21 Working Memory and Intelligence

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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.
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> Oberauer and colleagues (2005, p. 64)

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 conducting an internet search to find information about an intelligence researcher. To conduct the search you need to remember the researcher's name and institution, and perhaps a few keywords about their work. WM is required to keep these pieces of information in mind while typing and then navigating the search results. Many important cognitive behaviors, beyond searching the Internet – 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.

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 working memory and working memory capacity. Working memory 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 working memory capacity 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.

The focus of this chapter is on the relationship between WMC and fluid intelligence (G*f*) in healthy young adults. Two meta-analyses, conducted by different groups of researchers, estimate the correlation between WMC and G*f* to be somewhere between $r = 0.72$ (Kane, Hambrick, & Conway, 2005) and $r = 0.85$ (Oberauer et al., 2005). These estimates are remarkably consistent with a recent large sample study ($N = 2{,}200$) that found a correlation of $r = 0.77$ between WMC and G*f* (Gignac, 2014). 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 on acquired knowledge or skill (however, see Hambrick, 2003; Hambrick & Engle, 2002; Hambrick & Meinz, 2011; Hambrick & Oswald, 2005).

Fluid intelligence is defined as "the use of deliberate and controlled mental operations to solve novel problems that cannot be performed automatically" (McGrew, 2009, p. 5.). 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 et al., 1999).

This chapter begins with a brief review of the history of working memory, 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 & Engle, 2007), neuroimaging experiments (for a review, see Jonides et al., 2008), and computational models of WM (Ashby et al., 2005; Oberauer et al., 2012; 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 of the relationship between WMC and G*f*, with an emphasis on our new view, which we refer to as process overlap theory (Kovacs & Conway, 2016).

Historical Perspective on Working Memory

The *concept* of WM was first introduced by G. A. Miller, Galanter, and Pribram (1960) in their influential book, *Plans and the Structure of Behavior*. They proposed a dynamic and flexible short-term memory system that is necessary 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 people's performance on a range of complex cognitive tasks, particularly reasoning and planning (cf. Crowder, 1982). 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 could 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 in the section Contemporary View of Working Memory.

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 what then was called the Verbal section of the Scholastic Aptitude Test (SAT-V). STS capacity was assessed using a word span task, in which a series of words was presented, one word 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.

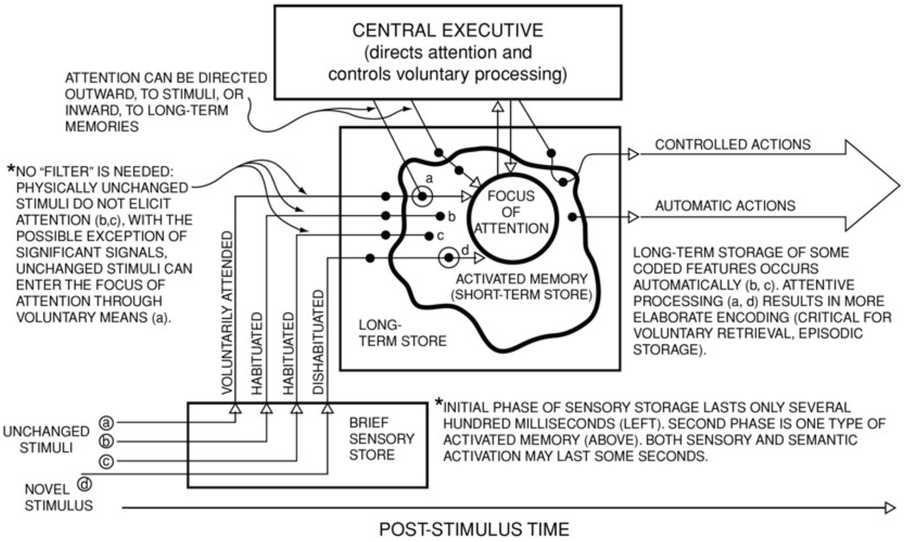
Consistent with the predictions of WM theory, the reading span task correlated more strongly with SAT-V ($r = 0.59$) than did the word span task ($r = 0.35$). This may not seem at all surprising, given that both the SAT-V and reading span involve *reading*. However, subsequent work by Turner and Engle (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 SAT-V. They had subjects solve simple mathematical operations while remembering words for later recall and showed, consistent with Daneman and Carpenter (1980), that this task – called operation span – predicted SAT-V more strongly than did the word span task. More recent research has shown that a variety of WM span tasks, all demanding parallel processing and storage but with diverse content, are strongly predictive of a wide range of complex cognitive tasks. This suggests that the relationship between WM span performance and complex cognition is largely domain-general (e.g., Kane et al., 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 an STS to explain short-term memory. Complex memory span tasks, such as reading span and operation span, 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.

Contemporary View of Working Memory

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, Cowan's model (1988, 1995, 2001, 2005), 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.

Cowan's model (see Figure 21.1) assumes that WM consists of activated long-term memory representations (see also Anderson, 1983; Atkinson & Shiffrin, 1971;



ATTENTION CAN BE DIRECTED OUTWARD, TO STIMULI, OR INWARD, TO LONG-TERM MEMORIES

*NO "FILTER" IS NEEDED: PHYSICALLY UNCHANGED STIMULI DO NOT ELICIT ATTENTION (b,c), WITH THE POSSIBLE EXCEPTION OF SIGNIFICANT SIGNALS, UNCHANGED STIMULI CAN ENTER THE FOCUS OF ATTENTION THROUGH VOLUNTARY MEANS (a).

LONG-TERM STORAGE OF SOME CODED FEATURES OCCURS AUTOMATICALLY (b, c). ATTENTIVE PROCESSING (a, d) RESULTS IN MORE ELABORATE ENCODING (CRITICAL FOR VOLUNTARY RETRIEVAL, EPISODIC STORAGE).

*INITIAL PHASE OF SENSORY STORAGE LASTS ONLY SEVERAL HUNDRED MILLISECONDS (LEFT). SECOND PHASE IS ONE TYPE OF ACTIVATED MEMORY (ABOVE). BOTH SENSORY AND SEMANTIC ACTIVATION MAY LAST SOME SECONDS.

Figure 21.1 *Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system (from Cowan, 1988). Reprinted with permission of the American Psychological Association.*

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 & Frank, 2006). Within this activated set of representations, or “short-term store,” there is a focus of attention that can maintain approximately four items in a readily accessible state (Cowan, 2001). In other words, we can “think of” approximately four mental representations at one time.

Our own view is quite similar to the model in Figure 21.1. 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 long-term memory (LTM) as a “store.” The reason for this distinction is that there is very little neuroscientific 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 et al., 2005), but we argue that these effects do not necessitate the assumption of a short-term store (for a review see Sederberg, Howard, & 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 three layers of representation in WM: (1) the focus of attention, limited to one item; (2) the region of direct access, limited to approximately four items; and (3) representations active above baseline but no longer in the region of direct access. To avoid confusion over Cowan versus 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. Complex cognitive behavior, such as reasoning, reading, and problem-solving, requires rapid access to more than four 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 (Ericsson & Kintsch, 1995).

Thus, we view WM as consisting of at least three main components: (1) cognitive control mechanisms (or 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; E. K. Miller & Cohen, 2001; O’Reilly & Frank, 2006); (2) one to four representations in the scope of attention, which are most likely maintained via activity in a frontoparietal 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, 2011; Nee & Jonides, 2008; Ranganath, 2006; O’Reilly & Norman, 2002; Unsworth & Engle, 2007).

Measurement of Working Memory Capacity

Several different WM tasks are used in contemporary research. These tasks vary in extremely important ways, which we discuss. Also, 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, 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 several items have been presented, typically between two and seven, the subject is prompted to recall all the to-be-remembered items in correct serial order. A common characteristic of all complex span tasks is that they require access to information (the digits) in the face of concurrent processing (for a review of these tasks see Conway et al., 2005).

As mentioned earlier, complex span tasks reveal strong correlations with the SAT-V (r approximately 0.5; see Daneman and Carpenter, 1980, 1983; Turner and Engle, 1989) and other measures of reading comprehension (r ranging from 0.50 to 0.90 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 and colleagues (2004) administered several verbal and several spatial complex span tasks and the range of correlations among all the tasks was $r = 0.39$ to $r = 0.51$. Moreover, the correlation between latent variables representing spatial complex span and verbal complex span was $r = 0.84$ and the correlation between a latent variable representing all complex span tasks and G*f* was $r = 0.76$. 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*.

Simple Span Tasks

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 discussed earlier, simple span tasks like digit span correlate less well with measures of complex cognition than complex span tasks (Conway et al., 2002; Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Engle et al., 1999; Kane et al., 2004). Also, 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).

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 do complex span tasks, and in some cases they 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 and colleagues (2005) found that running span correlates well with various measures of cognitive ability in children and adults (see also Mukunda & Hall, 1992). Cowan and colleagues argued that the rapid presentation (e.g., four items per second as compared to one 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 demonstrate why 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 4 × 4 matrix and a series of cells in the matrix flash, one location at a time, typically at a rate of one location per second. At the end of a series, the subject is required to recall the flashed locations in correct serial order. Kane and colleagues (2004) found that a latent variable derived from three spatial simple span tasks correlates as well with G*f* as a latent variable derived from three spatial complex span tasks.

Simple span tasks are also strong predictors of G*f* when only trials with long lists are considered. Reanalyzing data from Kane and colleagues (2004), Unsworth and Engle (2006a) 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 four 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 four 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 earlier, 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 four. 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 four 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 four 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, the subject is 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), the subject is then presented with another array and asked to judge whether the two arrays are the same or different. On half of 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 percent accuracy on this task when the number of items is fewer than four, but performance begins to drop as the number of items in the array increases beyond four.

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 in complex and simple span tasks, but research shows that scope of attention tasks account for nearly as much variance in cognitive ability as complex span tasks (Awh et al., 2009; Cowan et al., 2005; Cowan et al., 2006).

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, and alphabet recoding, as well as more complex tasks used by Kyllonen and Christal (1990) and Oberauer and colleagues (Oberauer, 2004; Oberauer et al., 2003; 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, for example, 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, such as 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 . Also, Oberauer and colleagues (2003) 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, suggesting 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*.

N-Back Tasks

In an n-back task, the subject is presented with a series of stimuli, one at a time, typically one every two to three 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 functional magnetic resonance imaging (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 matrix reasoning task (Raven's 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 Gf

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, two recent meta-analyses, conducted by two different groups of researchers, estimated the correlation between WMC and G*f* to be somewhere between $r = 0.72$ (Kane et al., 2005) and $r = 0.85$ (Oberauer et al., 2005). Kane and colleagues summarized the studies included in their meta-analysis in a table, which is reproduced here (see Table 21.1). Each of the studies included in the meta-analysis administered several tests of

Table 21.1 *Correlations between WMC and Gf/reasoning factors derived from confirmatory factor analyses of data from latent-variable studies with young adults*

Study	WMC tasks	G*f*/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	0.91 (0.89, 0.93)
Study 3: *N* = 393	Alphabet recoding, ABC	Arithmetic reasoning, AB grammatical reasoning, ABCD arrow, diagramming relations, following instructions, letter sets, necessary arithmetic operations, nonsense syllogisms	0.79 (0.75, 0.82)
Study 4: *N* = 562	Alphabet recoding, mental math	Arithmetic reasoning, verbal analogies, number sets, 123 symbol reduction, three term series, calendar test	0.83 (0.80, 0.85)
Engle et al. (1999); *N* = 133	Operation span, reading span, counting span, ABCD, keeping track, secondary memory/ immediate free recall	Raven, Cattell culture fair	0.60 (0.48, 0.70)
Miyake et al. (2001); *N* = 167	Letter rotation, dot matrix	Tower of Hanoi, random generation, paper folding, space relations, cards, flags	0.64 (0.54, 0.72)
Ackerman, Beier, & Boyle (2002); *N* = 135	ABCD order, alpha span, backward digit span, computation span, figural-spatial span, spatial span, word-sentence span	Raven, number series, problem-solving, necessary facts, paper folding, spatial analogy, cube comparison	0.66 (0.55, 0.75)
Conway et al. (2002); *N* = 120	Operation span, reading span, counting span	Raven, Cattell culture fair	0.54 (0.40, 0.66)
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	0.86 (0.81, 0.90)
Hambrick (2003); *N* = 171	Computation span, reading span	Raven, Cattell culture fair, abstraction, letter sets	0.71 (0.63, 0.78)
Mackintosh & Bennett (2003); *N* = 138b	Mental counters, reading span, spatial span	Raven, mental rotations	1.00

Table 21.1 (*cont.*)

Study	WMC tasks	G*f*/reasoning tasks	r (95% CI)
Colom et al. (2004) Study 1: *N* = 198	Mental counters, sentence verification, line formation	Raven, surface development	0.86 (0.82, 0.89)
Study 2: *N* = 203	Mental counters, sentence verification, line formation	Surface development, cards, figure classification	0.73 (0.82, 0.89)
Study 3; *N* = 193	Mental counters, sentence verification, line formation	Surface development, cards, figure classification	0.41 (0.29, 0.52)
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	0.67 (0.59, 0.73)

WMC = working memory capacity; G*f* = 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).

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 was used in these studies, including complex span, simple span, and coordination and transformation tasks. None of the studies referenced in Table 21.1 used tests designed to measure the scope of attention, such as 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 is a simple span (Conway et al., 2002; Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Engle et al., 1999; Kane et al., 2004).

These recent findings have important implications for theories of the relationship between WMC and G*f*. However, it is imperative to emphasize 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 reanalyzed data from Kane and colleagues (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 & Maybery, 1999). The results of this analysis are presented in Figure 21.2, 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 and colleagues to derive the G*f* factor had a slight bias toward spatial reasoning tests. When we model G*f* from only the verbal reasoning tests, we observe a different result (see Figure 21.2, 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 (2006a) 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 21.3. 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, none of the studies in the meta-analyses conducted by Kane and colleagues (2005) included tasks specifically designed to measure the scope of

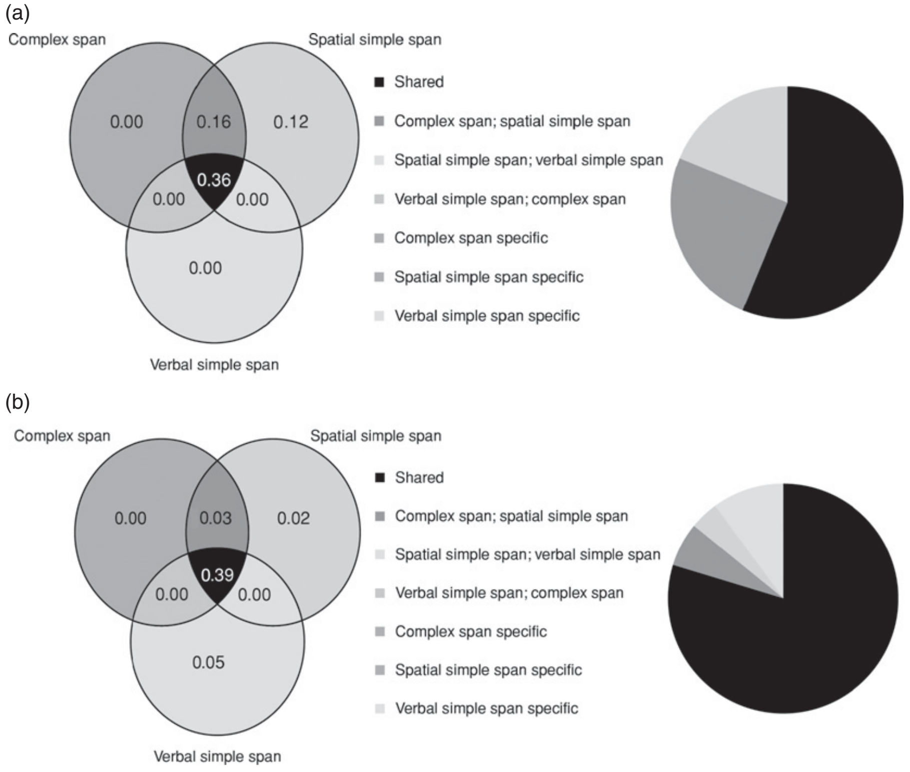


Figure 21.2 *Reanalysis of Kane et al. (2004). Reprinted with permission of the American Psychological Association.*
Panel (a): Complex span, spatial simple span, and verbal simple span predicting G*f* indexed by verbal reasoning, spatial reasoning, and figural matrix tasks. Panel (b): Complex span, spatial simple span and verbal simple span predicting verbal reasoning.

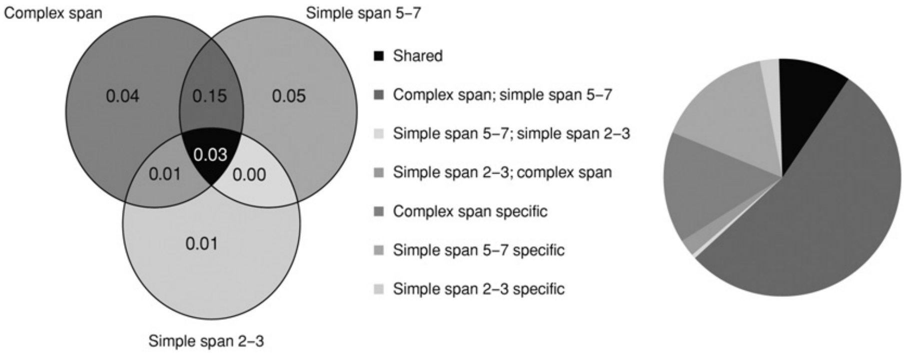


Figure 21.3 *Reanalysis of Unsworth and Engle (2006a). Reprinted with permission of Elsevier.*

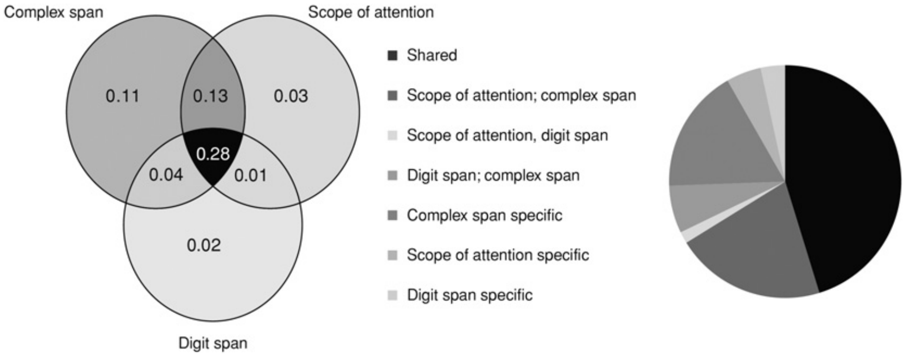


Figure 21.4 *Reanalysis of Cowan et al. (2005). Reprinted with permission of Elsevier.*

attention. However, Cowan and colleagues (2005) have conducted several recent studies to explore the relationship among 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 21.4. 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, 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

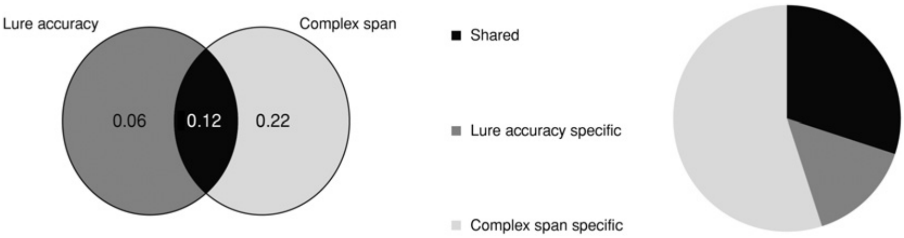


Figure 21.5 *Reanalysis of Burgess et al. (2011).*

accuracy to non-lure trials (Burgess et al., 2011; Gray et al., 2003; Kane et al., 2007). Burgess and colleagues examined the relationship between lure accuracy, complex span, and G*f*. The results of their analyses are reproduced in Figure 21.5. 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 Gf

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 in the section Process Overlap Theory: A Multi-Mechanism View.

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 more effective 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., 2011; Gray et al., 2003; Kane et al., 2007). Also, tasks that place heavy demands on cognitive control but little demand on memory predict G*f* (Dempster & Corkill, 1999).

Perhaps most striking, 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 three items (to build PI) and then switched on the fourth item (to release PI). The correlation between complex span and Raven's 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). Also, 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 they implement 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 four 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 & 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 in the section Process Overlap Theory: A Multi-Mechanism View. 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 and colleagues (2005), reproduced here in Figure 21.4, suggest that complex span tasks have something in common with G*f* that scope of attention tasks do not. However, Cowan and colleagues 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 among 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 et al., 2012). 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 in the section Coordination and Transformation Tasks, that WM tasks that require multiple bindings, such as coordination and transformation tasks, predict G*f* just as well as do 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, Unsworth and Engle (2006a, 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 21.4). 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 and colleagues (2010) 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 Unsworth and Engle (2007) 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, Loughry, & O'Reilly, 2001; E. K. 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., 2011; Kondo et al., 2004; Osaka et al., 2003; Osaka et al., 2004; Smith et al., 2001).

Unsworth and Engle (2007) 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., 2011).

Process Overlap Theory: 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 shaped by Unsworth and Engle's account discussed in the section Active Maintenance and Controlled Retrieval, 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., 2011; Nee & Jonides, 2008; Ranganath, 2006).

This multi-mechanism view of the relationship between WMC and G*f* is consistent with process overlap theory, a recent account of the general factor of intelligence

(Kovacs & Conway, 2016). The primary aim of the theory is to explain the finding that cognitive ability tests with diverse content all correlate positively. This finding, called the positive manifold, is the basis of the general factor, *g*, that explains 40–50 percent of the entire variance in IQ tests.

The multi-mechanism view in general and the idea of overlapping processes determining mental test performance in particular is not new. In fact, it dates back to one of the earliest criticisms 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, Thomson demonstrated that the positive manifold could be caused by multiple processes as long as a battery of tests tap these various processes in an overlapping fashion. This is the basis of so-called sampling theories (Thomson, 1916; Thorndike, 1927).

Thomson (1916) provided a mathematical proof of this, showing that the correlation between any two tests can be described as the function of the ratio of processes in common, that is, the number of processes sampled by both tests relative to the total number of processes sampled by each. Thus, *g* may not reflect a unitary construct; instead, it may emerge from a battery of tasks that sample overlapping domain-general mechanisms. It has since been reinforced with more elaborate mathematical methods that it is impossible to select between Spearman's and Thomson's explanation on a purely statistical basis (Bartholomew, Deary, & Lawn, 2009).

Besides subscribing to a multi-process, sampling approach to intelligence, process overlap theory also draws heavily on the concept of working memory capacity in explaining the positive manifold in intelligence. The theory postulates an overlap of cognitive processes activated by various mental ability tests and working memory tasks. In particular, it is hypothesized that any item or task requires a number of domain-specific as well as domain-general cognitive processes. Domain-general processes responsible for executive attention and cognitive control are central to performance on both mental tests and working memory tasks since they are activated by a large number of items, alongside domain-specific processes tapped by specific types of items/tests only.

The theory actually focuses on limitations. That is, the central processes that are tapped by a large numbers of tasks limit performance in a general way and make errors more likely regardless of the domain-specific processes that are also tapped by the same tasks. This way, executive processes function as a bottleneck and can potentially mask individual differences in specific processes. Hence process overlap theory, contrary to traditional models of sampling, proposes a nonadditive interaction of processes: Instead of simply adding scores on sampled processes, the mathematical model behind process overlap theory proposes that each individual dimension of a task has to be completed in order for someone to arrive at a correct solution. A single process can cancel the effect of all other processes and be the cause of error on its own.

Importantly, process overlap theory provides an explanation of the general factor of working memory capacity as well as *g*. It proposes that the same pool of domain-general executive resources is tapped by different working memory tasks as different psychometric tests of cognitive ability, especially the ones that measure fluid reasoning. According to the theory, that is why the general factors of working memory and fluid intelligence correlate so strongly.

Conclusions

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. This argument is more formally expressed in a framework we refer to as process overlap theory (Kovacs & Conway, 2016).

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, fMRI studies have illustrated that individual differences in activity in PFC during a WM task partly account for the relationship between WMC and G*f* (Burgess et al., 2011; Gray et al., 2003). One intriguing possibility is that individual differences in activity in different brain regions (or network of regions) account 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, account for different variance in G*f* rather 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 some research supporting this idea (Dahlin et al., 2009; Karbach & Kray, 2009) 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, consistent with process overlap theory (Kovacs & Conway, 2016). 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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