groups of digits will be correlated with each other in terms of the number of digits any two random samples have in common. Thus, *g* may not reflect a unitary construct. Instead, *g* will emerge from a battery of tasks that tap various important domain-general mechanisms in an overlapping fashion.

Recent trend: Training WM to boost intelligence

One interpretation of the relationship between WMC and g_f is that WMC *constrains* intelligent behavior. According to this perspective, if people were able to increase their WMC then they would be able to effectively increase their intelligence. Jaeggi, Buschkuehl, Jonides, and Perrig (2008) attempted to do just this and made what has been described as a "landmark" finding: training on a continuously adaptive dual n-back task transfers to performance on tests of g_f, such that subjects who underwent WM training performed better on tests of fluid intelligence than a control group that did not get WM training. This research was featured in the *New York Times* (Wang & Aamodt, 2009) and has formed the basis of an iPhone application called "IQ Boost."

Subjects in the study underwent either 8, 12, 17 or 19 days of training on a continuously adaptive dual n-back task. The dual n-back consisted of two strings of stimuli, letters and spatial locations (see Figure 7). Subjects were instructed to indicate whether the current stimulus was the same as the stimulus *n* back in the series. The value of *n* increased or decreased from block to block as performance improved or worsened. Thus, the task was titrated to individual performance and was consistently demanding. Participants were pre- and post-tested on different forms of a measure of g_f. A control group did not undergo any training and completed only the pre- and post-test measures. As previously mentioned, the training groups underwent 8, 12, 17 or 19 days of n-back training, though not all groups received the same format of the test of

g_f. This aspect of the design has received some criticism, as described below.

Jaeggi et al. found that all the training groups showed improvements in g_f, and the magnitude of the improvement increased with more training (see Figure 8). It should be noted that the control group also showed a significant increase in g_f, most likely due to practice effects. After taking pre-test g_f scores into account (as a covariate) a trend toward significant group differences emerged after 12 training days. After 17 training days, the difference in g_f between the training and control group was significant. Thus, transfer of training to g_f was dosage dependent – gains in fluid intelligence were a function of the amount of training. If reliable, this effect clearly has tremendous implications. However, several critiques of this work have been presented recently. We consider these, as well as our own, below.

One curious aspect of the Jaeggi et al. results, which is particularly relevant to this chapter, is that subjects showed training related transfer to digit span but *not* to the reading span task. As mentioned above, reading span is considered a complex span task, dependent upon active maintenance and controlled retrieval, whereas n-back is considered an updating task, dependent upon active maintenance and cognitive control but not necessarily retrieval (indeed, fMRI studies of n-back typically show prefrontal and parietal activation but not hippocampal activation). Thus, an intriguing possibility is that their WM training regimen tapped the PFC-parietal aspect of WM but not the PFC-MTL component and that a more comprehensive training regimen would show even stronger gains in g_f.

Jaeggi et al.'s choice of tasks to assess g_f has also come under criticism. Moody (2009) made the important point that while the group that received 8 days of training was tested on Ravens Advanced Progressive Matrices (RAPM) and showed little improvement between pre- and post-tests, the other groups, that did show improvement, were tested using the Bochumer

Matrices Test (BOMAT) (Hossiep, Turck & Hasella, 1999). Jaeggi et al. provide no rationale for switching from one test to another. RAPM and BOMAT are similar in that they both use visual analogies in matrix format and both tests are progressive, such that the items become successively more difficult. Typical administration of the BOMAT takes 45 minutes, however Jaeggi et al. only allowed 10 minutes. Moody argues that the speeded nature of the administration did not allow subjects to advance to more difficult problems, and thus, "transformed it from a test of fluid intelligence into a speed test of ability to solve the easier visual analogies" (Moody, pp. 327).

Jaeggi et al. are not the first to target improvements in cognition via WM training, nor or they the first to document transfer of WM training to a non-trained task. Klingberg, Forssberg, and Westerberg (2002) administered intensive and adaptive WM training to young adults with and without ADHD. These authors observed significant improvements post-training on RAPM as well as on a non-trained visuo-spatial WM task in both groups. A relative strength of this investigation was the use of an active control group that played computer games over the duration of training so as to control for the amount of time spent in front of the computer. A weakness of this study however, was the small sample size of only 4 participants. Olesen, Westerberg and Klingberg (2003) were able to pinpoint a biological mechanism for increased WMC after WM training for 5 weeks in 3 subjects. The authors propose that after training, the increased activity in the middle frontal gyrus and superior and inferior parietal cortices might be indicators of training-induced plasticity. While this finding is very suggestive, the claim must be supported by future studies with a larger sample size.

Future investigations of WM training and transfer to intelligence should aim to find transfer to complex span tasks for the reasons detailed above. Moreover, it is crucial that preand post-measures of g_f be consistent and administered in a valid manner. Further, an active control group would address the issue of training gains based on repeated exposure to a testing environment alone. Lastly, perhaps most importantly, the durability of training must be assessed. Jaeggi et al. fail to address the durability of the transfer of training to g_f. Their claims about increases in fluid intelligence would be further substantiated if they were able to demonstrate that these changes are not transient. A longitudinal follow up on participants' g_f would address this issue.

Conclusion

Working memory has emerged as a very useful construct in the field of psychology. Various measures of WMC have been shown to correlate quite strongly with measures of intelligence, accounting for at least half the variance in g_f. We argue that these correlations exist because tests of WMC and tests of g_f tap multiple domain-general cognitive mechanisms required for the active maintenance and rapid controlled retrieval of information. Also, recent research indicates that training WM, or specific aspects of WM, increases g_f, although more research is necessary to establish the reliability and durability of these results.

More research is also needed to better specify the various mechanisms underlying performance of WM and reasoning tests. Neuroimaging studies on healthy adults and neuropsychological tests of patients with various neurological damage or disease will be especially fruitful. For example, recent fMRI studies have illustrated that individual differences in activity in PFC during a WM task partly accounts for the relationship between WMC and g_f (Burgess et al., 2010; Gray et al., 2003). One intriguing possibility is that individual differences in activity in different brain regions (or network of regions) accounts for *different* variance in g_f. For example, based on the work of Unsworth and Engle (2007), it may be possible to demonstrate that individual differences in activity in the PFC, ACC, and parietal cortex, reflecting active maintenance during a WM task, accounts for different variance in g_f than individual differences in activity in PFC and hippocampus, reflecting controlled retrieval during a WM task.

The multi-mechanism view also has implications for research on WM training and for cognitive therapy for the elderly and patients with neural damage or disease. That is, rather than treat WM as a global construct, training and remediation could be tailored more specifically. Instead of "WM training" we envisage mechanism-specific training. That is, training a specific domain-general cognitive mechanism should result in improved performance across a variety of tasks. There is now some research supporting this idea (Dahlin, Neely, Larsson, Bäckman, & Nyberg, 2009; Karbach & Kray, in press) but again, more work is needed to confirm the reliability and durability of these results.

In sum, WMC is strongly correlated with g_f. We argue that the relationship between these constructs is driven by the operation of multiple domain-general cognitive mechanisms that are required for the performance of tasks designed to measure WMC and for the performance of test batteries designed to assess fluid intelligence. Future research in cognitive psychology and neuroscience will hopefully refine our understanding of these underlying mechanisms, which will in turn sharpen the multi-mechanism view.

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FIGURE 1

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

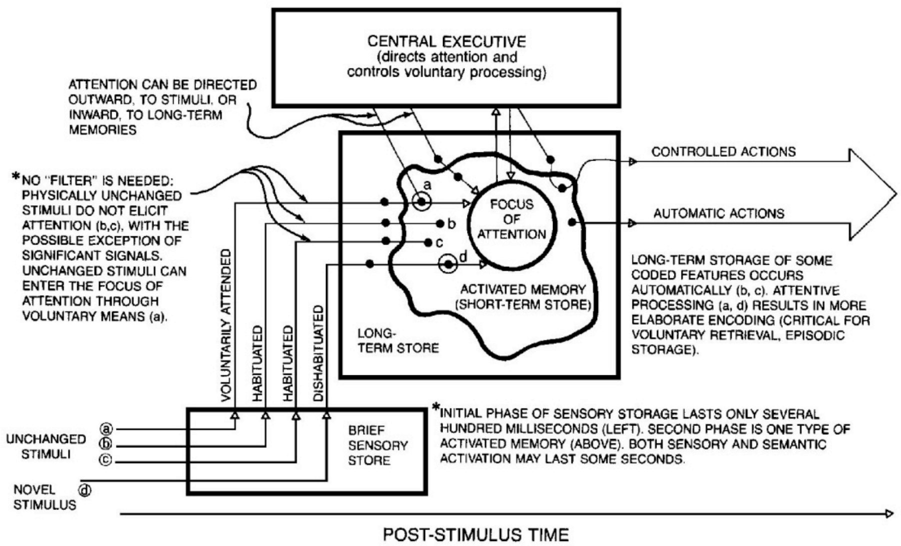


Figure 1. A revised model of the information-processing system. The time since stimulus reception is represented ordinally along the x axis. The components are arranged in real time, and stimulus information can be present in more than one component at the same time. Short-term storage is represented as an activated subset of long-term storage, and the focus of attention is represented as a subset of short-term storage. Habituated stimuli do not enter the focus of attention. The timing of involvement of the central executive in processing is flexible. The arrows represent the transfer of information from one form to another; these are discrete approximations to continuous processes that can occur in parallel or cascade. Pathways leading to awareness can come from three sources: changed stimuli for which there is dishabituation, items selected through effortful processing (whether of sensory origin or not), and the spontaneous activation of long-term memory information based on associations (not shown).

FIGURE 2

Jonides, J., Lewis, R.L., Nee, D.E., Lustig, C.A., Berman, M.G., and Moore K.S. (2008). The mind and brain of short-term memory. *Annual Review of Psychology, 59*, 193-224.

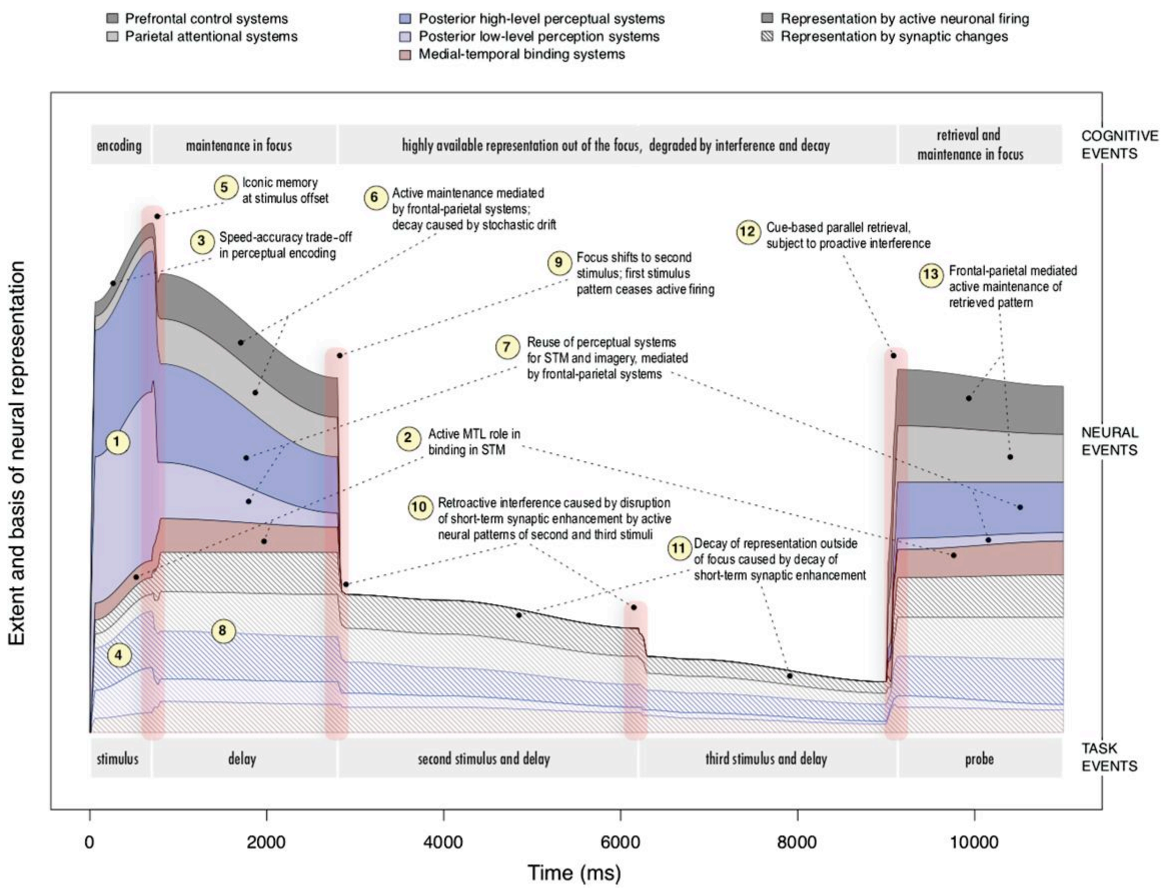
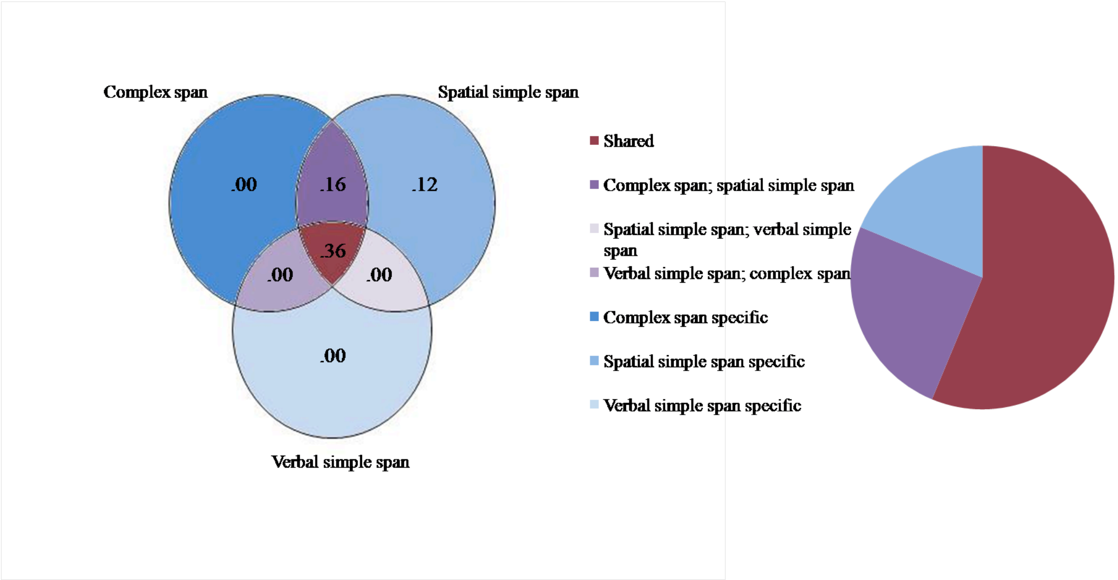


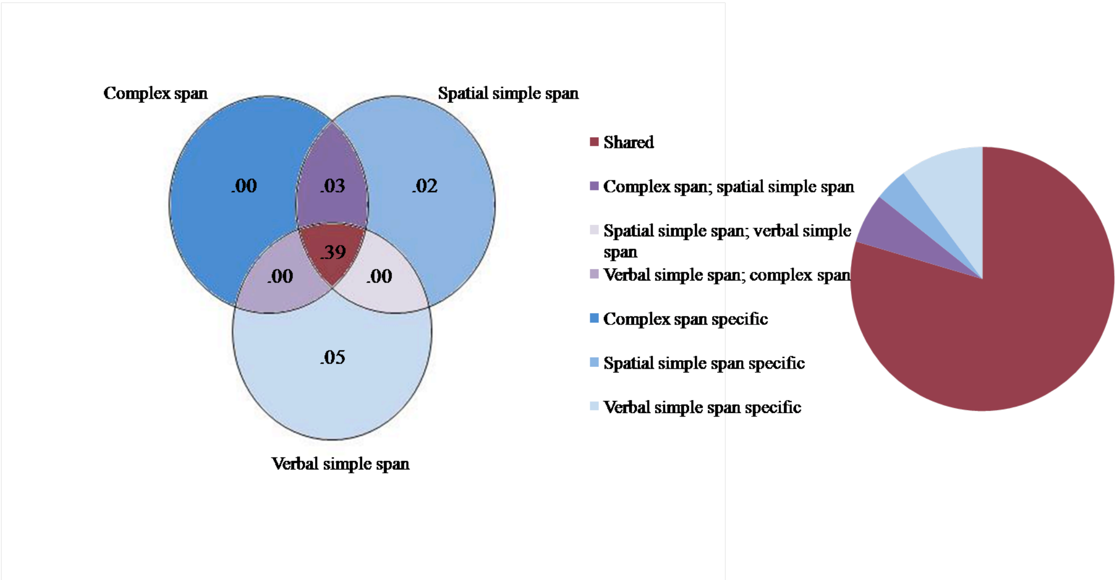
Figure 2

The processing and neural representation of one item in memory over the course of a few seconds in a hypothetical short-term memory task, assuming a simple single-item focus architecture. The cognitive events are demarcated at the top; the task events, at the bottom. The colored layers depict the extent to which different brain areas contribute to the representation of the item over time, at distinct functional stages of short-term memory processing. The colored layers also distinguish two basic types of neural representation: Solid layers depict memory supported by a coherent pattern of active neural firing, and hashed layers depict memory supported by changes in synaptic patterns. The example task requires processing and remembering three visual items; the figure traces the representation of the first item only. In this task, the three items are sequentially presented, and each is followed by a delay period. After the delay following the third item, a probe appears that requires retrieval of the first item.

FIGURE 3
Reanalysis of Kane et al. 2004



Panel A: Complex span, spatial simple span, and verbal simple span predicting Gf indexed by verbal reasoning, spatial reasoning, and figural matrix tasks



Panel B: Complex span, spatial simple span and verbal simple span predicting verbal reasoning

FIGURE 4

Reanalysis of

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

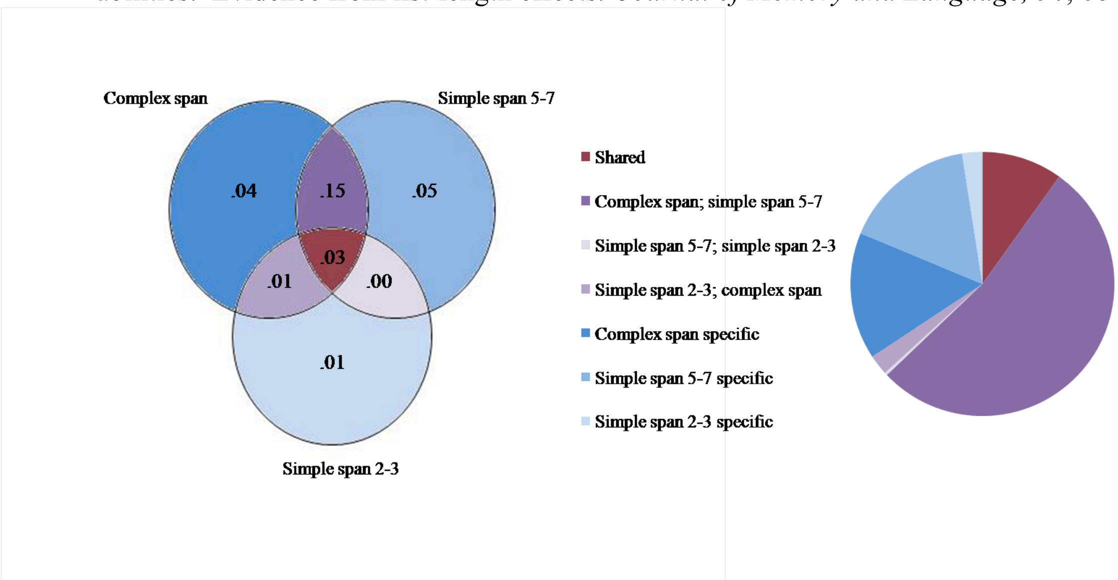


FIGURE 5

Reanalysis of

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

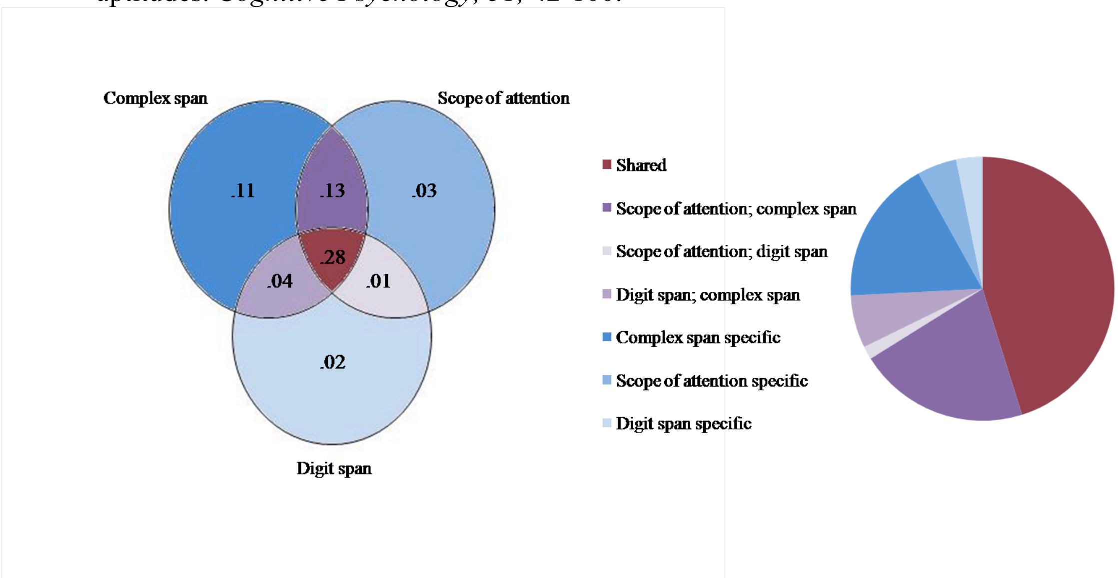
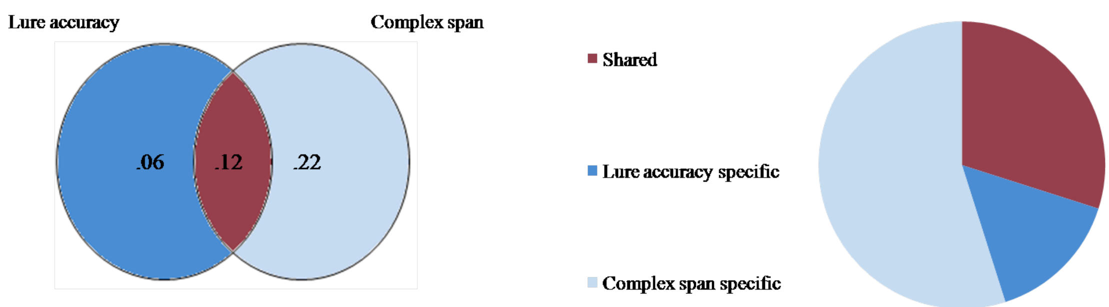


FIGURE 6

Reanalysis of

Burgess, G. C., Braver, T. S., Conway, A. R. A., & Gray, J. R. (2010). Neural mechanisms of interference control underlie the relationship between fluid intelligence and working memory span. Manuscript under review.



FIGURES 7&8

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences, 105(19)*, 6829-6833.

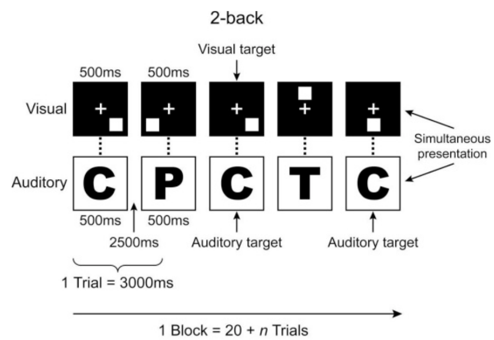


Figure 7

The *n*-back task that was used as the training task, illustrated for a 2-back condition. The letters were presented auditorily at the same rate as the spatial material was presented visually.

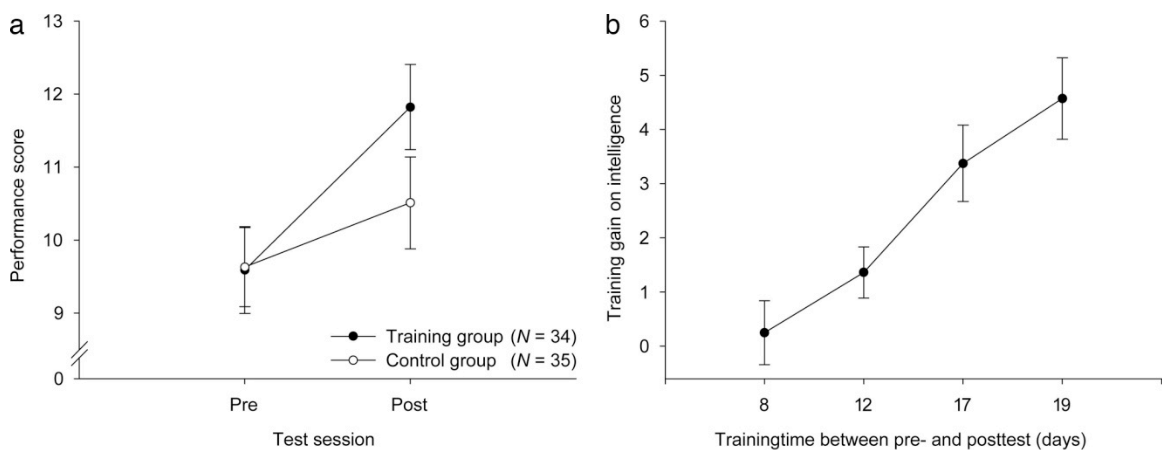


Figure 8

Transfer effects. (*a*) Mean values and corresponding standard errors of the fluid intelligence test scores for the control and the trained groups, collapsed over training time. (*b*) The gain scores (posttest minus pretest scores) of the intelligence improvement plotted for training group as a function of training time. Error bars represent standard errors.

TABLE 1

Kane, M. J., Hambrick, D. Z., & Conway, A. R. A. (2005). Working memory capacity and fluid intelligence are strongly related constructs: Comment on Ackerman, Beier, and Boyle (2004). *Psychological Bulletin, 131,* 66-71.

Table 1

Correlations Between WMC and Gf/Reasoning Factors Derived From Confirmatory Factor Analyses of Data From Latent-Variable Studies With Young Adults

Study	WMC tasks	Gf/reasoning tasks	*r*(95% CI)
Kyllonen & Christal (1990)			
Study 2: $n = 399$	ABC numerical assignment, mental arithmetic, alphabet recoding	Arithmetic reasoning, AB grammatical reasoning, verbal analogies, arrow grammatical reasoning, number sets	.91 (.89, .93)
Study 3: $n = 392$	Alphabet recoding, ABC21	Arithmetic reasoning, AB grammatical reasoning, ABCD arrow, diagramming relations, following instructions, letter sets, necessary arithmetic operations, nonsense syllogisms	.79 (.75, .82)
Study 4: $n = 562$	Alphabet recoding, mental math	Arithmetic reasoning, verbal analogies, number sets, 123 symbol reduction, three term series, calendar test	.83 (.80, .85)
Engle, Tuholski, et al. (1999; $N = 133$)	Operation span, reading span, counting span, ABCD, keeping track, secondary memory/immediate free recall	Raven, Cattell culture fair	.60 (.48, .70)
Miyake et al. (2001; $N = 167$)	Letter rotation, dot matrix	Tower of Hanoi, random generation, paper folding, space relations, cards, flags	.64 (.54, .72)
Ackerman et al. (2002; $N = 135$)	ABCD order, alpha span, backward digit span, computation span, figural-spatial span, spatial span, word-sentence span	Ravens, number series, problem solving, necessary facts, paper folding, spatial analogy, cube comparison	.66 (.55, .75)
Conway et al. (2002; $N = 120$)	Operation span, reading span, counting span	Raven, Cattell culture fair	.54 (.40, .66)
Süß et al. (2002; $N = 121$[a])	Reading span, computation span, alpha span, backward digit span, math span, verbal span, spatial working memory, spatial short-term memory, updating numerical, updating spatial, spatial coordination, verbal coordination	Number sequences, letter sequences, computational reasoning, verbal analogies, fact/opinion, senseless inferences, syllogisms, figural analogies, Charkow, Bongard, figure assembly, surface development	.86 (.81, .90)
Hambrick (2003; $N = 171$)	Computation span, reading span	Raven, Cattell culture fair, abstraction, letter sets	.71 (.63, .78)
Mackintosh & Bennett (2003; $N = 138$[b])	Mental counters, reading span, spatial span	Raven, mental rotations	1.00
Colom et al. (2004)			
Study 1: $n = 198$	Mental counters, sentence verification, line formation	Raven, surface development	.86 (.82, .89)
Study 2: $n = 203$	Mental counters, sentence verification, line formation	Surface development, cards, figure classification	.73 (.66, .79)
Study 3: $n = 193$	Mental counters, sentence verification, line formation	Surface development, cards, figure classification	.41 (.29, .52)
Kane et al. (2004; $N = 236$)	Operation span, reading span, counting span, rotation span, symmetry span, navigation span	Raven, WASI matrix, BETA III matrix, reading comprehension, verbal analogies, inferences, nonsense syllogisms, remote associates, paper folding, surface development, form board, space relations, rotated blocks	.67 (.59, .73)

Note. WMC = working memory capacity; Gf = general fluid intelligence; 95% CI = the 95% confidence interval around the correlations; WASI = Wechsler Abbreviated Scale of Intelligence.

[a] *N* with the complete data set available (personal communication, K. Oberauer, July 7, 2004). [b] *N* for each pairwise correlation ranged from 117 to 127.