3

Attentional Control and Working Memory Capacity

Matt E. Meier and Michael J. Kane

Working memory is a limited-capacity system that operates at the intersection of attention and memory. The capacity of this system (i.e., working-memory capacity [WMC]) is the functional limit on how many memory representations—or how well even one representation—can be kept active in the face of interference and conscious shifts of focus in the service of ongoing cognitive activities. WMC matters: Its variation across people predicts such important skills as reading comprehension (e.g., Daneman & Carpenter, 1980; McVay & Kane, 2012a), following classroom directions (Engle, Carullo, & Collins, 1991), learning computer languages (Kyllonen & Stephens, 1990; Shute, 1991), multitasking (e.g., Bühner, König, Pick, & Krumm, 2006; Hambrick, Oswald, Darowski, Rench, & Brou, 2010), and solving novel problems (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004; Martínez & Colom, 2009). The central role WMC plays in vital intellectual activities has made it an attractive target for interventions to increase its capabilities (for a review, see Melby-Lervag & Holme, 2013; Chapter 28 by Spencer-Smith & Klingberg in this volume).

Why does a chapter focused on WMC belong in a handbook of cognitive control? Because WMC impacts task performance, in part, through associated cognitive control processes. The processes covered within this chapter are examined via traditional 'attention' tasks, so we favour the label *attentional control*. Recently, two large-scale studies, using latent-variable techniques to assess the construct-related variance shared across multiple tasks, examined attentional accounts of WMC's contribution to higher-order cognition (Shipstead, Lindsey, Marshall, & Engle, 2014; Unsworth, Fukuda, Awh, & Vogel, 2014). Each study assessed the contributions of attentional control (using tasks such as antisaccade and Stroop), retrieval from long-term memory (using tasks such as source memory and paired-associate recall), and simple short-term memory (STM; using tasks such as change detection and sub-span immediate-recall tasks). In both studies, the best fitting structural model indicated that the relation between WMC and higher-order cognition was fully mediated by these three correlated factors, with all three factors accounting for substantial unique variance. This multifaceted conception of WMC is analogous to the 'unity and diversity' framework of executive functions advanced by Miyake and Friedman (2012), in which executive functions comprise several correlated but separable factors. That is, WMC represents the interactions of multiple

---

The Wiley Handbook of Cognitive Control, First Edition. Edited by Tobias Egner.

memorial and attentional processes and abilities. Of most importance, here, such studies (see also, Conway et al., 2002; Engle et al., 1999) suggest that attentional control is partly responsible for WMC's prediction of higher-order cognition.

Logic and Function of Individual-Differences Research

Individual-differences research serves an important role in building and testing the nomological net (Cronbach & Meehl, 1955) around the construct of WMC. Instead of viewing between-person variation as unfortunate noise, as in traditional experimental work, individual-difference researchers harness information provided by this variation to reveal critical associations among constructs, to specify boundaries among them, and to test how experimental treatments differentially affect people at different points along some construct (Cronbach, 1957). Underwood (1975) further proposed that individual differences can be used as a 'crucible' for theory construction, whereby individual-differences confirmations of nomothetic-theory predictions provide a 'thumbs up' signal to proceed, but disconfirmations condemn the theory to death. We do not take such a strong stance, as most psychological theories are protected from such falsification via auxiliary hypotheses (Meehl, 1990), but we do regard individual-differences evidence as valuable in testing and sharpening theories, in general, and specifying the relation between WMC and attentional control, in particular.

How Is WMC Measured?

Individual-differences research on WMC is conducted using a variety of tasks: updating (Oberauer, Süß, Schulze, Wilhelm, & Wittmann, 2000), change detection (Luck & Vogel, 1997), and complex span (Conway et al., 2005), most consistently. Complex span tasks have been more intensely studied and validated than other measures (as described below), so this chapter focuses on work operationalising WMC as complex span task performance.

Daneman and Carpenter (1980) developed the first complex span tasks to study the relation between WMC and reading comprehension. The tasks (two visual, one auditory) interleaved a simple memory span task (recall of a short list of items) with a processing task (read aloud or listen to sentences). After each set of 2–6 sentences, subjects recalled the last word from each. Complex span tasks thus required subjects to maintain or retrieve individual words while (or between) comprehending sentences. In two experiments, complex span performance correlated strongly with recalling facts from a story (*r*s = .67–.81), with verbal SAT scores (*r*s = .49–.59), and with passage-ending, pronoun-referent decisions (*r*s = .72–.90). Subsequent work indicated that the relation between complex span tasks and higher-order cognition does not depend on a close match in the stimuli or processing demands between the span task and the higher-order task (e.g., Turner & Engle, 1989). WMC, as measured by complex span tasks, is largely domain general. For example, complex span tasks using varied processing tasks (e.g., arithmetic, spatial rotation, symmetry judgements, counting, judging sensibility of sentences) and memory items (e.g., letters, words, matrix locations, arrow sizes and position) share substantial variance and predict verbal and spatial abilities (Kane et al., 2004).

Complex span scores are reliable, with moderate-to-high internal consistency (0.7–0.9; Conway et al., 2002; Engle et al., 1999; Kane et al., 2004; Unsworth, Heitz, Schrock, & Engle, 2005) and test-retest reliability (0.8–0.9; Klein & Fiss, 1999; Turley-Ames & Whitfield, 2003; Unsworth et al., 2005). Are they also valid? Because individual-differences research is correlational, we must rule out confounding variables that may drive WMC assessments and covariation with other constructs. Two potential confounds that have been investigated deeply are strategy use and effort. Dunlosky and Kane (2007) found that, although subjects performed better on complex span tasks when using normatively effective strategies, strategy usage did *not* statistically mediate the relation between WMC and verbal ability. Strategy use mediated WMC–criterion associations only when the same strategies benefited WMC and criterion tasks (e.g., paired-associate learning but not reading comprehension; Bailey, Dunlosky, & Kane, 2008). Taking a combined differential-experimental approach, Turley-Ames and Whitfield (2003) trained subjects to use an effective strategy and found that training did not close the gap between lower- and higher-WMC groups. Instead, it *increased* it because higher-WMC subjects profited more from training than did lower-WMC subjects. Simply put, strategy use does not drive WMC × complex cognition associations; differential strategy use is, instead, a suppressor variable, obscuring rather than contributing to WMC's covariation with other constructs.

We cannot account for complex span's predictive power by simply appealing to motivation or effort, either. First, Heitz, Schrock, Payne, and Engle (2008) found that when given monetary incentives, previously ascertained lower- and higher-WMC groups both equally improved their complex span performance, thus maintaining the original individual differences; moreover, pupillometry measures indicated equivalent effort expended by the WMC groups in response to both incentives and memory load. Second, Unsworth and McMillan (2013) assessed motivation and interest in a prose-reading task via self-report; they found that WMC was uncorrelated with both and that all three variables made statistically independent contributions to mind wandering while reading. Third, as discussed in detail below, WMC's discriminant validity—its patterns of correlation with some abilities but not others—cannot be explained by mere effort or motivation.

Evidence for the WMC–Attention Association

Evidence for a link between WMC and attentional control comes from two approaches: (1) explorations of the relation between WMC and a particular attentional-control task ('microanalytic'), usually manipulating theoretically relevant variables in the attention task to assess individual-by-treatment interactions; (2) latent-variable studies that use multiple tasks to assess each construct ('macroanalytic'), examining cognitive processes at the construct level by statistically isolating the variance that is shared across the marker tasks.

In an early microanalytic study connecting WMC to attentional control (Kane, Bleckley, Conway, & Engle, 2001), lower- and higher-WMC subjects (defined via complex span) completed an antisaccade task (Hallett, 1978). The antisaccade task required subjects to use an abrupt-onset, flashing cue to direct attention to a backward-masked target (*B*, *P*, or *R*) that subjects identified via key-press. Subjects completed two blocked within-subject conditions: prosaccade, where the target appeared at the cued location, and antisaccade, where the target appeared on the opposite side from the cue. For successful prosaccade performance, subjects could follow the habitual, exogenously driven orienting response. But in the antisaccade condition, subjects had to use endogenous control to either prevent orienting to the cue, or failing that, to quickly disengage from the cue and shift focus to the target. Variation in WMC did *not* predict the more automatic prosaccade performance. But in the antisaccade condition, where endogenous control was necessary to counter prepotency, lower-WMC subjects made more initial saccades towards the cue, and initiated antisaccades more slowly, than did higher-WMC subjects. Of course, the antisaccade task does not require maintaining a large amount of information in memory. WMC's prediction of antisaccade performance thus suggests it reflects more than the sheer amount that can be maintained in memory, but also (or instead) the executive regulation of cognition.

To further explore WMC's association with attention control, Unsworth, Schrock, and Engle (2004, Experiment 2) mixed prosaccade and antisaccade trials in a cued sequence, thus requiring controlled eye movements for each trial type. Lower-WMC subjects were slower and more erroneous on both anti- and prosaccade trials than were higher-WMC subjects. Experiment 3, in a similar vein, manipulated the control requirements of blocked trials by cuing the target location either exogenously (with a peripheral flash) or endogenously (with a central arrow). Lower-WMC subjects performed more poorly than higher-WMC subjects on endogenously cued prosaccade and antisaccade trials, and exogenously cued antisaccade trials, indicating a WMC-related deficit in the voluntary control of attention.

Evidence from latent-variable studies produces a more general type of evidence regarding the processes involved, because the analyses consider the commonality of processes tapped by different measures. Early latent-variable studies of attentional control in WMC examined the relationship between the residual variance from constructs composed of complex span measures after shared variance with STM measures was removed (Conway et al., 2002; Engle et al., 1999). The logic here was that, whereas both STM and WMC tasks require rehearsal and immediate recall of actively maintained stimuli, only WMC tasks do so in the face of the distracting processing task. Both studies found that the residual-WMC variance predicted fluid intelligence (rs = .60 and .49, respectively), supporting the suggestion that $WMC = STM + attentional\ control + measurement\ error$ (Engle et al., 1999). Although the work discussed above, by Shipstead et al. (2014) and Unsworth et al. (2014), further fractionated WMC and suggests that this conceptualisation was too simple, the evidence is still strong that WMC robustly predicts attentional-control capabilities. Recent research assessing the relation between these constructs (by independently measuring attention control in separate tasks, such as antisaccade, Stroop, and flanker) suggests moderate-to-strong correlations in the range of .5–.7 (e.g., Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; McVay & Kane, 2012a; Schweizer & Moosbrugger, 2004; Unsworth et al., 2014).

Characterising WMC-Related Attentional Control

WMC predicts attentional control, but what can we say (if anything) about the nature of attention-control processes and functions? Here, we highlight evidence that contributes to specifying the amorphous construct of attention (Anderson, 2011). Because prior work had demonstrated WMC-related individual differences in tasks that require attentional control (Kane et al., 2001; Kane & Engle, 2003), and prominent models of visual attention propose a role for endogenous, top-down processes (Treisman & Gelade, 1980; Wolfe, 1994), one might expect that higher-WMC subjects would be faster than lower-WMC subjects at visual search, that is, in locating targets within arrays of perceptually similar distractors. Kane, Poole, Tuholski, and Engle (2006) tested this idea in multiple experiments that included feature-absence, conjunction, and spatial-configuration searches. Regardless of search difficulty, they found no WMC effects. Thus, some effortful, controlled-attention tasks relate to WMC, and others do not.

To explore this boundary condition further, Sobel, Gerrie, Poole, and Kane (2007) manipulated a conjunction search task to examine particular top-down and bottom-up contributions. In displays that permitted bottom-up properties (through perceptual grouping) to drive efficient search, WMC again showed no effect. But in conditions where bottom-up influences had to be overcome by top-down strategies for efficient search, higher-WMC subjects had shallower search slopes than lower-WMC subjects. In three experiments, Poole and

Kane (2009) used a modified search paradigm to test whether WMC would predict search in tasks that cued subjects to possible target locations amid distractor locations. They found that WMC predicted search when—and only when—distractors were presented amid the possible target locations, and subjects had to maintain selective focus on those cued locations over a relatively long interval; WMC had no effect in the absence of distractors or when target arrays appeared almost immediately after cuing.

Taken together, the results from Kane et al. (2006), Sobel et al. (2007), and Poole and Kane (2009) suggest that WMC is not related to prototypical visual search, but search task requirements can be manipulated to produce WMC-related individual differences. When top-down control must override the influence of bottom-up processes, block distractor locations, or maintain focus on probable target locations, higher-WMC subjects outperform lower-WMC subjects. The lack of a relation between WMC and typical visual search demonstrates a critical boundary — that WMC is not related to all types of endogenous attentional control—and provided an early glimpse into the contextual nature of WMC-related individual differences.

A Two-Factor Theory of WMC and Cognitive Control

In five experiments using the Stroop (1935) task, in which subjects were presented with colour words displayed in either matching (congruent) or mismatching (incongruent) colours for colour naming, Kane and Engle (2003) manipulated the congruent trial proportion. For example, in Experiment 1, subjects either completed a task with 0% or 75% congruent trials, and in Experiment 2, all subjects first completed a block of 0% congruent trials and then a block of 75% congruent trials. Kane and Engle hypothesised that with a high proportion of congruent trials there is little environmental support for the goal of colour naming, because on most trials subjects can produce correct responses by reading the word. Support for this goal must be maintained endogenously, and so high-congruency conditions should reveal individual differences in goal-maintenance abilities. In low-congruency conditions, much of the endogenous burden of goal maintenance is removed because the frequent incongruent trials serve as goal reminders, but even when this goal is supported by the task context, it still needs to be executed effectively. (For an extensive review on the effects of proportion congruency on interference effects, see Chapter 5 by Bugg in this volume).

Critically, in high-congruency (low-goal-support) conditions, higher- and lower-WMC subjects differed in both the magnitude of error interference (incongruent minus congruent error rate) and reaction time (RT) facilitation (neutral minus congruent RT), with lower-WMC subjects making more errors and experiencing more facilitation than did higher-WMC subjects. Both findings suggest more frequent goal neglect and word-reading responses by lower-WMC subjects. That is, without support from frequent goal reminders (incongruent trials), the task goal was lost, and lower-WMC subjects resorted to the more habitual word reading (which evokes errors on incongruent trials and fast responses on congruent trials).

In contrast, in conditions that were supportive of the task goal (i.e., low proportion congruency), lower-WMC subjects showed only more RT interference than did higher-WMC subjects. These RT interference differences seem to reflect the ability to resolve response competition; that is, subjects executed the correct response, indicating adequate goal maintenance, but lower-WMC subjects took longer to resolve the actual word–colour conflict presented on those incongruent trials. Taken together, these Stroop results provide evidence for a two-factor theory of WMC's influence on attentional control (Engle & Kane, 2004; Kane, Brown et al., 2007). Higher WMC reflects a superior ability to maintain the novel task goal and also to resolve response competition. Kane and Engle's two-factor theory is similar to Braver and colleagues' proposal for dual mechanisms of control (Braver, Gray, & Burgess, 2007; Chapter 9 by Chiew & Braver in this volume), where WMC is related to performance through *proactive*, or anticipatory, control—akin to goal maintenance—and *reactive* control—similar to response competition).

Although the two-factor theory describes WMC-related control as enacted through two empirically dissociable mechanisms, these may not be wholly independent. Both superior goal maintenance and competition resolution could follow from the degree of goal activation. If the goal is maximally activated, it will affect performance in a top-down, proactive manner; if, however, the goal is less highly activated, it may only facilitate performance reactively, when conflict is actually encountered. That is, not only do goal-maintenance abilities (or activation levels) show themselves in preventing outright lapses of attention, but they may also show themselves in responding to conflict in the moment. Botvinick, Braver, Barch, Carter, and Cohen's (2001) model of cognitive control provides a blueprint of how this may work with a more highly activated goal representation biasing perception towards goal-relevant stimulus features and therefore producing better performance than someone using a less activated goal representation.

The Botvinick et al. (2001) model focuses on goal representations biasing performance on a trial-by-trial level. WMC-related attentional-control processes could affect task performance at different levels, however: at the more global, proactive, task-approach level (e.g., Chapter 5 by Bugg in this volume), or at the more local, reactive, trial-by-trial level (Chapter 4 by Egner in this volume). That is, higher-WMC subjects could show superior performance to lower-WMC subjects because of how they interpret and instantiate the task goal at the global level of the whole task. Or, they could excel because they better adjust cognitive-control settings at the local level in response to immediate demands (as in Botvinick et al.). It is therefore possible that the previously observed global effects of WMC on Stroop task performance (e.g., Kane & Engle, 2003) were the cumulative product of local, trial-level (local) WMC effects. One way to determine the level at which WMC-related attentional control exerts its effects to examine trial-level performance via congruency transitions between trials (e.g., Gratton, Coles, & Donchin, 1992), referred to here as congruency-sequence effects (for a review, see Egner, 2007; Chapter 4 by Egner in this volume). Congruency-sequence effects are often used as markers of in-the-moment cognitive control.

Work that has assessed the dynamics of WMC's association with attentional control has tested for its moderation of congruency-sequence effects. The results have been mixed. Using Stroop tasks, flanker tasks, or both, WMC has not predicted congruency-sequence effects (Keye, Wilhelm, Oberauer, & van Ravenzwaaij, 2009; Meier & Kane, 2013; Unsworth, Redick, Spillers, & Brewer, 2012). In Simon tasks, however, lower-WMC subjects exhibited more reactivity to the congruence of the prior trial when processing the current trial (Keye et al., 2009; Weldon, Mushlin, Kim, & Sohn, 2013). Finally, in a task that contained some trials that presented flanker-like conflict (i.e., conflict between stimulus features) and other trials that presented Simon-like conflict (i.e., conflict between stimulus and response features), Meier and Kane (in press) found no link between WMC and congruency-sequence effects in either trial type. The discrepancies among Simon-task findings from Meier and Kane, Keye et al., and Weldon et al. may be the product of different task approaches cultivated by the mixed trial presentation used by Meier and Kane versus the blocked presentations used by others. That is, subjects may set up different goal representations when performing blocked versus mixed trial tasks, and these may yield downstream performance differences. We suggest, in any case, that trial-to-trial calibrations of control do not drive the relation between WMC and attention-control tasks. The association seems to be caused, instead, by control at the global level of the task.

WMC and Goal Maintenance, Response Time Variability, and Mind Wandering

Off-task thoughts, or mind wandering, may indicate that the task goal has become dislodged or diminished in activation, and so we might expect lower-WMC subjects to mind-wander more frequently. Kane et al. (2007) pretested participants on WMC and later recruited them to carry personal digit assistants (PDAs) for one week. To provide information on the frequency and contextual predictors of mind wandering, the PDA beeped eight times a day prompting subjects to report whether or not their thoughts had wandered from their primary task. This question was followed by Likert-type questions about their context. Kane et al. found that, only as activities required more self-reported concentration, challenge, and effort did higher-WMC subjects better maintain the goal of the task at hand and resist mind wandering. Subsequent laboratory work has found that attentional lapses in the form of mind wandering (i.e., lapses of goal maintenance) partially mediate the relation between WMC and reading comprehension (McVay & Kane, 2012b) and SAT scores (Unsworth, Brewer, & Spillers, 2012; Unsworth, McMillan, Brewer, & Spillers, 2012).

Laboratory studies have also revealed a contextually determined relation between WMC and mind wandering. McVay and Kane (2009) used a variant of a go/no-go task to examine the relation. In this 45 min task, subjects responded via key-press to all stimuli except for infrequent targets (11% of trials). Mind wandering, assessed with task-embedded thought probes, accounted for approximately 50% of the covariation between WMC and task accuracy. A follow-up study (McVay & Kane, 2012a) also found that mind wandering partially mediated the relationship between WMC and go/no-go accuracy, and further investigated whether WMC's relation to performance differed according to task demands. They contrasted WMC relations on the go/no-go task, which required frequent responding to nontargets and rare withholding of responses to targets, to performance on a vigilance version of the task, which required withholding responses to the frequent nontargets and responding to the rare targets. In the go/no-go task, control over habitual responding (repeatedly pressing the space bar) is at a premium on critical no-go trials (see Chapter 6 by Verbruggen & Logan in this volume), whereas in the vigilance task, the level of interference is minimal. WMC variation related positively to accuracy and negatively to mind wandering in the go/no-go task, but was unrelated to both performance and mind wandering in the vigilance task. Here again, it seems that there needs to be a sufficient level of interference, conflict, or challenge in the task for WMC-related individual differences to arise (for similar mind-wandering findings, see Levinson, Smallwood, & Davidson, 2012; Rummel & Boywitt, 2014).

Although goal activation may be continuous, the binary/dichotomy account and continuum accounts have yet to be empirically distinguished. What we do know is that lower-WMC subjects, in addition to reporting more mind wandering and making more overt errors in tasks like the high-congruency Stroop, also respond more variably in RT tasks than do higher-WMC subjects. In both McVay and Kane (2009, 2012a) go/no-go tasks, within-subject RT variability on 'go' trials correlated negatively with WMC and positively with mind wandering. That is, lower-WMC subjects appeared to have trouble maintaining the goal of the task relative to higher-WMC subjects on some, but not all, trials (see also Unsworth, Redick, Lakey, & Young, 2010). Consistent with this idea, formal evidence-accumulation modelling indicated that the parameter reflecting trial-to-trial variation in drift rate correlated with WMC, mind-wandering rate, and RT variability (McVay & Kane, 2012b). Taking a latent-variable approach, Unsworth (2015) analysed data from several studies where subjects completed WMC tasks, mind-wandering probes, attentional-control tasks, and lexical-decision tasks. RT variability from the attentional-control tasks, but not the lexical-decision tasks, correlated significantly with WMC and mind-wandering constructs. WMC measures thus appear to index attentional abilities that predict the consistency with which one can maintain a novel task goal. These findings do not distinguish between dichotomous and continuous accounts of goal maintenance, but they do help visualise goal activation as waxing and waning in strength across attentionally demanding contexts.

WMC and Response Competition

Although considerable work has examined WMC and goal maintenance, much less has studied WMC and response competition. We recently explored whether WMC predicted resolving interference between competing stimulus elements, resolving interference between competing stimulus and response elements, or both (Meier & Kane, 2015). Put differently, we tested whether WMC resolved interference early, late, or throughout the information processing sequence, under the assumption that stimulus-stimulus (S-S) interference affects stimulus selection and/or identification (i.e., early), and stimulus-response (S-R) interference affects response selection and/or motor execution (i.e., late; see Kornblum, 1992; Kornblum, Hasbroucq, & Osman, 1990). To focus on response competition, subjects completed a task with one task goal that was reinforced by many conflict trials, but that elicited different types of interference. In this way, any WMC-related differences that we found between S-S and S-R interference types should primarily reflect competition-resolution processes and not goal-maintenance processes.

Subjects completed a task where different trials presented either S-S or S-R conflict. On each trial, subjects saw an upward- or a downward-pointing arrow that was either below or above, or to the left or right, of fixation (all equidistant from the centre). They reported whether the arrow pointed up or down with a left or right key-press. The irrelevant stimulus dimension of arrow location to the left or right of fixation overlapped with the horizontally oriented key-press responses. Thus, S-R conflict occurred when the arrow appeared on the opposite side of the screen from the appropriate response key. On trials where the arrow was above or below the screen's midpoint, however, the irrelevant (vertical location) and relevant (arrow direction) *stimulus* dimensions overlapped. S-S conflict thus occurred on trials where the arrow direction conflicted with the arrow location (e.g., an upward arrow presented below fixation; a downward arrow above fixation). For both trial types, though, stimulus location was always irrelevant, and the goal was the same.

In two experiments with 50% incongruent trials (half horizontally oriented and half vertically oriented), we found that WMC predicted conflict resolution RTs on S-S trials but not on S-R trials. That is, higher-WMC subjects were better able than lower-WMC subjects to combat the interference created from the S-S conflict of identifying upward arrows located below fixation and downward arrows above fixation. However, higher-WMC subjects were no better than lower-WMC subjects at resolving S-R conflict created from the arrows appearing contralateral to the response key; that is, WMC did not predict resolution of interference when the right key was needed to respond to an arrow on the left, or vice versa (if anything, lower-WMC subjects made fewer errors than higher-WMC subjects under S-R conflict).

Moreover, these S-S versus S-R patterns held on trials that presented combinations of stimulus-stimulus and stimulus-response conflict (Meier & Kane, 2015, Experiment 1). These trials presented an arrow that was slightly above or below the screen's midpoint as well as either slightly to the left or the right of centre (e.g., between 10:00 and 11:00 on a clock face). Here, again, WMC was only related to the resolution of S-S and not S-R interference. WMC's selective association with resolving S-S but not S-R competition indicates that higher-WMC subjects are better able than lower-WMC subjects, in early information processing stages, to identify and select relevant information amid distractions. However, in another experiment in which subjects completed the same task, but with 80% congruent trials to put a premium on goal maintenance for successful performance, a different pattern emerged. Consistent with the two-factor theory of WMC and executive control, higher-WMC subjects exhibited less S-S *and* S-R interference, presumably because they were better able to maintain the task goal in an accessible enough state to influence competition resolution. Task context can clearly tip the balance between the importance of goal-maintenance and response-competition processes, and therefore where WMC has its effects.

In addition to goal-maintenance abilities, the precise competition-resolution mechanisms through which WMC affects performance on S-S but not S-R conflict trials are not well understood. Early speculation has focused on WMC-related interference reduction mechanisms that are focused on removing items from working memory that interfere with stimulus representations but not response representations, and on the relevancy of task features to successful task completion. In Meier and Kane's (2015) arrow task, left-right location codes were necessary for response selection (i.e., action planning) and therefore were not truly task irrelevant, in contrast to location information present on trials where the arrow was presented on the vertical plane. Thus, higher-WMC subjects may be better than lower-WMC subjects at coping with 'pure' task-irrelevant interference.

WMC-Related Constraint of Visual Attention

Although it does not seem to be able to account for the S-S and S-R conflict dissociation, or the findings from antisaccade tasks, WMC also seems related to the precision and speed of selective visual attention. Bleckley, Durso, Crutchfield, Engle, and Khanna (2003) first demonstrated that WMC variation predicts how visual attention is spatially configured. From brief, masked displays, subjects identified a centrally presented target letter and then localised another displaced letter that could appear on one of three concentric rings around the central letter. The ring on which the displaced letter would appear was validly cued on 80% of trials with the words *close*, *medium*, or *distant*. Consider an invalidly cued trial where the subject receives a *distant* cue (i.e., the cue for the farthest ring from the centre). The subject should configure her attention to the screen's centre (for central letter identification) and the distant ring (for displaced target localisation), but not to the close or middle rings. When the target then appears unexpectedly on, say, the middle ring, subjects who were more tightly focused on just the distant ring should perform worse than the subject who was unable to deploy their attention as precisely and instead attended to the whole area from the outer ring to the centre. Bleckley et al. found that, for all subjects, invalidly cued letters occurring outside the cued ring were poorly localised (67% correct). Of most importance, however, lower-WMC subjects localised invalidly cued letters *inside* the cued ring better than did higher-WMC subjects (72% vs. 64%), suggesting that higher-WMC subjects configured their attention discontiguously (encompassing only the cued ring and centre location, but not in between), whereas lower-WMC subjects deployed their visual attention more diffusely, in a spotlight formation extending to the cued ring. Subsequent work by Bleckley, Foster, and Engle (2015) found that under a secondary memory load, higher-WMC subjects were no longer able to deploy their attention discontiguously in the ring-cuing task. The load task thus disrupted the more exquisite control that higher-WMC subjects had been normally able to use to configure their attention discontiguously.

These memory-load findings are consistent with those from Ahmed and de Fockert (2012, Experiment 2), who examined interference effects in a modified flanker task with higher- and lower-WMC groups under different working-memory load conditions. For low load, subjects recalled six digits in ascending order and for high load, six digits in random nonsequential order. In this flanker task, subjects reported whether the target on each trial was an X or a Z, while another (congruent or incongruent) flanking letter appeared above, below, or to the left or right of this target. The flanker was placed at one of four distances from the target on a given trial. Lower-WMC subjects and those under high load showed patterns of interference consistent with a more dispersed field of visual attention. That is, under these conditions, subjects were less able to constrain their attention to just the likely target location than were higher-WMC and low-load subjects, showing greater interference from incongruent flankers that appeared farther from the target.

In a more prototypical flanker task (Eriksen & Eriksen, 1974), subjects must identify a central target stimulus among a fixed horizontal array of flanking nontarget stimuli, and the flankers can match or mismatch the target. In congruent trials, the target and flanking stimuli match (e.g., SSSSS); in incongruent trials, the target and flanking stimuli do not match (e.g., HHSHH). Responding is slowed on incongruent trials compared to congruent trials and, because the target is typically in the centre of the horizontal array, uncertainty of target stimulus location, or visual search, cannot explain this slowing.

Higher-WMC subjects are also faster to constrain their attention to targets amid flanking distractors (Heitz & Engle, 2007). Heitz and Engle's (2007) design was based on previous work by Gratton, Coles, Sirevaag, Eriksen, and Donchin (1988), who examined the time course of information processing. The Gratton et al. results were consistent with a dynamic spotlight (or zoom lens) view of attention, where attention starts out in a diffuse state that permits information from both the target and distractors to enter the system. As time elapses, the focus of attention closes in on the target, limiting the influence of the response-incongruent distractors. Gratton et al. demonstrated this by examining conditional accuracy functions. In both congruent and incongruent trials, the fastest bin of trials was completed with chance accuracy. On incongruent but not congruent trials, the next fastest bin was performed at *below-chance* accuracy. This dip below chance suggests that visual focus has yet to be constrained to the target, so responses were based on the identity of the (incongruent) flanking stimuli. After this below-chance dip, performance gradually increased, and at the slowest RTs, the flanker effect (the difference in accuracy between congruent and incongruent trials) disappeared.

Heitz and Engle's (2007) findings paralleled those of Gratton et al. (1988), but of most importance, higher- and lower-WMC groups differed in performance at the intermediate time points on incongruent trials, while performing similarly on very fast and very slow incongruent trials and congruent trials. This pattern of results—equivalence at the fastest and slowest RTs, but WMC-related differences at the intermediate time points—provides evidence that higher-WMC subjects constrained their focus to the target more quickly than did lower-WMC subjects.

Conclusions

WMC is a strong predictor of higher-order cognition, due in part to the contributions of attention-control capabilities. We propose that these attentional-control mechanisms are arranged hierarchically with goal maintenance at the top and task-specific competition-resolution mechanisms, and the speed and precision of visual attention, below. In many ways, this proposal is similar to the Botvinick et al. (2001) conflict adaptation model, with (at least) one critical difference: WMC-related cognitive control is initiated in a more top-down manner (from goals instantiated from task objectives) rather than in response to local conflict. Variation in WMC predicts who is best able to maintain (or activate) the goal as well as implement some forms of attentional control to combat response competition. A theme that runs through much of the work presented here is that the WMC-attentional-control relationship is moderated by context, with WMC-related individual differences only being revealed in specific contexts, such as those that are rich in interference. More work is needed, however, to refine our understanding of the thresholds between contexts that trigger WMC-related control and those that do not.

References

Ahmed, L., & de Fockert, J. W. (2012). Focusing on attention: The effects of working memory capacity and load on selective attention. *PLoS ONE*, *7*(8), e43101.

Anderson, B. (2011). There is no such thing as attention. *Frontiers in Psychology*, *2*, 246.

Bailey, H., Dunlosky, J., & Kane, M. J. (2008). Why does working memory span predict complex cognition? Testing the strategy affordance hypothesis. *Memory & Cognition*, *36*(8), 1383–1390.

Bleckley, M. K., Durso, F. T., Crutchfield, J. M., Engle, R. W., & Khanna, M. M. (2003). Individual differences in working memory capacity predict visual attention allocation. *Psychonomic Bulletin and Review*, *10*, 884–889.

Bleckley, M. K., Foster, J. L., & Engle, R. W. (2015). Working memory capacity accounts for the ability to switch between object-based and location-based allocation of visual attention. *Memory & Cognition*, *43*(3), 379–388.

Braver, T. S., Gray, J. R., & Burgess, G. C. (2007). Explaining the many varieties of working memory variation: Dual mechanisms of cognitive control. In A. R. A. Conway, C. Jarrold, M. J. Kane, A. Miyake, & J. N. Towse (Eds.), *Variation in Working Memory* (pp. 76–106). New York: Oxford University Press.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624–652.

Bühner, M., König, C., Pick, M., & Krumm, S. (2006). Working memory dimensions as differential predictors of the speed and error aspect of multitasking performance. *Human Performance*, *19*(3), 253–275.

Colom, R., Abad, F. J., Quiroga, M. Á., Shih, P. C., & Flores-Mendoza, C. (2008). Working memory and intelligence are highly related constructs, but why? *Intelligence*, *36*(6), 584–606.

Conway, A. R. A., Cowan, N., Bunting, M. F., Therriault, D., & Minkoff, S. (2002). A latent variable analysis of working memory capacity, short term memory capacity, processing speed, and general fluid intelligence. *Intelligence*, *30*, 163–183.

Conway, A. R., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review*, *12*(5), 769–786.

Cronbach, L. J. (1957). The two disciplines of scientific psychology. *American Psychologist*, *12*, 671–684.

Cronbach, L. J., & Meehl, P. E. (1955). Construct validity in psychological tests. *Psychological Bulletin*, *52*, 281–302.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, *19*, 450–466.

Dunlosky, J., & Kane, M. J. (2007). The contributions of strategy use to working memory span: A comparison of strategy-assessment methods. *Quarterly Journal of Experimental Psychology*, *60*(9), 1227–1245.

Egner, T. (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective, & Behavioral Neuroscience*, *7*(4), 380–390.

Engle, R. W., Carullo, J. J., & Collins, K. W. (1991). Individual differences in working memory for comprehension and following directions. *Journal of Educational Research*, *84*, 253–262.

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. *Psychology of Learning and Motivation*, *44*, 145–199.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory and general fluid intelligence: A latent variable approach. *Journal of Experimental Psychology: General*, *128*, 309–331.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target in a non-search task. *Perception and Psychophysics*, *16*, 143–149.

Gratton, G., Coles, M. G., & Donchin, E. (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General*, *121*(4), 480–506.

Gratton, G., Coles, M. G. H., Sirevaag, E. J., Eriksen, C. W., & Donchin, E. (1988). Prestimulus and poststimulus activation of response channels: A psychophyiological analysis. *Journal of Experimental Psychology: Human Perception and Performance*, *14*, 331–344.

Hallett, P. E. (1978). Primary and secondary saccades to goals defined by instructions. *Vision Research*, *18*(10), 1279–1296.

Hambrick, D. Z., Oswald, F. L., Darowski, E. S., Rench, T. A., & Brou, R. (2010). Predictors of multitasking performance in a synthetic work paradigm. *Applied Cognitive Psychology*, *24*(8), 1149–1167.

Heitz, R. P., & Engle, R. W. (2007). Focusing the spotlight: Individual differences in visual attention control. *Journal of Experimental Psychology: General*, *136*, 217–240.

Heitz, R. P., Schrock, J. C., Payne, T. W., & Engle, R. W. (2008). Effects of incentive on working memory capacity: Behavioral and pupillometric data. *Psychophysiology*, *45*(1), 119–129.

Kane, M. J., Bleckley, M. K., Conway, A. R. A., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General*, *130*, 169–183.

Kane, M. J., Brown, L. E., McVay, J. C., Silvia, P. J., Myin-Germeys, I., & Kwapil, T. R. (2007). For whom the mind wanders, and when: An experience-sampling study of working memory and executive control in daily life. *Psychological Science*, *18*, 614–621.

Kane, M. J., Conway, A. R. A., Hambrick, D. Z., & Engle, R. W. (2007). Variation in working memory as variation in executive attention and control. In A. R. A. Conway, C. Jarrold, M. J. Kane, A. Miyake, & J. N. Towse (Eds.), *Variation in working memory* (pp. 21–48). New York: Oxford University Press.

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General*, *132*(1), 47–70.

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: A latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology-General*, *133*(2), 189–217.

Kane, M. J., Poole, B. J., Tuholski, S. W., & Engle, R. W. (2006). Working memory capacity and the top-down control of visual search: Exploring the boundaries of 'executive attention'. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*, 749–777.

Keye, D., Wilhelm, O., Oberauer, K., & van Ravenzwaaij, D. (2009). Individual differences in conflict-monitoring: Testing means and covariance hypothesis about the Simon and the Eriksen Flanker task. *Psychological Research*, *73*(6), 762–776.

Klein, K., & Fiss, W. H. (1999). The reliability and stability of the Turner and Engle working memory task. *Behavior Research Methods, Instruments and Computers*, *31*, 429–432.

Kornblum, S. (1992). Dimensional overlap and dimensional relevance in stimulus-response and stimulus- stimulus compatibility. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior II* (pp. 743–777). Amsterdam, North Holland: Elsevier Press.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility—A model and taxonomy. *Psychological Review*, *97*, 253–270.

Kyllonen, P. C., & Stephens, D. L. (1990). Cognitive abilities as determinants of success in acquiring logic skill. *Learning and Individual Differences*, *2*, 129–160.

Levinson, D. B., Smallwood, J., & Davidson, R. J. (2012). The persistence of thought evidence for a role of working memory in the maintenance of task-unrelated thinking. *Psychological Science*, *23*(4), 375–380.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*(6657), 279–281.

Martínez, K., & Colom, R. (2009). Working memory capacity and processing efficiency predict fluid but not crystallized and spatial intelligence: Evidence supporting the neural noise hypothesis. *Personality and Individual Differences*, *46*, 281–286.

McVay, J. C., & Kane, M. J. (2009). Conducting the train of thought: Working memory capacity, goal neglect, and mind wandering in an executive-control task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(1), 196–204.

McVay, J. C., & Kane, M. J. (2012a). Drifting from slow to 'd'oh!': Working memory capacity and mind wandering predict extreme reaction times and executive control errors. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*(3), 525–549.

McVay, J. C., & Kane, M. J. (2012b). Why does working memory capacity predict variation in reading comprehension? On the influence of mind wandering and executive attention. *Journal of Experimental Psychology: General*, *141*(2), 302–320.

Meehl, P. E. (1990). Appraising and amending theories: The strategy of Lakatosian defense and two principles that warrant it. *Psychological Inquiry*, *1*(2), 108–141.

Meier, M. E., & Kane, M. J. (2013). Working memory capacity and Stroop interference: Global versus local indices of executive control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(3), 748–759.

Meier, M. E., & Kane, M. J. (2015). Carving executive control at its joints: Working memory capacity predicts stimulus-stimulus, but not stimulus-response, conflict. Journal of Experimental Psychology*: Learning, Memory, and Cognition*.

Melby-Lervåg, M., & Hulme, C. (2013). Is working memory training effective? A meta-analytic review. *Developmental Psychology*, *49*(2), 270–291.

Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions: Four general conclusions. *Current Directions in Psychological Science*, *21*, 8–14.

Oberauer, K., Süß, H. M., Schulze, R., Wilhelm, O., & Wittmann, W. W. (2000). Working memory capacity—Facets of a cognitive ability construct. *Personality and Individual Differences*, *29*(6), 1017–1045.

Poole, B. J., & Kane, M. J. (2009). Working memory capacity predicts the executive control of visual search among distractors: The influences of sustained and selective attention. *Quarterly Journal of Experimental Psychology*, *62*, 1430–1454.

Rummel, J., & Boywitt, C. D. (2014). Controlling the stream of thought: Working memory capacity predicts adjustment of mind-wandering to situational demands. *Psychonomic Bulletin & Review*, *21*(5), 1309–1315.

Schweizer, K., & Moosbrugger, H. (2004). Attention and working memory as predictors of intelligence. *Intelligence*, *32*(4), 329–347.

Shipstead, Z., Lindsey, D. R., Marshall, R. L., & Engle, R. W. (2014). The mechanisms of working memory capacity: Primary memory, secondary memory, and attention control. *Journal of Memory and Language*, *72*, 116–141.

Shute, V. J. (1991). Who is likely to acquire programming skills? *Journal of Educational Computing Research*, *7*, 1–24.

Sobel, K. V., Gerrie, M. P., Poole, B. J., & Kane, M. J. (2007). Individual differences in working memory capacity and visual search: The roles of top-down and bottom-up processing. *Psychonomic Bulletin & Review*, *14*, 840–845.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643–662.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*, 97–136.

Turley-Ames, K. J., & Whitfield, M. M. (2003). Strategy training and working memory task performance. *Journal of Memory and Language*, *49*, 446–468.

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language*, *28*, 127–154.

Underwood, B. J. (1975). Individual differences as a crucible in theory construction. *American Psychologist*, *30*, 128–134.

Unsworth, N. (2015). Consistency of attentional control as an important cognitive trait: A latent variable analysis. *Intelligence*, *49*, 110–128.

Unsworth, N., Brewer, G. A., & Spillers, G. J. (2012). Variation in cognitive failures: An individual differences investigation of everyday attention and memory failures. *Journal of Memory and Language*, *67*(1), 1–16.

Unsworth, N., Fukuda, K., Awh, E., & Vogel, E. K. (2014). Working memory and fluid intelligence: Capacity, attention control, and secondary memory retrieval. *Cognitive Psychology*, *71*, 1–26.

Unsworth, N., Heitz, R. C., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods*, *37*, 498–505.

Unsworth, N., & McMillan, B. D. (2013). Mind wandering and reading comprehension: Examining the roles of working memory capacity, interest, motivation, and topic experience. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(3), 832–842.

Unsworth, N., McMillan, B. D., Brewer, G. A., & Spillers, G. J. (2012). Everyday attention failures: An individual differences investigation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*(6), 1765–1772.

Unsworth, N., Redick, T. S., Lakey, C. E., & Young, D. L. (2010). Lapses in sustained attention and their relation to executive control and fluid abilities: An individual differences investigation. *Intelligence*, *38*, 111–122.

Unsworth, N., Redick, T. S., Spillers, G. J., & Brewer, G. A. (2012). Variation in working memory capacity and cognitive control: Goal maintenance and microadjustments of control. *The Quarterly Journal of Experimental Psychology*, *65*(2), 326–355.

Unsworth, N., Schrock, J. C., & Engle, R. W. (2004). Working memory capacity and the antisaccade task: Individual differences in voluntary saccade control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*, 1302–1321.

Weldon, R. B., Mushlin, H., Kim, B., & Sohn, M. H. (2013). The effect of working memory capacity on conflict monitoring. *Acta Psychologica*, *142*(1), 6–14.

Wolfe, J. M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review*, *1*, 202–238.