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Variation in Working Memory Capacity as Variation in Executive Attention and Control

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If, as many psychologists seem to believe, immediate memory represents a distinct system or set of processes from long-term memory (LTM), then what might it be for? This fundamental, functional question was surprisingly unanswerable in the 1970s, given the volume of research that had explored short-term memory (STM), and given the ostensible role that STM was thought to play in cognitive control (Atkinson & Shiffrin, 1971). Indeed, failed attempts to link STM to complex cognitive functions, such as reading comprehension, loomed large in Crowder's (1982) obituary for the concept.

Baddeley and Hitch (1974) tried to validate immediate memory's functions by testing subjects in reasoning, comprehension, and list-learning tasks at the same time their memory was occupied by irrelevant material. Generally, small memory loads (i.e., three or fewer items) were retained with virtually no effect on the primary tasks, whereas memory loads of six items consistently impaired reasoning, comprehension, and learning. Baddeley and Hitch therefore argued that "working memory" (WM) is a flexible and limited-resource system with storage and processing capabilities that are traded off as needed. In this system, small memory loads are handled alone by a peripheral phonemic buffer, leaving central processing unaffected, whereas larger loads require additional resources of a central executive. Thus, WM was proposed to be a dynamic system that enabled active maintenance of task-relevant information in support of the simultaneous execution of complex cognitive tasks.

As we will detail below, there are certainly aspects of our theoretical perspective that can be traced to Baddeley and Hitch's (1974) views. But our approach to conducting WM research is also strongly influenced by another article that appeared at about the same time, entitled "Individual differences as a crucible in theory construction." In this report, Underwood (1975) argued that psychological theories should be subjected promptly to an individual-differences test as a means of falsification. Most nomothetic theories in psychology make predictions about individual differences, even if only implicitly, and so testing these predictions is an efficient means to determine whether a theory merits further pursuit. Although Baddeley and Hitch (1974) formulated and pursued WM theory based on experiment, the question of WM function obviously lent itself to individual-differences predictions. Quite simply, if WM were a central mechanism to higher-order cognition, then individuals with greater WM capacity should perform better on complex cognitive tasks than those with lesser WM capacity.

These important predictions became testable a half-decade later, when Daneman and Carpenter (1980) created the "complex span" tasks that initiated an individual-differences approach to WM research. These span measures were dual tasks, requiring information storage in the context of simultaneous processing of other information. They therefore reflected Baddeley and Hitch's (1974) idea that the executive component of WM must be measured in a dual processing and storage context. Most importantly, scores on complex span tasks correlated strongly with measures of language comprehension, and this provided important validation for WM theory. Indeed, subsequent individual-differences research has led the way in fulfilling the theory's greatest promise—to elucidate the function of immediate memory—by linking variation in WM to diverse aspects of higher-order cognition, including language learning (e.g., Baddeley, Gathercole & Papagno, 1998), comprehension (e.g., Daneman & Merikle, 1996), reasoning (e.g., Kyllonen & Christal, 1990), and cognitive control (e.g., Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). These correlational findings have indicated that WM plays an important role in a host of complex cognitive capabilities and that WM measures have practical value in assessing intellectual ability.

However, the magnitude and breadth of the correlations between WM span and other cognitive measures do not necessarily illuminate the psychological source of those correlations. We suggest that individual-differences research will have its greatest impact on basic WM theory only when it pursues questions of mechanism simultaneously with questions of function. Our research program has therefore addressed both mechanism and function, in the spirit of Cronbach's (1957) call to align the "two disciplines of scientific psychology" and his argument that scientific psychology should aim to understand *individual* minds as well as the general, nomothetic principles of mind. To do so, we use both experimental and correlational methodologies and examine individual-by-treatment interactions. The central question that drives our research, then, which is unapologetically tied to individual differences, has clear ramifications for general WM theory: *Why do WM capacity (WMC) measures so successfully predict performance across a range of cognitive abilities?*

OVERVIEW OF AN "EXECUTIVE ATTENTION" THEORY OF WORKING MEMORY CAPACITY

Our approach to understanding WMC and its variation emphasizes the synergy of "attentional" and "memorial" processes in maintaining and recovering access to information that is relevant to ongoing tasks and in blocking access to task-irrelevant information (e.g., Engle & Kane, 2004; Engle, Kane, & Tuholski, 1999; Kane & Engle, 2002; Kane, Hambrick, & Conway, 2005). Our theory, which follows in part from Cowan (1995), is depicted in Figure 2.1. We view STM as a metaphorical "store" represented by LTM traces activated above threshold. These traces may be maintained in the limited focus of attention (conscious awareness) or kept active and accessible through domain-specific rehearsal and coding processes (e.g., inner speech, chunking, imagery). Domain-general executive attention processes may also be engaged to sustain activation of information beyond attentional focus, or to retrieve no-longer active information from outside of conscious focus. These executive processes will be particularly useful when rehearsal or coding routines are relatively unpracticed or not useful in a particular context (e.g., with novel visuospatial materials, or in dual-task situations). These same executive attention mechanisms may also be deployed to block or inhibit goal-irrelevant representations or responses elicited by the environment.

We propose that the extent to which executive attention is engaged by a task, for maintenance,

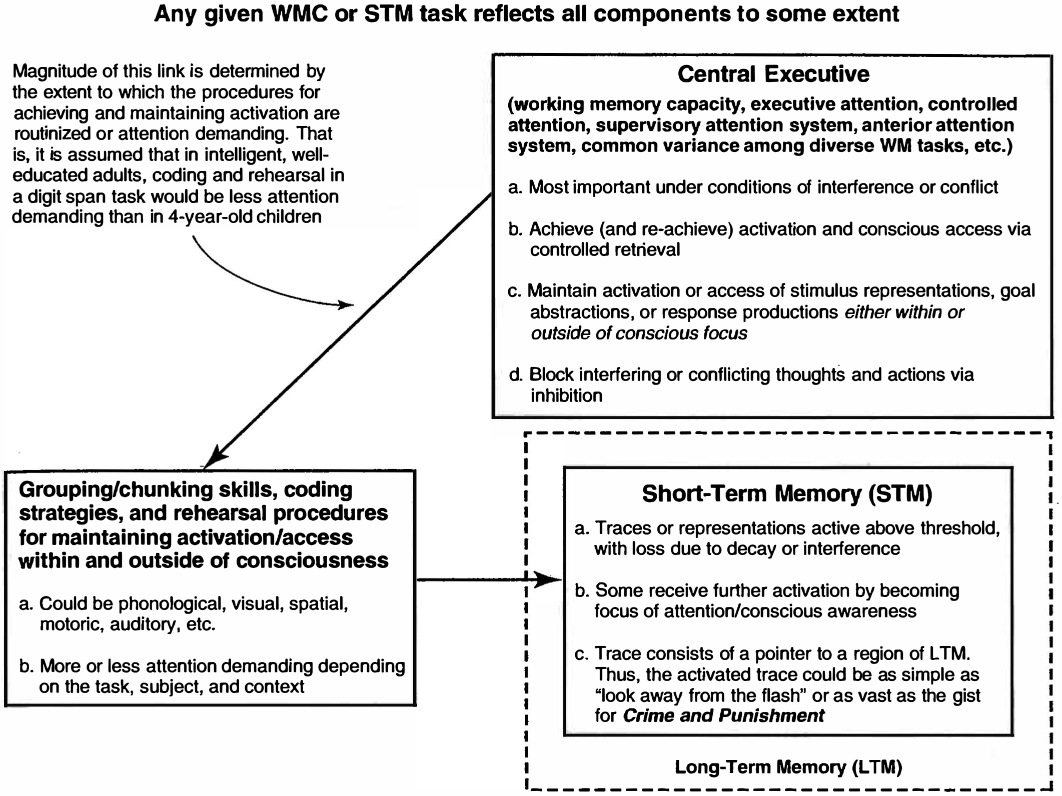

Figure 2.1. Measurement model of the working memory system, version 1.2. (Adapted from Engle, Kane et al., 1999 [version 1.0], and Engle & Kane, 2004 [version 1.1].)

retrieval, or for blocking, is critically determined by the degree of interference or conflict presented by the context. Proactive interference from prior events may, for example, slow the search for one's car in a familiar parking lot. Or, the environment may induce competition between habitual responses and more novel ones when the context is ambiguous or unusual, such as when an American drives on the wrong side of the road in Dublin. Our view is that the presence of such interference or conflict makes the executive functions of WM most helpful and readily measurable (Norman & Shallice, 1986). Thus, when we use the term *working memory capacity*, we refer to the attentional processes that allow for goal-directed behavior by maintaining relevant information in an active, easily accessible state outside of conscious focus, or to retrieve that information from inactive memory, under conditions of interference, distraction, or conflict.

Working Memory Capacity, Executive Attention, and Working Memory Span Tasks

Our perspective is closely tied to the complex span tasks we have used to measure WMC, which show good reliability by internal-consistency and test-retest measures (e.g., Klein & Fiss, 1999; Turner & Engle, 1989; but see Chapter 11, this volume).[1] These WM span tasks present subjects with the traditional memory span demand to immediately recall short lists of unrelated stimuli. Additionally, and critically, WM span tasks challenge memory maintenance by presenting a secondary processing task in alternation with each memory item. Reading span (Daneman & Carpenter, 1980), for example, requires subjects to read series of sentences for comprehension and then recall the sentence-ending words from the series (or sometimes, to recall an isolated word or letter that followed each sentence); operation span, in contrast, presents subjects with series of equations to verify, with each equation followed by an unrelated word to memorize (Turner & Engle, 1989). Less verbal tasks include counting span, which presents series of arrays in which to-be-counted target items are surrounded by distractors and subjects must recall the count from each array in the series (Case, Kurland, & Goldberg, 1982), and spatial (rotation) span, which presents series of rotated letters that subjects judge to be normal or reversed while memorizing the letters' original orientations (e.g., Shah & Miyake, 1996).

Working memory span tasks are obviously complex and multiply determined tasks, and so none of them can be considered a process-pure measure of "executive function." Instead, WM span tasks measure, in part, executive attention processes that we believe are domain general and contribute to WM span performance irrespective of the skills or stimuli involved. In addition, WM span tasks reflect the contributions of rehearsal, coding, storage, processing skills, and strategies that are domain specific and vary with the component tasks and stimuli presented (see also Chapters 5 and 6). Our view is that WM span tasks reflect primarily general executive processes and secondarily, domain-specific rehearsal and storage processes. Moreover, the broad predictive utility of WM span tasks derives from the general, executive attention contributions to performance. Short-term memory span tasks, in contrast, reflect domain-specific storage and rehearsal skills and strategies primarily and executive attention processes only secondarily. That said, we should emphasize that we do not claim that STM tasks are pure measures of storage and rehearsal, without any influence of attention processes; nor do we claim that WM span tasks measure or correlate with all possible aspects of attentional processing. Instead, we think that WM span tasks are reasonably good measures of a domain-general attentional capability that is involved in the control of behavior and thought and is important to many cognitive abilities. Thus WM span tasks are generally better measures of the executive attention construct than STM span tasks (see Kane et al., 2005).

Working memory span tasks tap into executive attention by requiring subjects to maintain or recover access to target information under proactive interference from prior trials (e.g., Lustig, May, & Hasher, 2001), while that access or retrieval is challenged by intermittently shifting attentional focus between the memory and secondary processing tasks (e.g., Barrouillet, Bernadin, & Camos, 2004; Hitch, Towse, & Hutton, 2001). That is, interference encourages subjects to rely on sustained, active access to the memoranda, rather than on LTM retrieval, but subjects cannot easily maintain that access because the processing task prevents them from keeping target items in the focus of attention (the processing task also limits use of rehearsal or chunking strategies). Executive processes thus help maintain or recover access to the target items in the absence of focal attention and effective rehearsal procedures.

EXECUTIVE ATTENTION AS THE CRITICAL SOURCE OF WORKING MEMORY CAPACITY VARIATION

Our proposal, that WMC variation is driven largely by individual differences in executive attention processes, represents a web of inference across correlational and experimental studies. Some of these studies, which we have described as "macroanalytic" (Engle & Kane, 2004; see Salthouse & Craik, 2001), have examined the relations between WMC and other hypothetical constructs, such as general fluid intelligence, using large subject samples and multiple tasks to identify each construct. Two other kinds of studies, which we term "microanalytic," take a more focused approach to analyzing span–ability relations. One line of microanalytic work combines correlational and experimental designs by manipulating variables within WM span tasks to determine how those manipulations affect the span–ability correlation. These are essentially task analyses of WM span that consider not only the processes required by span tasks but also the processes shared between span and other measures. The second line of microanalytic research, using quasi-experimental designs, tests for WM span–related differences by comparing individuals with high WM span scores (*high spans,* from the upper quartile of a university student distribution) to those with low scores (*low spans,* from the lower quartile) in the performance of "elementary" cognitive tasks from the memory and attention literatures. We discuss these three sets of macro- and microanalytic findings in detail below.

Macroanalytic Studies of Working Memory Capacity

The use of large-scale, structural equation modeling studies in WMC research has increased recently, influenced by the growing confluence of the WMC and intelligence literatures (for reviews, see Conway, Kane, & Engle, 2003; Kane et al., 2005). An advantage of these techniques is that they permit the use of latent variables, which reflect the shared variance among a number of tasks hypothesized to reflect the same construct (e.g., WMC). As such, latent variables are free from the measurement error associated with any one multiply determined task. Through use of latent variables and structural equation modeling, research conclusions can be shifted from the level of observed variables, which always reflect some measurement error, to the theoretical constructs of interest.

The Relation of Working Memory Capacity to Short-Term Memory and Fluid Intelligence

Engle, Tuholski, Laughlin, and Conway (1999) tested 135 university subjects in WMC tasks (operation span, reading span, counting span), STM tasks (backward and forward word span), and tests of fluid intelligence, or psychometric *Gf* (novel figural and spatial reasoning). Our questions for this study were whether WMC and STM were dissociable constructs and, if so, whether WMC was the better predictor of Gf. In fact, WMC and STM were separable: the two latent variables correlated substantially (.68), but a model forcing a single factor onto the span data did not fit well. We believe that the correlation between STM and WMC was driven primarily by the shared requirement among span tasks to immediately recall short lists of verbal items—that is, it reflected primarily "storage" (although some shared variance between STM and WMC will also reflect executive attention). The unique residual variance in WMC reflected the dual-task demand in the WMC tasks only, that is, the increased demand they made on executive attention for active maintenance outside of conscious focus.

Given that WMC and STM reflected both shared and unique variance, which might contribute to general intellectual ability? We found that the WMC factor, but not STM, predicted unique variance in Gf, suggesting that the greater executive demands of WM span tasks are the source of WMC–Gf correlations, rather than the "simple" storage demands shared by STM and WM tasks. However, as a further test of this idea, we constructed a hierarchical model of our span data (illustrated in Fig. 2.2). Here, separate factors were derived for WMC and STM, but in addition, the considerable variance shared between WMC and STM was modeled as a second-order factor. This second-order "common" factor ostensibly represented the storage, coding, and rehearsal (and some executive) processes involved in both WMC and STM tasks, and it shared significant, unique variance with Gf. However, the residual, unique variance from WMC (i.e., WMC with STM factored out) predicted Gf more strongly. Whatever WM span tasks demand beyond simple storage seems to account primarily for the WM–Gf correlation. We interpret this residual WMC variance to reflect the relatively strong executive attention demands of WM span tasks, elicited by their dual-task requirements.

Processing Speed and Working Memory Capacity–Gf Association

Conway, Cowan, Bunting, Therriault, and Minkoff (2002) replicated these findings while additionally testing the contribution of processing speed to predicting Gf and accounting for the WMC–Gf correlation. Developmental research clearly shows that speeded measures of

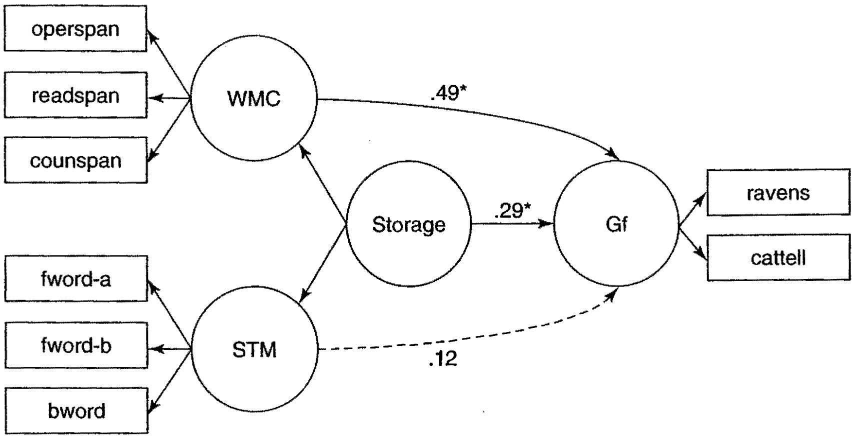

Figure 2.2. Structural-equation model, adapted from Engle, Tuholski et al. (1999). Circles represent latent variables and boxes represent individual tasks. Solid arrows with path coefficients with asterisks represent significant shared variance between constructs. Counspan = Counting span task; Fword-a = Forward Word span task, version a; Fword-b = Forward Word span task, version b; bword = Backward word span task. Gf = general fluid intelligence; Operspan = Operation span task; Readspan = Reading span task; WMC = working memory capacity; STM = short-term memory.

simple cognitive processes often account for a lion's share of age-related variance in higher-order cognition, overwhelming the contribution of WMC (Kail & Salthouse, 1994). Much less clear, however, is whether processing-speed variation within an age group can account for the relation between WMC and intelligence. To find out, we tested 113 university subjects in the WM span and Gf tasks used by Engle, Tuholski et al. (1999), along with several STM and speed tasks. The latter were paper-and-pencil tasks requiring subjects to copy or compare lists of stimuli quickly and accurately. Because correlations between processing speed and Gf measures typically increase with the complexity of speeded tasks (e.g., Jensen, 1998), thus clouding the interpretation of what "processing speed" reflects, we chose simple speed tasks as a most stringent test of their importance.

In order to examine the independent contributions of executive attention and storage, coding, and rehearsal to the association between WMC and Gf, we used a nested structure in which all the span tasks loaded onto a common "STM–storage" factor to represent their shared storage, coding, and rehearsal variance. WMC tasks also loaded onto a residual factor, reflecting the additional executive attention processes engaged by the dual-task nature of the WM span tasks. As shown in Figure 2.3, the shared "storage" variance was a relatively weak predictor of Gf, and the residual WMC variance was stronger. These findings support the idea that "executive" variance, tapped by WMC tasks to a greater degree than by STM tasks, drives the WMC–Gf relationship. It is also worth noting here that not only did speed fail to predict Gf while controlling for WMC, but speed also correlated more strongly with STM–storage than WMC–executive processes. Among young adults, then, with relatively "simple" tests of processing speed and with untimed measures of WMC, the two constructs share little variance, and only WMC is a significant source of variation in general ability.

Domain Generality of Working Memory Capacity and Short-Term Memory

Our latent-variable research shows strong correlations between WMC and Gf, therefore suggesting WMC to be an important mechanism of general cognitive ability. Moreover, our WMC latent variables were derived from *verbal, symbolic* WM span tasks and the Gf latent

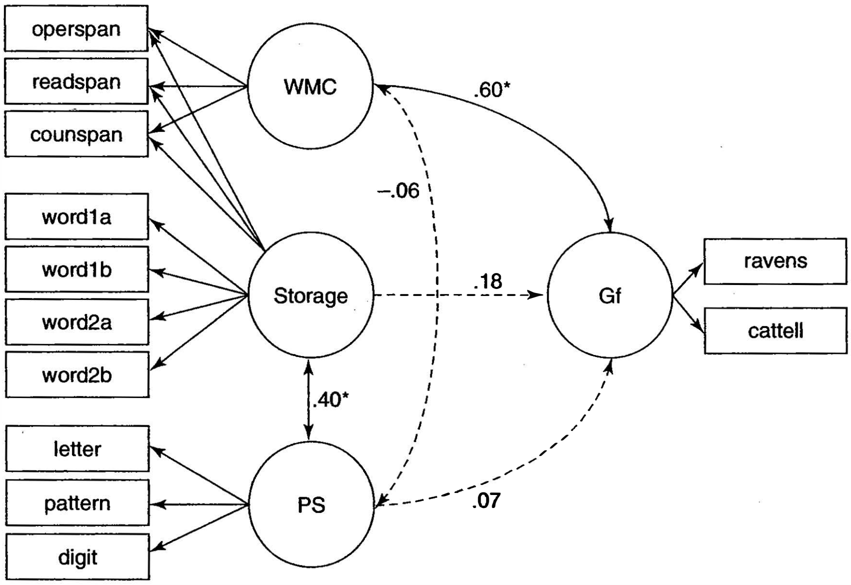

Figure 2.3. Structural-equation model, adapted from Conway et al. (2002). WMC = working memory capacity; STM = short-term memory; PS = processing speed; Gf = general fluid intelligence; Operspan = Operation span task; Readspan = Reading span task; Counspan = Counting span task.

variables were created from *nonverbal, figural* reasoning tasks. This cross-domain generality indicates that the variance common to WM span tasks cannot be substantially verbal. Instead, we submit that the executive attention variance that is shared among WM span tasks reflects domain-general processes.

However, a few studies indicate domain specificity in WM span, with low correlations between individual verbal and visuospatial WM span tasks, low cross-domain correlations between WM span and ability, or both (e.g., Shah & Miyake, 1996). We suspect that restricted ranges of general ability and measurement error biased these studies toward finding exaggerated domain specificity in WMC. All were derived from samples of university students, some from prestigious schools, that might represent a narrow range of general intellectual ability relative to the population at large. Without suitable variation in general ability in a sample, any variability in cognitive performance must result from something else, such as domain-specific abilities, skills, or strategies. (Because universities are more likely to select students from a narrow range of general ability than from a narrow range of any one specific ability, samples drawn from these populations are more likely to represent restricted ranges of general ability.) Moreover, with respect to measurement error, these "domain-specific" studies used only one measure each of verbal and spatial WMC. With only one task per construct, the low correlations might result from dissociable constructs (i.e., verbal and spatial WMC), or instead from other, non-WMC abilities, skills, and processes tapped by complex span tasks.

To address these possibilities, Kane et al. (2004) tested 236 subjects from both competitive and comprehensive universities, as well as from two urban community samples, in multiple tests of verbal and spatial WM and STM span. We thus ensured some degree of variation in domain-general ability in our sample and used latent-variable models to factor out sources of measurement error. We first contrasted the fit of two kinds of models for the WM span data: unitary models derived from all six WM span tasks and two-factor models with separate verbal and spatial WMC factors.

Depending on the technical details of these models, verbal and spatial WMC factors shared 70%–85% of their variance (correlations from .84 to .93), demonstrating that WM span measures tap primarily general processes and abilities. In contrast, verbal and spatial STM measures shared only 40% of their variance, consistent with our view that complex WM span tasks measure primarily the contribution of general executive processes and simple STM span tasks measure primarily the contributions of domain-specific ones. We also tested whether the domain generality of WMC and STM varied with the range of Gf in the sample, by dividing our subjects into different groups on the basis of their matrix-reasoning performance: a high-Gf group, a low-Gf group, and two groups representing the full range of Gf. We found that both WMC and STM were much more domain specific in our high-Gf group than they were among our low-Gf subjects or our full Gf–range sample. Thus, as we suspected, prior findings of domain-specific WMC may have resulted from testing subjects from a restricted range of high general ability.

Like Engle, Tuholski et al. (1999) and Conway et al. (2002), we also tested whether the general executive contributions to span, or domain-specific STM–storage contributions, were the primary source of the WMC–Gf correlation. In our nested-factor model, depicted on the left side of Figure 2.4, all 12 of the verbal and spatial WMC and STM tasks loaded onto a common factor reflecting their shared variance. Additionally, the six verbal and spatial span tasks each loaded onto a domain-specific residual factor. The logic, again, was that both WM and STM span tasks reflect joint contributions of general executive attention and domain-specific STM and storage. At the same time, WM span taps primarily general executive attention processes and STM span taps primarily domain-specific storage, coding, and rehearsal processes. However, in contrast to the Engle and Conway models, note that we interpreted the common factor to represent general executive attention variance and

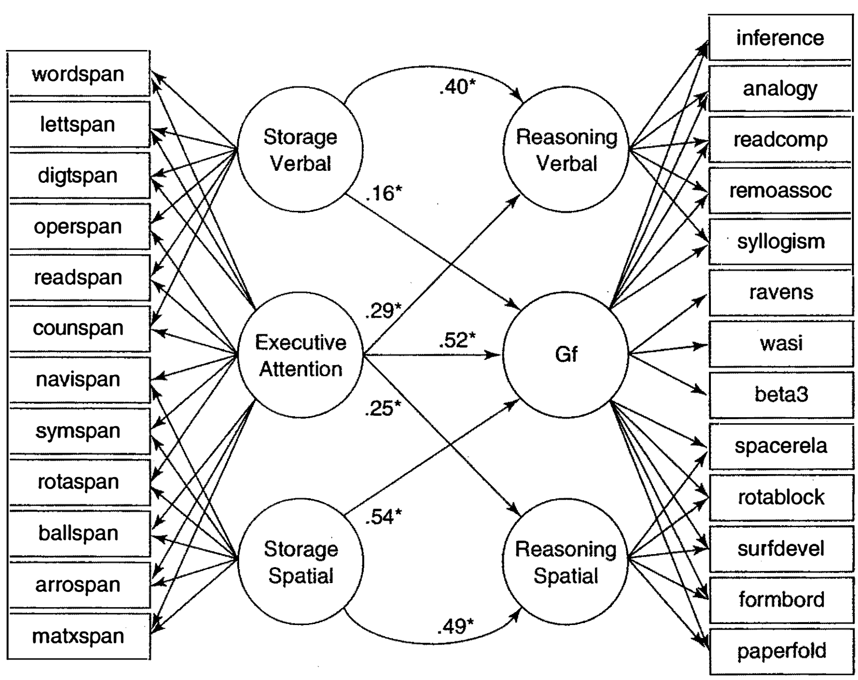

Figure 2.4. Structural-equation model, adapted from Kane et al. (2004). Gf = general fluid intelligence. For descriptions of the individual span and reasoning tasks, see Kane et al. (2004).

the residual factors to represent domain-specific STM–storage variance, rather than the reverse.

Our interpretation of these factors had rational and empirical grounding. First, given the substantial dissociability between verbal and spatial STM span in our data and in others' (see Jonides et al., 1996, for a review), it is unlikely that shared variance among verbal and spatial span measures reflected *domain-specific* storage and rehearsal abilities. Second, the WMC and STM tasks loaded differently onto the "executive" and "STM–storage" factors. The WMC tasks all had higher loadings on the common "executive" factor than did the STM tasks, and they had higher loadings on the executive factor than on their respective "storage" factors. The STM tasks showed the opposite pattern. Thus, the executive attention factor captured more variance from WMC than STM tasks, and the storage factors showed the opposite pattern. In this data set, then, the common span variance reflected domain-general executive attention and the domain-specific residual variance reflected STM storage and rehearsal processes. Of most importance, the executive attention factor strongly predicted Gf (path coefficient = .52), with a similar magnitude to our previous studies. Moreover, it was similar to the correlation we found in a separate model where Gf was predicted by a WMC factor derived from only the six WM span tasks (.64). This consistency across models and studies is compelling, given that we defined WMC and Gf much more broadly here than in our prior work, with Gf reflecting shared variance among verbal and visuospatial reasoning tests. Indeed, in a separate article we reanalyzed all the published latent variable data on the WMC–Gf correlation and found that WMC accounted for approximately 50% of the variance in Gf (i.e., the median correlation between WMC and Gf constructs across studies was .72; Kane et al., 2005). This shared variance is not strong enough to claim that WMC and Gf are synonymous. However, we submit that WMC, which reflects primarily a general executive construct, is one critical source of Gf variation. Short-term memory, in contrast, reflects more domain-specific storage and rehearsal processes that are less important to general aspects of ability.[2]

Summary of Macroanalytic Research

As measured by a variety of span tasks, WMC and STM are strongly correlated constructs. However, despite this close relationship, the attentional processes engaged primarily by WM span tasks (and to a lesser extent by STM tasks) are responsible for WM span's general and superior predictive utility. The executive attention processes that contribute to WM span tasks are an important mechanism of fluid intelligence, and furthermore, these executive attention processes are domain general. In contrast, variance associated with simple storage and rehearsal activities, captured primarily by STM tasks, is relatively domain specific (for alternative views on WMC's domain generality, see Chapters 6 and 8).

Microanalytic Studies of Working Memory Capacity

Two lines of "microanalytic" research, using smaller scale quasi-experiments and regression- or ANOVA-based analytic approaches, have addressed the mechanisms of span task performance and its relation to complex cognitive abilities. One line has clarified which processes are *not* important to WMC variation and covariation. We discuss this work first. We then review research that more closely and specifically links WMC to the constructs of attention and executive control.

Ruling out Some Mechanisms of Variation and Covariation in Working Memory Capacity

Task skill and processing efficiency The idea that individual differences in task-specific skills affect the correlations between WM span and higher-order cognitive measures is an old one. Daneman, Carpenter, and colleagues (e.g., Daneman & Carpenter 1980) proposed that good comprehenders could devote fewer WM resources to the reading and listening component of the span task than could poor comprehenders, thereby relieving more resources for the simultaneous task of memory storage. Thus, strong language skills lead to a larger functional WMC for language, rather than a larger WMC leading to stronger language skills. In a similar vein, MacDonald and Christiansen (2002) claimed that "the reading span task is simply a measure of language processing skills" (p. 39). However, our research (Conway & Engle, 1996; Engle, Cantor, & Carullo, 1992) demonstrates that partialing out subjects' processing speed during span tasks does not diminish the correlation between WM span and verbal ability, nor does tailoring the difficulty of the span task processing demand to each subjects' individual skill level. If partialing out processing speed and matching processing skills do not reduce span–ability correlations, then the relationship must reflect more than domain-specific processing skills.

Strategy use Given the complexity of WM span tasks, individual differences in strategies might contribute to WM span scores, as well as to the general patterns of WMC covariation with other constructs. In fact, when McNamara and Scott (2001) trained subjects to use a semantic "chaining" strategy during simple word span tasks, they found that it substantially increased subsequent reading span (WMC) scores. Moreover, subjects who initially reported using a semantic strategy to remember the STM task words had higher reading span and verbal Scholastic Aptitude Test (VSAT) scores than those of subjects who reported using only rehearsal or no strategies.

However, despite the effects of strategy use on WM span scores overall, we believe that McNamara and Scott's (2001) data actually argue against the importance of strategy variables to WMC variation and covariation. First, standard deviations in WM span were generally larger after training than before training, indicating that training *increased*, rather than reduced, span variability. Second, initially high-strategic subjects benefited more from strategy training than did initially low-strategic subjects, and so WMC seems to determine how effectively people learn and use demanding strategies. Third, higher WM span scores were associated with higher VSAT and math SAT (MSAT) scores, but high strategy use was associated only with higher VSAT and not with MSAT. Strategy use therefore cannot account for the *general* predictive power of reading span. Finally, McNamara and Scott did not report what should be critical evidence concerning a strategy hypothesis—if individual differences in strategy use account for WM–ability correlations, then a span–ability correlation should be weaker after strategy instruction than before it.

The few studies that have directly tested whether indices of strategy use might account for the covariation between WMC and complex cognition have been negative. In two different WM span tasks, Engle et al. (1992) allowed subjects to control their study time for each to-be-recalled word. Those subjects with high spans studied the target words for more time than those with low spans, but when Engle et al. partialed out study time from the span–VSAT correlations, they actually *increased* nonsignificantly. Thus, strategic allocation of study time did not drive covariation between WMC and verbal ability; if anything, strategy use suppressed measurement of the relationship (see also Friedman & Miyake, 2004).

A series of training studies by Turley-Ames and Whitfield (2003) also found strategy use to suppress correlations between WMC and verbal ability. Following a pretest on operation span, subjects were instructed to engage in rehearsal, imagery, or semantic chaining to help them remember the target words. Instructed subjects greatly improved their span scores relative to uninstructed control subjects, but scores following strategy instruction were more *strongly* correlated with verbal ability than were control scores. That is, matching subjects in their knowledge and encouragement of effective WM strategies did not make the span–ability correlation go away, as it should have if strategic differences accounted for the correlation. Instead, normal variation in strategy use (as reflected by control subjects) actually worked against finding correlations between WM span and verbal ability. Variation in strategy use during WM span tasks, even if substantial, does not account for shared variance between WMC and ability measures.

Summary Microanalytic studies have not found the contributions of processing efficiency, processing skill, or strategy use to be compelling; they either fail to account for performance of WM span tasks or, if they do affect WM span scores, they do not contribute to the correlations between WM span and higher-order abilities. Something else drives the predictive power of WMC measures. We can rule out STM storage and rehearsal as well, because macroanalytic studies find that STM tasks are not as good predictors of general ability as WM tasks, and the demands made by WM span tasks, beyond STM storage and rehearsal, drive their association with complex cognition.

We think the studies described in this section serve as good examples of the importance of combining experimental and correlational approaches to WM research. Experimental task analyses of WM span tasks may suggest any number of variables that serve to either increase or decrease span scores. Such findings may be interesting in their own right, but it is a mistake to infer from them that any of these variables must contribute to the correlations between WM span and other tasks. At least some variables that affect span scores clearly have no influence on WM span correlations.

Variation in Working Memory Capacity and Individual Differences in Executive Attention

With the elimination of processing skill or efficiency, strategy use, and STM storage as causes of the WMC–ability relationship, we infer that the attentional demands made by WM span tasks are most important in producing that relationship. Moreover, our second line of microanalytic work, discussed below, provides direct evidence for an association between WMC and executive attention capabilities. First we review evidence linking individual differences in WMC to the attentional control of interference in memory. We then discuss evidence from relatively low-level attention tasks, not involving memory retrieval, that WMC predicts control over goal-directed behavior. Specifically, we find that WMC is associated with successful maintenance of task goals and the attendant blocking of strong but contextually inappropriate responses, mechanisms that may be analogous to the "proactive" and "reactive" control modes, respectively, proposed by Braver et al. (Chapter 4).

Working memory capacity and executive attention in resolving memory interference Our executive attention theory holds that the control of memory retrieval in the face of interference is central to the attentional construct measured by WM tasks. The supporting evidence—a strong connection between WMC and interference vulnerability—comes from a variety of experimental preparations that pose different types of interference and competition (e.g., retroactive, fan-type, output). In these studies, extreme (quartile) groups of high– and low–WM span subjects, identified via operation span, differ in recall accuracy or latency under high-interference but not low-interference conditions (e.g., Conway & Engle, 1994).

Proactive interference, for example, affects low- more than high-WMC individuals. Kane and Engle (2000) tested subjects in a delayed free-recall task presenting three consecutive lists of 10 words each, with recall preceded by a 15 s rehearsal prevention task. To maximize interference, the words from all three lists belonged to one semantic category (e.g., animals). On List 1, in the absence of interference, the two span groups showed equivalent free recall. However, by List 3, under proactive interference from prior lists, low-span subjects' recall dropped more precipitously than that of high-span subjects ($Ms \approx -50\%$ vs. -30%, respectively). Rosen and Engle (1998) demonstrated span differences in interference susceptibility during learning of paired associates. In List 1, all subjects learned 12 compound word pairs (e.g., *bird-bath*). In List 2, control subjects learned 12 pairs of semantically related words that were unrelated to the List 1 pairs (e.g., *eye-tear*), while interference subjects learned pairs using the List 1 cues (e.g., *bird-dawn*). High and low spans reached learning criterion equally quickly for List 1, where interference was absent. However, in List 2, low spans required an average of two more learning trials than did high spans overall, and low spans' impairment was especially evident in the interference condition. Low spans under interference also committed more overt List 1 intrusions during List 2 learning than did high spans.

These studies additionally yielded evidence that WMC-related variation in interference arises from attention-control variation, consistent with theories linking interference resistance to attentional inhibition (e.g., Anderson & Neely, 1996; Hasher & Zacks, 1988). Most directly, Kane and Engle (2000) tested some subjects under dual-task conditions, in which they continuously maintained a complex finger-tapping sequence during either study or recall of each list. Under both these dual-task conditions, the span groups showed *equivalent* interference. The secondary task had no effect on the low-span group's interference vulnerability but it increased the high-span group's interference vulnerability to that of the low-span group. These counterintuitive findings indicate that span differences in proactive interference normally result from high spans' superior use of controlled processes to combat it (e.g., via inhibition, blocking, source monitoring, etc.). Thwarting high spans' control by imposing a secondary task increased their interference susceptibility. In contrast, low span subjects were less effective in engaging controlled processing to limit interference in the first place, so dividing their attention was irrelevant—they could not lose what they were not already using.

Rosen and Engle (1998) inferred a role for attention in interference differences more indirectly. Their subjects attempted to relearn List 1 (e.g., *bird-bath*) after learning List 2 (e.g., *bird-dawn*). The critical dependent measure here was cued-recall latency following the very first learning trial for each list. Note that if high spans under interference conditions had blocked their List 1 associations in learning List 2 via an inhibitory process, then these pairs should subsequently suffer some residually impaired accessibility. Accordingly, high span subjects under interference should be slower to recall List 1 than they had been in originally learning them, and they should be slower to recall List 1 than control subjects. Low span subjects, by contrast, should show no evidence of inaccessibility for List 1. This is precisely what was found. High spans' relearning latencies in the interference condition were significantly longer than those in the control condition. In contrast, low-span individuals' response times (RTs) were actually *shorter* in the interference than in the control condition. Moreover, high spans' relearning latencies were significantly slower than their own List 1 learning latencies; low spans' latencies were statistically equivalent to one another. Thus, only high spans showed something analogous to a negative priming effect in relearning a list that had previously been a source of interference, and so was inhibited.

High- and low-span subjects recall information from LTM equivalently quickly and accurately in the absence of interference. Thus, WM span does not predict variability in *all* aspects of remembering. Instead, WMC appears important for learning and retrieval only when the environment presents a substantial source of interference and competition. Moreover, our dual-task and RT results strongly suggest that high spans' relative invulnerability to interference stems from a superior executive attention capability, whereby potentially competing information is blocked or inhibited. Only high spans show an effect of divided attention on their interference susceptibility, and only high spans show impaired access to initially learned but subsequently interfering associations.

Working memory capacity and executive attention in resolving response competition. If WMC reflects an attentional construct, as we claim, then WMC differences should be observable in contexts that make no explicit memory-retrieval demands. That is, variation in WMC should be associated with variation not only in memory-interference tasks but also in simpler indices of attention control. In fact, high spans (as measured by operation span) are less vulnerable to salient distractors in dichotic listening than are low spans. Conway, Cowan, and Bunting (2001) had subjects shadow a list of unrelated words presented to their right ear while distractor words were presented to their left ear. Either 4 or 5 min into the task, the subject's name was presented in the distractor channel. Prior research indicated that approximately 33% of subjects report hearing their name in such contexts (e.g., Wood & Cowan, 1995). Here, only 20% of the high span subjects, but 65% of the low span subjects, reported hearing their name.

WMC-related differences also arise in the arguably simpler "antisaccade" task of attention control. In two experiments, Kane, Bleckley, Conway, and Engle (2001) tested high and low spans in prosaccadic and antisaccadic versions of a letter-identification task. Each trial briefly displayed a letter to the right or left of fixation for identification. In prosaccade trial blocks the target location was always cued by a flashing stimulus near its upcoming location, so subjects could allow reflexive orienting responses to guide, or "pull," their attention and eyes to the target. Here, both high- and low-span subjects identified targets equivalently quickly. In contrast, antisaccade trial blocks always cued the target by presenting the flash to the *opposite* screen location, and so subjects had to block, or quickly recover from, the orienting response to the flash and endogenously "push" their attention and eyes toward the target. In both experiments, high spans identified antisaccade targets more quickly than did low spans. Moreover, Experiment 2 measured eye movements across hundreds of antisaccade trials, and high span subjects showed fewer saccades toward the cue, faster recovery from these saccade errors, and faster correctly guided saccades than did low span subjects.

Both the dichotic-listening and antisaccade tasks make few demands on subjects beyond blocking a habitual orienting response in the service of a novel goal. How do subjects actually succeed? We hypothesize that a critical aspect of preventing elicited but inappropriate response tendencies from controlling behavior is to actively maintain access to the novel goal. That is, to successfully block a prepotent response, such as looking toward a flash, one must keep this goal especially accessible. Although it may be trivial to recall from LTM the rules of a task, the rules of decorum, or the laws of the land, it is often quite a bit more challenging to behave, *in the moment*, according to these rules. Our view is that active goal maintenance and the resolution of response competition are interdependent processes of executive control, therefore, "memory" is an important determinant of "attentional" behavior (see also Chapter 4, this volume; De Jong, 2001; for an alternative view, see Butler, Zacks, & Henderson, 1999).

To explicitly test the idea that WMC may be tied to the executive acts of goal maintenance and competition resolution, Kane and Engle (2003) tested subjects with high and low spans in several versions of the Stroop color-word task. The Stroop task is a paradigmatic example of an executive attention task—a habitual, overlearned reading response must be held in check to allow the novel color-naming goal to control behavior. In order to manipulate the requirement to actively maintain access to task goals, we varied the proportion of *congruent* trials in the task. In high-congruency contexts, most trials presented words that matched their colors (e.g., *RED* appearing in red), so the task environment did not reinforce the goal of ignoring the word. Because the automatically elicited response to most stimuli was correct, it should have been easy to slip into word reading rather than color naming. Here, then, accurate responding on the rare incongruent trials, which presented conflicting color words (*BLUE* appearing in red), required that subjects maintained adequate access—in the moment—to the task goal. Failures of executive control should therefore be evident in accuracy.

In contrast, in Stroop contexts that presented few congruent trials and mostly incongruent trials, the stimuli reinforced subjects' goal. When every trial demands that the word be ignored, it may be unnecessary to do the mental work required to actively maintain goal access; the task environment acts as an external "executive." Just as Americans are helped to drive on the correct side of the road in London by road signs, traffic patterns, and the ergonomics of the car's controls, so too may subjects be kept on the desired path to color naming by a preponderance of incongruent Stroop trials. Under these circumstances, Stroop interference is unlikely to reflect goal maintenance to any great degree, and it is also unlikely to be reflected primarily in overt errors. Instead, interference in low-congruency contexts should reflect primarily the effectiveness of the competition resolution processes carried out by the externally cued goal, and should therefore be evident primarily in response latencies—that is, in slow but correct responses.

In fact, when 75% or 80% of the trials were congruent, Kane and Engle (2003) found that low spans had substantially larger error-interference effects than did high spans. These effects, across four samples in three experiments, indicate a low-span deficit in goal maintenance. Although low-span subjects understood the goal of the task, and in some experiments even received accuracy feedback after every trial, they nonetheless often "zoned out" and made word-reading errors on incongruent trials (low-span subjects also responded faster to congruent trials than high-span subjects, a finding suggesting that they periodically read the words aloud on these trials). In contrast, when only 0% or 20% of the trials were congruent, we found modest span effects in RT interference, requiring large samples to reach statistical significance. WMC-related differences were not found in errors indicative of goal neglect but rather in latencies, suggesting a slowed resolution of conflict between elicited and desired responses.

Summary Evidence from dichotic listening, antisaccade, and Stroop tasks converges to suggest that WMC predicts action control in deceptively "simple" attention tasks. Low spans are less able than high spans to act according to novel goals when that action conflicts with well-learned, if not reflexive, response tendencies. Our view is that executive attention processes largely determine performance of both WM span and these attention-control tasks, and so WM per se does not cause attention differences. Instead, a third variable, representing a low-level executive attention capability, influences functioning on all of these selective-attention, WM-span, and memory-retrieval tasks (and, presumably, on indices of Gf as well). Moreover, this executive attention capability has two aspects, one engaged to keep goals of novel tasks accessible in the face of conflict, and the other to resolve the conflict presented by habitual and goal-directed responses, or, in memory-retrieval contexts, to resolve interference between memories for similar events.

We see these goal-maintenance and competition-resolution functions of executive control as being quite similar to the proactive and reactive control modes, respectively, proposed by Braver et al. (Chapter 4) in their dual-process theory of cognitive control. Like Braver et al., we are not yet sure how these dissociable systems of control may interact with one another. On one hand, we propose that goal maintenance is necessary for the proactive blocking of competition, as in high-congruency Stroop tasks, and so here blocking or inhibition is dependent upon maintenance. On the other hand, the more reactive resolution of conflict seems to be accomplished independently of goal maintenance, and these mechanisms may also be the ones required for the resolution of memory interference (e.g., Conway & Engle, 1994; Kane & Engle, 2000; Rosen & Engle, 1998).

CHALLENGES FOR AN EXECUTIVE ATTENTION VIEW OF VARIATION IN WORKING MEMORY CAPACITY

Evidence from a variety of macroanalytic and microanalytic studies indicates that normal variation in WMC reflects primarily the function of executive attention processes. We propose that these executive processes keep representations of goal-relevant plans, responses, and stimuli in a highly accessible state in the presence of interference from prior events and distraction or conflict from the task environment. However, in the sections that follow, we discuss some current challenges for our theory of WMC variation. We first discuss two recent findings from our laboratories that may pose constraints on our conceptualization of executive attention. We then consider several complications that surround the measurement of the executive attention construct.

Boundary Conditions to the Relation between Memory Capacity and Executive Attention?

When we began investigating the connection between WMC and attention control, we had the naïve sense that most cognitive processes widely agreed to be "controlled" or "executive" would be sensitive to individual differences in WMC. However, two lines of research on visual search and task-set switching have shown that simplistic view to be incorrect.

The Problem

Following the seminal work of Treisman and Gelade (1980), visual search for targets among perceptually similar distractors has been widely considered a controlled process. That is, failing the automatic "pop out" of a unique visual feature from an array, attention is required to serially integrate the independently processed features into coherent object representations. We therefore reasoned that subjects with high spans should locate visual targets more quickly than those with low spans when attention-demanding search is required to find a target sharing features with its surround. We were wrong. After a pilot study indicated no span differences in visual search for either "automatic" or "controlled" search targets, Kane, Poole, Tuholski, and Engle (2006) replicated this span equivalence in larger samples across several different tasks. In one experiment, high- and low- span subjects searched for a target letter **F** among either **O**s (allowing more automatic, or *efficient* search) or **E**s (forcing more controlled, or *inefficient* search). Displays presented 1, 4, or 16 stimuli, arranged either in a regular matrix or psuedorandomly on-screen. Regardless of the array characteristics, the span groups showed identical search latencies and slopes across display sizes. In a second experiment, subjects searched for targets defined by a conjunction of features (**F**s among **E**s and horizontally tilted **T**s in one block, red vertical bars amidst red horizontal and green vertical bars in another); here, again, high- and low-span subjects demonstrated equivalently large search slopes. Whatever attentional processes are engaged by typical instantiations of visual search are not linked to those captured by WM span.

Inefficient search may be commonly considered a "controlled" task, but it is not nearly the gold-standard measure of executive control that task-set switching is thought to be (see Monsell & Driver, 2001). In these tasks, subjects regularly or unpredictably switch back and forth between two or more response sets for ambiguous stimuli; in either case, task-switch sequences elicit an RT "switch cost" compared to task-repeat sequences. We have so far failed to demonstrate a connection between WMC and switch cost in two prototypical preparations (see also Chapter 3). In our first three experiments, Kane, Poole, Tuholski & Engle (2003) tested high and low spans in a numerical Stroop task where subjects either identified or enumerated the digits in a horizontal string (e.g., 2222 = "two" or "four"). Within a cued prime-probe procedure, half the trial pairs repeated the task between displays and half switched the task. High and low spans showed equivalent RT switch costs in all three experiments. We were surprised by these findings, but also concerned that the prime-probe procedure might be measuring something different than the more typical "alternating-runs" preparation (e.g., Rogers & Monsell, 1995). So, in a fourth experiment we tested subjects in one of four different versions of the alternating-runs task (differing from each other in task-cuing and response-mapping details). Each trial displayed a letter and number, and subjects classified either the letter as vowel or consonant or the number as odd or even. In pure-trial blocks, the same task repeated over trials; in mixed-trial bocks, the tasks alternated in an AABB sequence. In all four versions of the task, high- and low-span subjects showed equivalent RTs in all of the pure- and mixed-trial conditions.

Clearly, we find no evidence for a deficit in visual search or task-set switching in low spans. What should we conclude from these findings? Oberauer et al. (Chapter 3) suggest that our executive attention view of WMC is falsified. We disagree, in part because we find robust WMC differences in a variety of other attention-control tasks. However, it may be that the attentional processes engaged by WM span tasks are related only to "inhibitory" attention tasks requiring prepotent responses to be withheld, as in Stroop and antisaccade tests (see Chapter 9). This idea does not appeal to us either, for a number of reasons. First, as we conceive it, goal maintenance and competition resolution should be quite generally important executive capabilities.

Second, the higher-order cognitive abilities that WMC predicts, such as reading comprehension and inductive reasoning, do not necessarily involve much response conflict or restraint of habit. Third, we do find WMC-related differences in several visual-attention tasks that do not seem to fundamentally measure control of habit or prepotency. For example, Tuholski, Engle, and Bayliss (2001) found that subjects with high spans could count the number of objects presented in a disorganized visual array faster than subjects with low spans when the tally exceeded the "subitizing" (pattern recognition) range of one to four items. Here there was no obvious prepotent response to keep in check (which also suggests a problem for a purely inhibitory view of WMC variation). Likewise, in a very different visual task, Bleckley, Durso, Crutchfield, Engle, and Khanna (2003) asked high- and low-span subjects to identify a letter presented briefly at central fixation. At the same time, another letter appeared in one of 24 locations along three concentric rings around fixation, and subjects tried to identify its location. The ring on which the second letter would appear was cued (with 80% validity) as "close," "medium," or "distant." As expected from "spotlight" or "zoom lens" theories of visual attention (e.g., Eriksen & Murphy, 1987), letters appearing outside the cued ring on invalid trials (i.e., outside the spotlight) were localized more poorly than letters appearing along the cued ring. More interestingly, for high spans only, letters appearing *interior* to the cued ring were also localized more poorly than letters along the cued ring. These findings suggest that high-span subjects flexibly configured attention discontiguously, focusing on the letter at fixation and on a ring beyond fixation, at the exclusion of intermediary rings of space. This pattern suggests that high spans adopted an object-based attentional focus. Low-span subjects, in contrast, showed a benefit for any location along or interior to a cued ring, indicative of a spotlight configuration and a space-based attentional focus.

A Solution?

Given these visual-attention findings that are not obviously inhibitory in nature, how should we reconcile our failures to link WMC to search and switching? We suggest that, unlike the tasks that have yielded WMC correlations, prototypical search and switching methods do not tap volitional, executive-control processes. Of course, if we want to avoid circularity in defining "executive attention" as simply anything that correlates with WMC, we must consider more closely what search and switching actually entail.

With respect to visual search, "guided search" theory (Wolfe, 1994) proposes that attention is pulled across a master map of visual locations, based on activation flowing preattentively from multiple feature maps. That is, attention is probabilistically guided from the highest activation peak to successively lower peaks, with activation summed from "bottom-up" and "top-down" sources. Bottom-up activation accrues from physical differences among stimuli: the more an object differs from its surround, the greater the bottom-up activation to that location. In contrast, the top-down signal represents the subject's knowledge of the features that specify the desired target, expressed as a verbal category (e.g., "red"). If the subject knows the target is red amidst blue and yellow objects, then red features will prompt top-down activation to their locations on the master map.

Despite the "top-down" label, we see little relation between this use of advance knowledge and the attention-control processes we think are central to WMC, because search is proposed here to be passively "pulled" rather than endogenously "pushed." However, there may be some contexts in which top-down control is, in fact, more controlled. Wolfe (1994) proposes that top-down effects may sometimes act to reduce bottom-up contributions to the activation map. For example, if the target is a red horizontal bar amidst many red vertical bars and few green horizontal bars, then color is less diagnostic of the target than is orientation. Based on this knowledge, the bottom-up contribution of orientation could be amplified or that of color reduced. As evidence for this kind of volitional modulation, when experimenters manipulate the proportions of particular non-target features, subjects use this information to speed their search (e.g., Bacon & Egeth, 1997). We wonder whether this top-down ability to amplify or dampen bottom-up influences might vary with WMC, whereas typical conjunction search prevents its expression by presenting equal numbers of non-target types.

With respect to task-set switching, we had many reasons to expect an association with WMC. For example, De Jong (2001) argues that switch costs result largely from periodic failures to engage and maintain goal-related preparation (a parallel to our "goal maintenance" idea). This failure-to-engage hypothesis is supported by findings that variables expected to affect subjects' ability to sustain goals in active memory also affect switch costs. Moreover, mixture models that assume switch trials to produce a distribution of fast RTs on one hand (due to adequate goal maintenance) plus a distribution of slow RTs on the other (due to engagement failures) provide a good fit to the cumulative RT functions from switch trials. As another reason to expect an association with WMC, Allport and Wylie (2000) propose that a proactive interference–like perseveration of task set contributes to switch costs. Using Stroop-like stimuli, they find asymmetrical switch costs that depend more on the difficulty of the task to be switched *from* than the task to be switched to: for example, the cost of switching from color naming to word reading is larger than the reverse. Our findings of WMC span differences in proactive interference might therefore suggest WMC-related differences in switching.

At the same time, however, there are growing concerns that task-set switching may not be the "executive" measure it is widely assumed to be (e.g., Altmann, 2002). To discuss just one specific issue, most switching studies cue the task set for each trial by presenting either its name or an abstract symbol, and this cuing allows ostensibly non-executive encoding and retrieval processes to contaminate measurement of switch cost. Specifically, cuing paradigms confound task and cue switches (Logan & Bundesen, 2003). That is, when subjects switch tasks, the new task is signaled by a cue that is different from the immediately preceding one, whereas task-repeat trials always repeat the cue. Logan and Bundesen argue that these switch costs actually reflect a *benefit of repeating the cue on task-repeat trials*. Their idea is that the cue-plus-stimulus compound, by itself, provides all the information needed to determine a response. No executive process is needed to switch task set, so task-switching paradigms actually require only *one* task: identify the cue and target and use them to retrieve prior stimulus and cue episodes. Critically, when cues repeat, cue identification and retrieval are facilitated, and so task-repeat trials yield faster responses than those of task-switch trials.

Evidence for these ideas comes from experiments in which cues and tasks repeated or switched independently (e.g., Logan & Bundesen, 2003). For example, subjects were cued to make digit-magnitude judgments following the cues *Magnitude* or *HighLow* and parity judgments following the cues *Parity* or *EvenOdd*. When both the cue and task repeated across trials (e.g., *Parity* → *Parity*), RTs were substantially faster than when the cue switched but the task repeated (e.g., *EvenOdd* → *Parity*), indicating a cue-switch cost in the absence of a task switch. Moreover, RTs for cue-switch trials were virtually identical to actual task-switch RTs (e.g., *Magnitude* → *Parity*). Data like these suggest that cue switches are responsible for most of the switch cost observed in cued procedures. Thus, in order to tap truly volitional and executive processes (and to be sensitive to WMC variation), task-switching procedures must eliminate the roles of cue encoding and cue-based retrieval processes.

Summary

It may be surprising, initially, that WMC is unrelated to search slopes and switch costs. And, taken at face value, these null findings may seem to call our "executive attention" theory of WMC into question (see Chapter 3). However, we suggest that our null effects are less surprising when we appreciate the complexity of visual search and task switching. Most task-switching and visual-search paradigms are simply not good indices of executive control, and just because researchers label search and switching tasks as "controlled" or "executive" does not make them so. More broadly, given the number of WMC–attention associations we have observed, we submit that the mere failure to find a correlation between WMC and any particular executive task does not necessarily falsify our view. However, such failures do point to obviously important questions for future research on the nature of both WMC and executive control, and the *tasks that we use to measure them.*

Measuring Working Memory Capacity and Executive Attention

We view WM span tasks as reasonably good measures of executive attention (along with a host of other processes) because their dual-task requirements challenge subjects to maintain access to information outside of conscious awareness, recover access to information that was outside of awareness, or both, all in the face of proactive interference. However, a WMC measure need not be a dual task in order to tax attention control. Indeed, Oberauer and colleagues have shown that a latent factor derived from various "coordination" tasks can be indistinguishable from a "storage-plus-processing" WM span factor (see Chapter 3). These coordination tasks generally require subjects to keep track of a large number of stimuli at the same time, or to rapidly switch attention among these active stimuli, and so they also require maintained access to information that is momentarily outside the focus of attention.

Indeed, prototypical STM span tasks should also make non-negligible demands on executive control, particularly when routinized rehearsal techniques are made ineffective or when the lists are too long to be maintained entirely in conscious focus. In fact, spatial STM tasks, which do not afford phonological rehearsal, seem to be quite good measures of the WMC–executive construct and correlate strongly with general ability (e.g., Kane et al., 2004; see also Chapters 3 and 8, this volume). Moreover, Unsworth and Engle (2006) found that long lists from verbal STM span tasks correlate strongly with all list lengths from verbal WMC span tasks, and long STM lists predict similar variance in Gf, as do long and short WMC lists. Because the focus of attention comprises only about 4 ± 1 items (Cowan, 2001), and because the phonological loop can hold only what can be spoken in about 2 s (Baddeley, 1986), verbal STM lengths larger than four items or so will require some degree of executive attention to be maintained or recovered from outside conscious focus.

By this view, span tasks (or any other memory tasks) cannot be dichotomized as reflecting either STM or WMC, or either storage or executive control, because all immediate memory tasks are complex and determined by a host of factors, including both storage and executive attention. The challenge for researchers of WM variation is to assess the contributions of these various processes to the associations between memory tasks and measures of higher-order cognition (or between these memory tasks and age, or personality, or psychopathology, etc.). We have focused our research on WM span because these tasks have undergone more parametric and task-analytic work than the alternatives, and we suggest that researchers conduct similar explorations of other candidate WMC tasks to move the field forward.

Before leaving a consideration of WMC measurement, we must accept a shortcoming of our view, pointed out in Chapter 3. Our research has demonstrated a strong association between WMC and Gf on one hand, and statistically significant differences between high- and low-span subjects in attention performance on the other hand. From these findings, we have inferred that executive attention processes tapped by WMC tasks are responsible for its covariation with Gf and cognitive ability. Note, however, that there are two important inferences here that require more explicit support, preferably from a latent-variable approach. First, we have not yet established the strength of the correlation between WM span and attention-control measures; our extreme-group designs testing high- vs. low-span subjects may overestimate the WMC effect size. Second, if executive attention is responsible for the covariation between WMC and cognitive ability, then a latent factor comprised of *the shared variance among WMC and attention-control tasks* should predict substantial variance in Gf. At the same time, any remaining, unique WMC and attention-control variance should not correlate with Gf as strongly. If WMC and attention-control constructs correlate weakly, or if shared WMC–attention variance is not a strong predictor of cognitive ability, then our theory is in trouble.

OUR EXECUTIVE ATTENTION VIEW IN RELATION TO OTHER THEORIES

General Theories of Working Memory

Our view is that WM span tasks are complex and determined by many general and domain-specific processes, skills, and strategies. However, variation in WMC, as measured by individual differences in WM span, reflects primarily executive attention capabilities. These executive activities are general and important to a range of intellectual functions, from controlling inappropriate actions, to learning and recalling information amidst competing memories, to solving complex verbal and nonverbal problems. Before we reflect upon particular "competing" perspectives on WMC variation, we first consider our views in light of important nomothetic WM theories, such as Baddeley's "multiple-component" WM theory (Baddeley, 1986, 2000), and Nairne's very different, more process-oriented approach (Nairne, 2002).

The Multiple-Component Working Memory Model

Our theory of WM variation is inspired by Baddeley and Hitch's (1974) demonstration that the cognitive problem of balancing memory storage and ongoing mental activity is central to a range of intellectual capabilities. Moreover, our distinction between general attention processes and domain-specific storage processes is consistent with Baddeley's (1986, 2000) separation of the central-executive (attentional) component from the phonological-loop and visuospatial-sketchpad (storage/rehearsal) components of the WM system.

However, our view differs from the multiple-component model in emphasizing function and process over structure. That is, we view the domain specificity of "STM storage" to reflect different perceptual bases of, and rehearsal activities afforded by, different stimuli. As we stated earlier, our process-oriented view is more akin to Cowan's (1995) conception of immediate memory. "STM" is represented by graded activation of LTM traces (with "focal attention" representing the limited, conscious portion of activated LTM), along with routinized and executive processes that maintain activation. Cowan's model, in turn, closely resembles Wundt's (1912/1973) conception of consciousness. Wundt distinguished *apprehension*, the graded entrance of objects into consciousness, from *apperception*, the entrance of apprehended objects into awareness. In today's terms, Wundt argued that information could remain accessible (or activated) outside attentional focus. Moreover, Wundt claimed, like Cowan, that the focus of attention is strictly limited, whereas above-threshold activation is more broad and variable in scope. These ideas resonate with our claims regarding WMC, particularly that executive processes maintain or recover access to "apprehended" representations of goals, response productions and stimuli in the absence of focal attention or skilled rehearsal routines, and in the presence of interference or conflict.

The Baddeley (1986, 2000) model is most obviously characterized by its structural focus, that is, by its separation of WM into distinct components with different attributes and functions. In general, we are unenthusiastic about such neo-structuralist approaches to memory theorizing. Although Baddeley has been more restrained in proposing structures to account for new dissociations than have LTM researchers, WM structures have begun to proliferate. Theorists now pose separate buffers for semantic information (e.g., Haarmann, Davelaar, & Usher, 2003), visual imagery vs. visual rehearsal (Pearson, 2001), and assigning syntactic structures (Caplan, Waters, and DeDe, Chapter 11). As in LTM research, consensual and specific criteria for proposing new immediate-memory systems are lacking, and we therefore envision an undisciplined explosion of WM buffers as "explanations" for behavior.

Baddeley's (2000, 2001) most recent incarnation of the WM model makes a structural claim that is most relevant to our work. A new subsystem, the "episodic buffer," is proposed to handle some problems for the model, such as how verbal material is maintained under articulatory suppression. The episodic buffer is essentially an immediate-memory version of episodic memory, a mnemonic store for maintenance of integrated, multidimensional representations of objects and events. Of primary concern here, Baddeley (2001) speculates that the episodic buffer underlies performance of WM span tasks: by the multiple-component view, the phonological loop cannot support verbal WM span when the processing-task stimuli are read aloud (and thus provide articulatory suppression). From our perspective, however, the episodic buffer currently offers little to research on WM variation. Baddeley has not yet clarified the buffer's importance to the predictive power of WM span: is it incidental, with the executive driving the correlations, or does the buffer's multimodal nature make it critical to cognition broadly? Furthermore, the "constrained-sentence span" task, designed to measure the capacity of the episodic buffer (Baddeley, 2001), seems a minor variation on the reading span task. We are therefore skeptical that individual-differences research will soon clarify the nature or utility of this new WM component, or vice versa.

Functionalist and Process-Oriented Approaches to Immediate Memory

Our view of immediate memory is less structural than Baddeley's (1986, 2000) model. Nonetheless, we do identify the executive attention processes tapped by WM span tasks with particular brain systems, particularly the circuitry of the dorsolateral prefrontal cortex (dPFC; Kane & Engle, 2002). Moreover, like many cognitive psychologists, we retain a conceptual distinction between immediate memory and LTM, regarding the former as an activated portion of the latter.

Our comfort with the dichotomy of active and inactive memory is not for lack of a good alternative. Research deriving from the verbal-learning and functionalist traditions generally assumed a unitary memory, and neofunctionalist and proceduralist views draw upon this heritage (e.g., Crowder, 1982; Melton, 1963; Toth & Hunt, 1999). According to these accounts, one set of processing rules governs remembering: memory is an activity, not a thing, and remembering over the "short term" and "long term" is identical, despite the phenomenological and folk-psychological distinction. Most recently, Nairne (2002) questioned the activation metaphor of immediate memory, arguing that evidence is wanting for such a special memory state, its loss through decay, and its protection via rehearsal. By Nairne's view, which is widely agreed upon in the study of LTM, memories have no special status outside of a given constellation of cues. Remembering is not determined by the strength of a trace, but rather by the discriminability of the target event amidst competitors, given a specific task environment. In Nairne's "feature model," specifically, all retrieval is governed by the match between environmental cues and the fragile (non-conscious) "processing records" of recent events that are vulnerable to interference. Forgetting thus occurs when the cue and/or processing records fail to uniquely prompt recollection of the target event.

The activation and decay of representations are appealing metaphors for WM research, including that on WM variation. Indeed, our research relies heavily on the activation metaphor to describe the heightened accessibility of information, resulting from rehearsal or executive attention processes, which contributes to various complex cognitive tasks. Nairne (2002) provides compelling arguments and evidence against decay and the protective powers of rehearsal, but we still find the activation concept useful. Heuristically, it provides language with which to describe the ways in which goals may control behavior in the face of conflict, as in Stroop tasks, as well as to conceive of the relation between measures of WM span and attention control more broadly. The feature model, emphasizing cue-driven discrimination among stored processing records, is not easily extended into the domain of WM variation. If WMC reflected such memory-discrimination processes, even if closely tied to interference, we do not yet see how they should relate to reading comprehension, spatial visualization, or moving one's eyes away from a flash. In contrast, the idea that WMC reflects an ability to maintain information in an activated or accessible state during ongoing processing is more easily applied across simple and complex cognitive tasks.[3]

Moreover, recent research suggests a strong link between WMC and dPFC functioning, and in the realm of neuroscience, the activation metaphor is less of a metaphor. For example, individual dPFC cells that are "tuned" to particular locations, objects, rules, or their combinations maintain a pattern of sustained firing over memory delays for their preferred stimuli. What's more, these dPFC cells, unlike those in posterior brain areas, maintain their activity when distracting stimuli are presented during the delay (for a review, see Kane & Engle, 2002). Such target-specific, delay-related activity is difficult to interpret from a neo-functional perspective that denies a special state of activity tied to immediate memory. It fits quite well, however, with our view that executive attention involves the active maintenance of goal-relevant information in the face of interference and distraction.

As an "attentional" example, sustained dPFC activity that is related to goal maintenance predicts Stroop interference. Under functional magnetic resonance imaging (fMRI), MacDonald, Cohen, Stenger, and Carter (2000) presented subjects with word-reading and color-naming Stroop tasks, unpredictably cued 11 s before each stimulus. Fifty percent of the trials were congruent, and so in combination with the frequent word-reading demand, the overall task environment did not reinforce the color-naming goal. On color-naming trials, which demanded an anti-habitual response, dPFC activity increased steadily over the cue-to-target delay and this increase correlated negatively with interference magnitude ($r = -.63$). Subjects who were better able to activate and sustain the "ignore-the-word" goal were also better able to resist interference from the words.

Across memory and attention studies in the neuroscience literatures, then, we see a parallel between neural activity and WM maintenance, and we view these more literal demonstrations of activation as license to use the activation metaphor in describing normal behavioral variation in WMC.

Theories of Variation in Working Memory Capacity

The most popular alternative views of WMC variation that we analyze below, processing-speed and attentional-inhibition theories, have been most widely and successfully applied to studies of life span cognitive development. Indeed, we will claim that, whereas processing speed seems to be important to age-related variation in WMC, it has yet to prove its mettle in accounting for within-age variation. Our discussion of attentional inhibition will be more nuanced and less decisive because, in our view, the inhibition approach is only subtly different from our own. First, however, we briefly consider the overlapping, recently developed views of Oberauer et al. (Chapter 3) and Cowan (2004).

Capacity of Attentional Focus and Region of Direct Access

Although Oberauer et al. (Chapter 3) accept Cowan's (1995) conceptualization of the WM system, as do we, our view of WMC variation is distinguishable from both of these views. Cowan (2005a, 2005b) recently suggested that WMC variation and covariation may reflect the size, or capacity, of attentional focus. Thus, WMC is a true "capacity" by Cowan's view, corresponding to a structural limit in the amount of material that can be held in a particular state, in parallel to the 7 ± 2 capacity limit for STM proposed by Miller (1956). Our view, in contrast, is that high-WMC individuals are not necessarily able to hold more discreet representations in consciousness than are low-WMC individuals, but high spans are better able to actively maintain task-relevant information outside of consciousness and to do the mental work necessary to quickly recover information from inactive memory despite interference.

We see evidence against Cowan's view in two findings of WMC equivalence in ostensible signatures of focused-attention capacity: subitizing and primary memory. Tuholski et al. (2001) found that high- and low-span subjects could enumerate in parallel (or "subitize") an equal number of visual objects (3.35 and 3.25, respectively), but low spans showed a much steeper counting slope *beyond* the subitizing range than that of high spans. Engle, Tuholski et al. (1999) tested subjects in an immediate free-recall task, and their derived estimates of primary memory capacity did not correlate with WMC; only estimates of secondary memory capacity did. Both results suggest that high and low spans can keep a similar number of representations available in the conscious focus of attention. Where they differ, instead, is in processing and recovering representations *outside* attentional focus. Because Oberauer et al. (Chapter 3) equate their "direct-access" component of WM with Cowan's focus of attention, their view that individual differences in WMC and reasoning ability centrally reflect variation in direct access also seems to be contradicted by our findings.

General Processing Speed

General processing-speed (PS) theories broadly propose to account for variation in higher-order cognition via the measurement of latencies from simple cognitive tasks (e.g., Jensen, 1998). The idea is that people with low PS complete fewer mental operations per unit time, and this leads to a failure in completing some critical operations, a greater likelihood of losing the products of processing through decay, or a reduced ability to keep multiple processing streams active via rehearsal or switching. With respect to life span cognitive development, a key finding is that age-related variance in complex cognitive activity, and in WMC, is reduced dramatically after statistically controlling for variance in mean PS (Kail & Salthouse, 1994; see also Chapters 6 and 8, this volume).

However, we have already reported findings from our research indicating that PS is not a promising mechanism for WMC variation among young adults. First, PS measures neither correlate strongly with WMC nor account for the shared variance between WMC and Gf (Conway et al., 2002). Second, studies of retrieval interference find that high and low spans' recognition latencies are equivalent in the absence, but not the presence, of response competition (Conway & Engle, 1994). Indeed, high-span subjects' recall latencies are actually *longer* than those of low-span subjects when the target information had previously been suppressed when related information was learned (Rosen & Engle, 1998). Third, high and low spans' letter-identification latencies are equivalent in the prosaccade task when it was presented before antisaccade (Kane et al., 2001), and span differences in baseline Stroop RTs come and go across experiments independently of interference differences (Kane & Engle, 2003). Fourth, and finally, in visual search and task switching, high and low spans show equivalent RTs in relatively complex conditions with long mean latencies.

Processing-speed theory cannot accommodate these results. However, even if it could be modified to do so without incorporating our theoretical premises, we would remain unenthusiastic because PS theory has yet to provide a reasonably specific *psychological* account for its variation or covariation. Conway, Kane, and Engle (1999) suggested that researchers consider the role of variation in attention control in producing variation in PS within and across age groups (see also Chapter 9). For example, increases in PS–ability correlations with PS task complexity and decreases in PS–ability correlations with task practice seem fit for an attentional explanation. Furthermore, in studies of young adults, individuals' *variability* in RT is often more strongly correlated with cognitive ability than is median RT (Jensen, 1998). Given that RT variability may reflect failures of sustained attention, RT variability may reflect executive-control difficulties. At least among young adults, then, WMC–attention variation might drive PS variation, rather than the reverse.

Attentional Inhibition

Finally, an influential research program by Hasher, Zacks, and colleagues suggests that WM variation derives from the operation of inhibitory attentional mechanisms (e.g., Hasher & Zacks, 1988; see Chapter 9). Their claim is that what appears to be a structurally reduced WMC in some individuals (e.g., the elderly, or young adults at their off-peak hours) actually reflects a *functional* reduction due to the intrusion and persistence of irrelevant information. Inhibitory attention mechanisms, which control cognition by restricting access to and deleting information from WM, often fail with aging and circadian variation. Thus, individuals with ineffective inhibition due to aging, normal individual differences, variation in circadian arousal, or what have you, suffer disproportionately from memory interference, language production and comprehension difficulties, and contextually inappropriate responding. Interference and distraction are thus central problems of control and WM variation.

These ideas have significantly influenced our view of WMC variation, and indeed, the difference between the inhibitory view and ours is quite subtle. Hasher and colleagues argue that WMC variation is driven largely by variation in inhibitory control. As evidence, their microanalytic work has investigated the role of proactive interference in determining WM span scores. In typical "ascending" administrations of reading span, large sets are encountered only after interference from prior trials builds up. Thus, interference-vulnerable individuals, such as the elderly, are disadvantaged on the large sets that are most critical to the span score. Lustig et al. (2001) therefore tested some subjects with an ascending task, proceeding from set-size 2 to 4, and others in a descending task, proceeding from size 4 to 2. Additional young subjects were tested on a descending task with filled breaks between every set to reduce interference further. Lustig et al. found significant age differences in WM span in the ascending but not the descending condition—reducing proactive interference reduced age differences. Furthermore, within age groups, the span condition with the least interference (descending for older adults, descending-with-breaks for younger adults) showed no correlation with reading comprehension. Thus, interference resistance, assumed to reflect inhibition, mediated span correlations with age and ability (see also Bunting, 2006).

We have characterized the executive-attention and attentional-inhibition views as providing a "chicken–egg" dilemma, where one assumes WMC to determine inhibitory control and the other, the reverse (Kane et al., 2001). However, upon further reflection we do not think this is quite right. Instead, whereas the inhibitory view assumes inhibition to determine WMC, we submit that a third variable causes both. Our view is that executive attention processes block sources of interference and competition, as well as keep information active in interference- and conflict-rich contexts and in the service of ongoing cognitive processes. Thus, WMC and inhibition are strongly linked, but indirectly through a more basic attentional construct.

Although interference clearly contributes to particular tests of reading comprehension, WM span predicts performance in many tasks where interference or inhibition are not obviously relevant but active maintenance should be, such as mental rotation, verbal analogies, or counting visual objects (Kane et al., 2004; Tuholski et al., 2001). In addition, our Stroop findings, as well as those reviewed from the neuroscience literature, suggest that PFC maintenance of stimuli and goals allows for effective inhibition under some conditions. We are unsure how inhibition might account for sustained memory-related activity of dPFC cells, increasing dPFC activation prompted by Stroop-task cues, or congruency effects on span differences in Stroop interference. Moreover, if resistance to proactive interference actually reflects inhibition (but for alternative views, see Hasher & Johnson, 1975; Underwood & Ekstrand, 1967), we find that high spans' inhibitory control is impaired by secondary tasks, which suggests that some more fundamental control process governs inhibition (Kane & Engle, 2000). Thus, we believe our more general, "executive attention" view to be more comprehensive than the inhibitory view in accounting for the breadth of the cognitive and neuroscience findings regarding the covariation of WMC with other cognitive activities and abilities.

BOX 2.1. SUMMARY ANSWERS TO BOOK QUESTIONS

1. THE OVERARCHING THEORY OF WORKING MEMORY

Following Cowan (1995), we view WM as an integrated memory and attention system, comprised of long-term memory representations (for stimuli, goals, or action plans) activated above threshold, procedural skills for rehearsal and stimulus coding, and executive attention processes. Activated representations represent the contents of "short-term memory," and a very limited subset of these are experienced as the focus of conscious awareness, or "focused attention." Procedural skills and executive attention are engaged to maintain activation or access to goal-relevant representations, particularly those outside of focused attention, which would otherwise return to baseline as a result of decay or interference.

2. CRITICAL SOURCES OF WORKING MEMORY VARIATION

Variation may occur in any WM component. However, in healthy adults, WM capacity's covariation with general cognitive ability stems from variation in executive attention. Executive attention maintains activation to goal-relevant representations outside of conscious focus, recovers access to non-active representations against interference, and resolves competition between co-active representations or between habitual and goal-appropriate actions. *Macroanalytic,* latent-variable studies suggest that WMC and Gf share substantial variance while controlling for STM. As well, *microanalytic,* quasi-experimental studies indicate that WMC variation predicts individual differences in a variety of memory-interference and attention-control tasks.

3. OTHER SOURCES OF WORKING MEMORY VARIATION

Our executive attention view, emphasizing goal maintenance and competition resolution, parallels the dual mechanisms of cognitive control proposed by Braver et al. (Chapter 4), and is only subtly different from the inhibitory view of Hasher et al. (Chapter 9), who suggest that inhibition drives WMC. We argue that a common attention-control capability underlies WMC and inhibition. However, our view is incompatible with those of others. Although measures of processing speed account for age-related variance in WMC and cognitive ability (see Chapter 8), they do not account for WMC–ability covariation in young adults. In addition, WMC differences do not correspond to measures of focused-attention capacity, but rather to processing beyond conscious focus, contradicting proposals by Cowan (2005a,b) and Oberauer et al. (Chapter 3).

4. CONTRIBUTIONS TO GENERAL WORKING MEMORY THEORY

The study of WMC variation has led the way in fulfilling WM theory's original and greatest promise—to illuminate the *functions* of immediate memory. This work shows that the domain-general, executive components of the WM system support a broad range of cognitive abilities, and may even provide the scaffolding for a cognition-based understanding of intelligence. Correlational research also provides support for the dissociability of domain-specific storage and rehearsal processes and for the idea that domain-specific memory processes and domain-general attention processes are intimately linked (if not synthesized) within the WM system.

Notes

1. Demonstrations of low reliability reported by Caplan et al. (Chapter 11) are troubling. However, Turley-Ames and Whitfield (2003) showed operation span to be reliable over minutes ($rs = .7-.8$), Klein and Fiss (1999) showed it to be reliable over weeks and months ($rs = .7-.8$), and an automated version of operation span had a test-retest reliability of .83 with an average lag of 13 days (Unsworth,

Heitz, Schrock, & Engle, 2005). Of course, strong correlations between WM and cognitive ability measures, reported throughout the literature, also indicate their reliability.

2. In the Kane et al. (2004) model (Fig. 2.4), verbal storage correlated substantially with only verbal reasoning, but spatial storage strongly predicted both spatial and general reasoning. Indeed, the storage–Gf correlation appeared despite the model's controlling for the executive–Gf association. Spatial storage processes thus accounted for as much unique variance in Gf as did executive attention, consistent with correlational evidence that spatial STM tasks are good measures of general ability (see also Chapters 3 and 8).
3. Nairne's approach could be made somewhat more compatible with ours by assuming that executive attention were involved in cue-driven retrieval under interference.

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