Variation in working memory capacity and cognitive control: Goal maintenance and microadjustments of control

Nash Unsworth [a] , Thomas S. Redick [b] , Gregory J. Spillers [a] & Gene A. Brewer [c]

[a] Department of Psychology, University of Oregon, Eugene, OR, USA

[b] School of Psychology, Georgia Institute of Technology, Atlanta, GA, USA

[c] Department of Psychology, Arizona State University, Tempe, AR, USA

PLEASE SCROLL DOWN FOR ARTICLE

Psychology Press
Taylor & Francis Group

Variation in working memory capacity and cognitive control: Goal maintenance and microadjustments of control

Nash Unsworth[1], Thomas S. Redick[2], Gregory J. Spillers[1], and Gene A. Brewer[3]

[1]Department of Psychology, University of Oregon, Eugene, OR, USA
[2]School of Psychology, Georgia Institute of Technology, Atlanta, GA, USA
[3]Department of Psychology, Arizona State University, Tempe, AR, USA

Variation in working memory capacity (WMC) and cognitive control was examined in four experiments. In the experiments high- and low-WMC individuals performed a choice reaction time task (Experiment 1), a version of the antisaccade task (Experiment 2), a version of the Stroop task (Experiment 3), and an arrow version of the flanker task (Experiment 4). An examination of response time distributions suggested that high- and low-WMC individuals primarily differed in the slowest responses in each experiment, consistent with the notion that WMC is related to active maintenance abilities. Examination of two indicators of microadjustments of control (posterror slowing and conflict adaptation effects) suggested no differences between high- and low-WMC individuals. Collectively these results suggest that variation in WMC is related to some, but not all, cognitive control operations. The results are interpreted within the executive attention theory of WMC.

Keywords: Cognitive control; Working memory capacity; Individual differences.

Cognitive control, the ability to guide processing and behaviour in the service of task goals, is a fundamental aspect of the cognitive system and is thought to be important for a number of higher level functions. Important components of cognitive control include actively maintaining task goals, selectively and dynamically updating task goals, detecting and monitoring conflict, and making adequate control adjustments in the presence of conflict (Cohen, Aston-Jones, & Gilzenrat, 2004). These components are thought to influence processing in a wide range of tasks and situations. As such, the ability to effectively utilize cognitive control should be an important determinant of an individual's performance in such situations. Recent research has suggested that individual differences in working memory capacity (WMC) reflect basic differences in cognitive control (Engle & Kane, 2004), and these differences largely account for the strong and consistent correlation between WMC and fluid intelligence (e.g., Engle, Tuholski, Laughlin, & Conway, 1999). However, the precise cognitive control components that are related to WMC differences are still not well understood. The goal

of the present study was to better examine WMC differences in cognitive control in order to better determine which cognitive control components are related to variation in WMC.

Cognitive control, conflict monitoring, and microadjustments in control

A prominent theory of cognitive control suggests that cognitive control is implemented by the prefrontal cortex (PFC) in situations where task goals have to be actively maintained and dynamically updated (Miller & Cohen, 2001). In this theory top-down attention control processes are needed to maintain task goals and bias responding so that appropriate behaviour is executed. In many situations, participants will have to actively maintain a novel task goal that is in direct opposition to prepotent response tendencies (Roberts & Pennington, 1996). If there is a failure of active goal maintenance, then it is likely that prepotent response tendencies will guide behaviour, leading to the execution of the incorrect response leading to goal neglect (Duncan, 1995). That is, in situations when attention is tightly focused on the task goal, performance will be both fast and accurate. However, if attention is not tightly focused on the task goal, goal neglect can occur, which will lead to overall slower responses or to very fast errors that are guided by prepotent tendencies. For instance, consider the Stroop task. In this task participants are required to name the colour in which colour names are printed. When the colour and the word match (e.g., red presented in red ink), the task is quite easy. However, when the colour and the word conflict (e.g., blue presented in red ink), both reaction time and error rates increase. According to views of cognitive control, because the prepotent response conflicts with the task goal (e.g., "Say the colour not the word"), a loss of goal maintenance (perhaps due to a lapse in attention) should result in the prepotent response guiding behaviour and hence the occurrence of fast word-naming errors or slower overall response times (Cohen, Dunbar, & McClelland, 1990).

A similar situation occurs in the antisaccade task, in which participants are required to fixate on a central cue, and after a variable amount of time, a flashing cue appears either to the right or to the left of fixation (Hallet, 1978; see Everling & Fischer, 1998, for a review). With the onset of the flashing cue, the participant's task is to shift their attention and gaze to the opposite side of the screen as quickly and accurately as possible. According to cognitive control views, it is critically important to maintain the task goal ("if flash on the left—look right") in order to successfully perform the task given that the required response is directly opposite to the habitual response (i.e., looking at the flashing cue). Thus, any lapses in attention (or intention) will result in the prepotent response guiding behaviour and hence the occurrence of a fast reflexive error (i.e., looking at the flashing cue; Unsworth, Schrock, & Engle, 2004), or a much slower than normal response time. Thus, according to cognitive control theories, cognitive control is needed to actively maintain task goals in order to bias responding to ensure that the correct response is executed. Of course, other potential sources of errors are likely to occur in this type of task. For instance, errors can occur due to failures to inhibit the incorrect response or due to motor selection problems. What is important for the current discussion is that lapses in attention potentially account for some of the errors found in these types of tasks.

In addition to assuming that active goal maintenance is important, recent work has also suggested that a critical component of cognitive control is the ability to monitor and detect conflict and to adjust current control settings in response to the presence of conflict (Botvinick, Braver, Barch, Carter, & Cohen, 2001). Specifically, according to the conflict-monitoring framework (Botvinick et al., 2001), the anterior cingulate cortex (ACC) monitors and detects conflict between competing responses. If conflict is detected, the ACC signals the PFC to adjust its current control settings in proportion to the amount of conflict detected. Thus, ACC is important for monitoring for conflict and signalling for the recruitment of cognitive control, but it is the PFC that actually implements that

control (see Carter & van Veen, 2007, for a review). This theory suggests that while the PFC is actively maintaining task goals throughout the task, if conflict is detected by the ACC, the PFC will make microadjustments of control (Ridderinkhof, 2002) in order to ensure that the control settings are appropriate for upcoming trials. Important evidence for the conflict-monitoring framework and for the notion of microadjustments of control comes from the finding that participants performance on the current trial (trial n) is determined, in part, on what occurred on trial $n-1$. That is, speed and accuracy on the current trial is related to performance on the immediately preceding trial. Two primary examples of these microadjustments of control are posterror slowing and conflict adaptation effects.

Posterror slowing refers to the finding in which responses following errors in choice response time tasks are much slower (and more accurate) than the average of other correct responses (Laming, 1979; Rabbitt, 1966). That is, following an error, participants respond slower (and are more accurate) on the very next trial (as well as a few subsequent trials). This is typically explained as being due to local changes in the speed–accuracy trade-off function, in which in following an error participants adopt a more conservative strategy sacrificing speed in order to ensure accurate performance. According to the conflict-monitoring framework, posterror slowing reflects a microadjustment of control by the PFC on trial n after the ACC detects conflict (the occurrence of an error) on trial $n-1$—that is, as an error probably reflects a high degree of conflict (i.e., a response in opposition to the task goal), which is detected by the ACC. Upon detection, the ACC signals the PFC to adjust the control settings accordingly, thus biasing the likelihood that subsequent behaviour will be consistent with the task goal. The high degree of conflict on trial $n-1$ resulted in the greater recruitment of cognitive control on trial n.

Evidence consistent with the conflict-monitoring explanation of posterror slowing comes from a number of neuroimaging studies that have found that ACC activation is related to the amount of posterror error slowing found (Debener et al., 2005). Furthermore, Kerns et al., (2005) found that

following an error, PFC activity increased, and this increase was directly related to the amount of activation found in the ACC. Further evidence in favour of the conflict-monitoring account of posterror slowing comes from an examination of neuropsychological populations. For instance, di Pellegrino, Ciaramelli, and Làdavas (2007) found that patients with damage to rostral ACC did not exhibit a significant posterror slowing effect, whereas control participants did. Furthermore, Schachar et al., (2004) found that children with ADHD demonstrated significantly less posterror slowing than control participants, and Kerns et al. (2005) found that schizophrenic patients demonstrated significantly less ACC activation and less posterror slowing than control participants. Overall, these results suggest that the ACC seems to play some role in detecting the occurrence of an error, resulting in adjustments of control (i.e., response slowing on the next trial), which may be implemented by the PFC.

Conflict adaptation effects have also been taken as evidence in favour of the conflict-monitoring theory of cognitive control (Botvinick et al., 2001; Carter & van Veen, 2007). Conflict adaptation effects refer to the finding that performance differences between congruent and incongruent trials in tasks like the flanker task (Gratton, Coles, & Donchin, 1992), the Stroop task (Kerns et al., 2005), and the Simon task (Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002) are partially dependent on the type (congruent vs. incongruent) of the previous trial. Specifically, when an incongruent trial is preceded by a correct incongruent trial (an iI trial) response times (RTs) are faster than when an incongruent trial is preceded by a congruent trial (a cI trial). Likewise, when a congruent trial is preceded by a congruent trial (a cC trial), RTs are faster than when a congruent trial is preceded by an incongruent trial (a iC trial). Thus, there is a significant interaction between the trial type of the current trial and trial type of the previous trial. According to the conflict-monitoring framework, conflict adaptation effects occur because the ACC detects conflict in the form of an incongruent trial on the prior trial signalling the PFC to adjust control settings for the next upcoming trial. This results in

greater top-down control and greater focusing of attention on the next trial than when there is little conflict on the prior trial (i.e., the prior trial was a congruent trial). Thus, like posterror slowing, this suggests that performance on trial n is influenced by the amount of conflict present on trial $n - 1$. When there is a great deal of conflict on trial $n - 1$, performance increases on trial n due to an increase in cognitive control on that trial.

Like posterror slowing effects, evidence consistent with the conflict-monitoring account of conflict adaptation effects comes from both neuroimaging and neuropsychological studies. Specifically, research has demonstrated consistent ACC activation for cI trials and has found that PFC activation is related to reduction in conflict found on current trials (Egner & Hirsch, 2005). Furthermore, much like posterror slowing effects, ACC activation for conflict trials seems to be related to both the amount of PFC activation and overall performance levels on the next trial (Kerns et al., 2005). Additionally, recent research has demonstrated that certain populations fail to demonstrate conflict adaptation effects. These include patients with rostral ACC damage (di Pellegrino et al., 2007) and patients with schizophrenia (Kerns et al., 2005).

Executive attention view of working memory capacity

Recently, Engle, Kane, and colleagues (Engle & Kane, 2004; Kane, Conway, Hambrick, & Engle, 2007) have suggested that individual differences in WMC are reflective of overall differences in executive attention (or cognitive control) abilities that are needed in host of low-level and high-level cognitive tasks. Specifically, the executive attention view suggests that high- and low-WMC individuals differ in a number of tasks because low-WMC individuals are less able use attention control to actively maintain task goals than high-WMC individuals are, probably due to differences in PFC functioning. In particular, this view suggests that individuals high in WMC are better at controlling aspects of their attention to actively maintain goal-relevant information in order to successfully perform a task than are

individuals low in WMC. Furthermore, these differences are especially pronounced under conditions of high interference or distraction in which attentional capture away from task or goal-relevant information is likely (e.g., Engle & Kane, 2004; Fukuda & Vogel, 2009). Thus, high-WMC individuals are better at preventing interference or distraction than low-WMC individuals, and this attention control ability is needed in a host of activities regardless of specific stimulus or processing domains.

As a prime example of this view, we return to the antisaccade task. Recall that in this task, participants are told to fixate at centre and that after a variable amount of time one of two boxes at either side of the screen is going to flash. In the prosaccade version of this task, participants are instructed to simply look at the flashing cue. In the antisaccade version, however, participants are instructed to not look at the flashing cue, and instead to look at the box on the opposite side of the screen. According to the executive attention view of WMC, this task requires a great deal of attention control in order to maintain the task goal (e.g., "look away from the flash") in the presence of a potent distractor that will likely capture attention. Thus, any lapse of attention (or goal neglect; De Jong, Berendsen, & Cools, 1999; Duncan, 1995) in this task will likely lead to a loss of the task goal and will result in attention being automatically captured by the cue leading to an error. Of course, some attention must be allocated, at least covertly, to the cue in order to know where to look (i.e., away from the flash). Importantly, if attention is fully captured by the cue, such that an overall shift of attention occurs, then it is likely that a fast reflexive error will occur. In terms of individual differences in WMC, this means that high- and low-WMC individuals should not differ on relatively automatic prosaccades, but that low-WMC individuals should make more errors and be slower to respond on the attention-demanding antisaccades. Support for this view comes from a number of studies in which low-WMC individuals consistently performed worse on the antisaccade task than did high-WMC individuals (e.g., Kane, Bleckley, Conway, & Engle, 2001; Unsworth et al., 2004). Corroborating evidence for the executive attention

view of WMC comes from a number of studies that have demonstrated WMC differences in dichotic listening (Colflesh & Conway, 2007; Conway, Cowan, & Bunting, 2001), Stroop interference (Kane & Engle, 2003; Long & Prat, 2002), and flanker interference (Heitz & Engle, 2007; Redick & Engle, 2006), as well as differences in flexible visual attention allocation (Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003). In each case, high-WMC individuals were better at controlling aspects of their attention than low-WMC individuals. Overall, the results from these studies suggest that high-WMC individuals are better at actively maintaining task goals than low-WMC individuals, and that low-WMC individuals are more likely to experience periodic failures of goal maintenance (i.e., goal neglect) than high-WMC individuals.

Recently, we directly examined the notion that WMC is related to periodic failures of goal maintenance in a sustained-attention task (Unsworth, Redick, Lakey, & Young, 2010). In this study, participants performed the psychomotor vigilance task (Dinges & Powell, 1985) along with multiple measures of WMC. Based on the executive attention view, we predicted that WMC would primarily be related to the slowest responses in the psychomotor vigilance task with little or no relation between WMC and the fastest responses. To examine this, we rank ordered each individual's RT from fastest to slowest and placed them into quintiles. Using confirmatory factor analysis, the results suggested no relation between WMC and the fastest quintile, but a moderate relation between WMC and the slowest quintiles (see also Schmiedek, Oberauer, Wilhelm, Süß, & Wittmann, 2007). Thus, the slowest, but not the fastest, RTs were significantly related to WMC. According to the executive attention view of WMC, this is because these slow RTs represent periodic losses of goal maintenance (i.e., lapses of attention) in which low-WMC individuals temporarily lost access to the task goal, resulting in much slower than normal RTs. That is, Kane and Engle (2003) suggested that a "subset of very slow responses in the tail of the distribution represents trials on which the goal was lost but then recovered before an overt error was committed, thus leading to much slower responses than on trials on which the

goal was maintained and implemented immediately" (p. 64). Accordingly, low-WMC individuals should have more slow responses in the tail of the distribution in a variety of tasks if WMC differences reflect differences in goal maintenance.

Present study

Our goal in the present study was to better examine variation in WMC and cognitive control. Cognitive control theories suggest that active goal maintenance and dynamic adjustments of control following conflict are two important components of cognitive control (Cohen et al., 2004). Likewise, the executive attention theory of WMC suggests that high- and low-WMC individuals differ in cognitive control and specifically seem to differ in goal maintenance abilities (Engle & Kane, 2004). As noted previously, the executive attention theory predicts that these differences in goal maintenance abilities should be partially reflected in RT differences in the slowest end of the distribution in a variety of tasks. Specifically, regardless of the task, if low-WMC individuals have more periodic lapses of goal maintenance than high-WMC individuals then high- and low-WMC individuals should differ primarily in the slowest end of the distribution. Thus, the first question addressed in the current study was whether WMC differences in RT are due primarily to differences in the slowest end of the distribution in a number of tasks. In order to examine this across four experiments, we had high- and low-WMC individuals perform various RT tasks (i.e., four-choice RT task, antisaccade, Stroop, flankers) and then examined the RT distributions for high- and low-WMC individuals via quintile analyses. Prior work has shown that performance on these four tasks is sensitive to variation in WMC. Thus, these tasks were chosen because prior work has suggested a relation between WMC and performance, but the extent to which the RT differences are primarily due to the tail of the distribution has not been fully examined. Across all tasks it was expected that high- and low-WMC individuals would differ primarily in the slowest quintile with little to no differences occurring in the fastest quintile.

An additional goal of the current study was to examine whether WMC differences reflect global differences in cognitive control or whether these differences seem to be primarily localized to differences in goal maintenance. That is, do high- and low-WMC individuals differ in goal maintenance and in microadjustments of control or do they only seem to differ in goal maintenance? If we think that variation in WMC is due to broad differences in cognitive control, then we should expect to see that not only do high- and low-WMC individuals differ in goal maintenance abilities, but they should also differ in microadjustments of control reflected in differences in posterror slowing and conflict adaptation effects. Specifically, if low-WMC individuals have poorer cognitive control (as well as possibly differences in conflict monitoring) than high-WMC individuals, then low-WMC individuals should show far less posterror slowing than high-WMC individuals. As noted previously, certain groups (i.e., patients with ACC damage; children with attention-deficit/hyperactivity disorder, ADHD; schizophrenics) have all been found to demonstrate little, if any, posterror slowing, suggesting that these groups are deficient in their ability to make microadjustments of control (Carter & van Veen, 2007). Thus it is possible that low-WMC individuals will similarly show little, if any, posterror slowing if they too have deficiencies in cognitive control. However, other research with participants thought to be low in WMC (i.e., patients with PFC damage, children, older adults, individuals with low IQs) has suggested that these groups actually demonstrate more posterror slowing than their controls, suggesting that perhaps these groups are not deficient in microadjustments of control and actually overcompensate compared to control participants (Brewer & Smith, 1984, 1989; Gehring & Knight, 2000; Smith & Brewer, 1995; West & Moore, 2005). Thus, it is possible that low-WMC individuals will not differ in microadjustments of control compared to high-WMC individuals.

Similarly, if low-WMC individuals have global cognitive control deficits, then we might expect them to demonstrate little, if any, conflict adaptation effects, whereas high-WMC individuals should demonstrate typical conflict adaptation effects. That is, if low-WMC individuals do not make microadjustments of control, then there should be little effect of prior trial congruency on performance for the current trial. As noted previously, other between-group studies have demonstrated exactly this pattern of results with patients with damage to the ACC (di Pellegrino et al., 2007) as well as with schizophrenic patients (Kerns et al., 2005). However, like posterror slowing results, other research suggests no differences between groups including comparing TBI patients with control participants (Larson, Kaufman, & Perlstein, 2009). In order to examine whether high- and low-WMC individuals differ in microadjustments of control, we examined posterror slowing in four RT tasks (i.e., four-choice RT task, antisaccade, Stroop, flankers), and we examined conflict adaptation effects in two tasks (Stroop and flankers). Posterror slowing was examined in all four tasks because errors should occur in all four tasks and thus allow for an examination of posterror slowing. Conflict adaptation was examined only in the Stroop and flanker tasks because in both of these tasks congruent and incongruent trials are intermixed, thus allowing for an examination of conflict adaptation. If high- and low-WMC individuals differ in microadjustments of control, we should see that high-WMC individuals demonstrate more posterror slowing and larger conflict adaptation effects across all experiments.

Examining WMC variation in lapses of goal maintenance and microadjustments of control will allow us to better specify those mechanisms that are important for WMC and which individuals differ on. If variation in WMC is due to broad differences in cognitive control, we should see differences in both lapses of goal maintenance and differences in microadjustments of control (see, for example, Keye, Wilhelm, Oberauer, & van Ravenzwaaij, 2008). If, however, variation in WMC is only due to differences in goal maintenance, then we should see differences in lapses of goal maintenance but no differences in microadjustments of control. Such findings would go a long way towards better specifying WMC mechanisms, elucidating the link between WMC and higher order cognition and constraining theories of WMC.

EXPERIMENT 1

In Experiment 1, we examined WMC differences in a basic four-choice RT task. In this task, an asterisk appeared at one of four different horizontal screen locations. Participants were instructed to press the key that corresponded with the location of the asterisk as quickly and accurately as possible. This basic choice RT task is similar to what has been used previously to examine posterror slowing in general (Laming, 1979; Rabbitt, 1966) as well as group differences in posterror slowing (Brewer & Smith, 1984, 1989; Smith & Brewer, 1995). If high- and low-WMC individuals differ in goal maintenance abilities in order to sustain attention on the task, then we should see that low-WMC individuals have more lapses in maintenance as indexed by a greater proportion of slow responses in the tail of the distribution than in high-WMC individuals, but with no differences in the rest of the distribution. Additionally, if low-WMC individuals have deficits in microadjustments of control, we should see that they demonstrate considerably less posterror slowing than high-WMC individuals.

Method

Participants and WMC screening

Participants were recruited from the participant pool at the University of Georgia. Individuals were selected based on a z score composite of the two complex span tasks.[1] Only participants falling in the upper (high-WMC individuals) and lower (low-WMC individuals) quartiles of the composite distribution were selected.

Operation span. Participants solved a series of maths operations while trying to remember a set of unrelated letters that were presented for 1 s each.

Immediately after the letter had been presented, the next operation was presented. Three trials of each list-length (3–7) were presented, with the order of list-length varying randomly. At recall, letters from the current set were recalled in the correct order by clicking on the appropriate letters. Participants received three sets (of list-length 2) of practice. For all of the span measures, the score was the proportion of correct items in the correct position (see Unsworth, Heitz, Schrock, & Engle, 2005, for more task information).

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

Composite score

For the composite score, scores for the two complex span tasks were z-transformed for each participant. These z scores were then averaged together, and quartiles were computed from the averaged distribution. Participants were 26 high-WMC individuals (z-WMC = 0.95, $SD = 0.19$) and 26 low-WMC individuals (z-WMC = –0.86, $SD = 0.43$), as determined by the composite measure. The mean age for both groups was roughly 18.5

---

[1] In Experiment 1, WMC was based on two complex span tasks (operation span, Ospan; and reading span, Rspan), whereas in the other three experiments WMC was based on three complex span tasks (Ospan; Rspan; and symmetry span, Symspan). The change to three tasks reflects a change in our overall screening procedure in which we added symmetry span to ensure that visual spatial skills were being measured along with verbal skills. In a large sample of participants ($N = 1,785$) from our laboratory, the three tasks all correlate well with one another (Ospan–Rspan = .61, Ospan–Symspan = .43, Rspan–Symspan = .42). Given these strong correlations, excluding Symspan in Experiments 2–4 led to qualitatively identical results to those reported.

years, which did not differ as a function of WMC, $p > .65$. Both groups were composed of 67% females. High and low WMC scores on each complex span task and each experiment can be found in the Appendix.

Choice reaction time task

The stimulus consisted of an asterisk centred at one of four underlined horizontal locations. The asterisk and the underlined locations were presented in white in Courier New in 32-point font on a black background. The asterisk randomly appeared over one of the four horizontal locations, with the exception that the asterisk could not appear at the same location twice in a row. The response–stimulus interval was 300 ms. Responses were made by pressing one of four keys (F, G, H, J) corresponding to the location of the asterisk on the screen. Participants were instructed to use the index and middle fingers on each hand, so that the left fingers were positioned on "F" and "G", and the right fingers were positioned on "H" and "J", respectively. Participants also were instructed to respond as fast as possible and to be as accurate as possible. Following 20 practice trials, participants completed 210 real trials.

Results

For all the RT results reported, only correct RTs were examined. In addition, RTs that fell below 200 ms or 3 standard deviations below the individual's mean or above 2,000 ms or 3 standard deviations above the individual's mean were excluded from all RT analyses. This resulted in the exclusion of less than 2% of the responses.

Overall effects

As shown in Table 1, overall performance was similar for both high- and low-WMC individuals. Specifically, high- and low-WMC individuals demonstrated similar levels of accuracy, $t(50) = 1.55$, $p > .13$, $\eta^2 = .05$, and RT, $t(50) = 1.34$, $p > .18$, $\eta^2 = .04$. Thus, high- and low-WMC individuals did not seem to differ in overall performance on this basic choice RT task.

Table 1. *Mean accuracy and reaction time in the choice reaction time task as a function of WMC*

| WMC	Accuracy	RT
High	.96 (.01)	436 (6)
Low	.95 (.01)	451 (10)

Note: WMC = working memory capacity. RT = reaction time. Standard errors are in parentheses.

Quintile analyses

Next, we more fully examined WMC differences in RT by examining the full distribution of RTs. Specifically, each individual's RTs were rank-ordered from fastest to slowest. Next, these rank-ordered responses were placed into five bins such that 20% of each individual's responses were placed into each bin. These quintiles were then averaged across participants in order to examine potential WMC differences in the distributions. Shown in Figure 1 are the quintile plots as a function of WMC. As can be seen, overall the distributions for high- and low-WMC individuals were very similar. However, as can also be seen, high- and low-WMC individuals do seem to differ in the tail of the distribution with low-WMC individuals producing more slow responses than high-WMC individuals. Indeed, there was a significant WMC by quintile interaction, $F(4, 200) = 5.04$, $MSE = 807.84$, $p < .01$, $\eta_p^2 = .09$. Follow-up analyses suggested that high- and low-WMC individuals did not differ for Quintiles 1–4, all $ps > .12$, but the groups did differ for Quintile 5, $t(50) = 2.02$, $p < .05$, $\eta^2 = .08$. Thus, although the overall distributions for high- and low-WMC individuals were very similar, low-WMC individuals had significantly slower RTs in the tail of the distribution.

Posterror slowing

For our final analysis, we examined WMC differences in posterror slowing. Although overall accuracy was high, all participants made some errors (on average there were 9.5 per person). Therefore, in order to examine posterror slowing, we compared correct RTs for trials where the preceding response was correct with trials where the preceding response
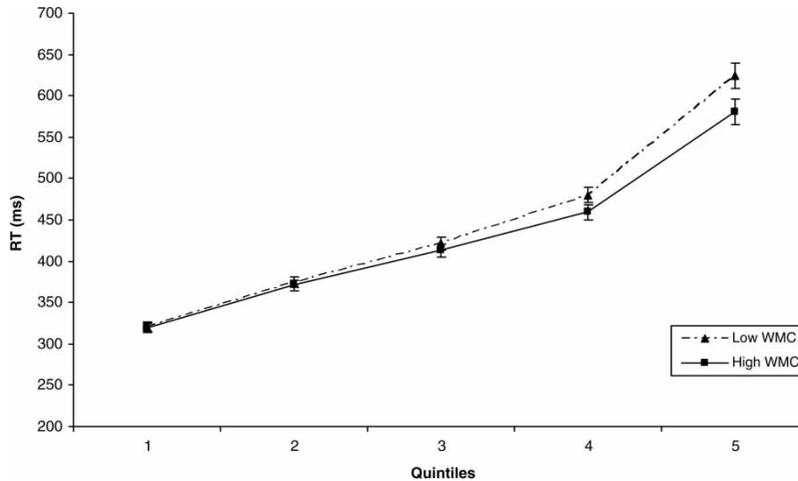
Figure 1. *Quintile plots as a function of working memory capacity (WMC) for the choice reaction time (RT) task in Experiment 1. Note, error bars reflect one standard error of the mean.*

was incorrect. Consistent with prior research, there was a substantial posterror slowing effect such that following an error, participants were approximately 87 ms ($SE = 10$) slower on the next correct trial. That is, participants were significantly slower when the preceding response was incorrect than when it was correct, $t(51) = 9.05$, $p < .01$. Examining differences between high- and low-WMC individuals suggested that both groups demonstrated a posterror slowing effect, and the posterror slowing effect was of the same magnitude. Specifically, high-WMC individuals slowed down by 80 ms ($SE = 12$), and low-WMC individuals slowed down by 94 ms ($SE = 15$), and this did not differ between the groups, $t(50) = 0.74$, $p > .46$, $\eta^2 = .01$.

Discussion

The results from Experiment 1 suggested that high- and low-WMC individuals largely did not differ in performance on a basic choice RT task. Overall, the distributions of correct RT were very similar for high- and low-WMC individuals with the exception that low-WMC individuals had slower responses in the tail of the distribution (the slowest quintile) than did high-WMC individuals. This finding is consistent with the notion that high-

and low-WMC individuals differ in goal maintenance abilities, such that low-WMC individuals are more likely to have lapses in goal maintenance (i.e., lapses in attention) than high-WMC individuals, leading to more slow responses on some trials. Interestingly, the WMC differences in the distribution analyses occurred without WMC differences in measures of central tendency (accuracy and RT). The finding replicates and extends prior work suggesting that high- and low-WMC individuals will differ in RT primarily in the slowest responses (e.g., Unsworth et al., 2010) even for basic RT tasks (see also Schmiedek et al., 2007). Additionally, the current results demonstrated a posterror slowing effect such that following an error, participants were slower on the next trial by approximately 87 ms. This effect, however, did not differ as a function of WMC, with high- and low-WMC individuals having equivalent posterror slowing effects. These results are consistent with prior work suggesting that some participants thought to have WMC deficits (i.e., patients with PFC damage) have equivalent posterror slowing effects to those of their corresponding control group (Gehring & Knight, 2000). Overall, the results from Experiment 1 suggest that high- and low-WMC individuals probably differ in goal maintenance abilities, but do not seem to differ in

microadjustments of control as indexed by posterror slowing effects.

EXPERIMENT 2

Experiment 2 was conducted to better examine the notion that high- and low-WMC individuals differ in goal maintenance abilities and to see whether variation in posterror slowing could be found. To this end, we had high- and low-WMC individuals perform an antisaccade task. In this task, a cue flashed briefly on one side of the screen, and participants were instructed to shift their attention and their gaze to the opposite side of the screen in order to identify a briefly presented letter (Kane et al., 2001). As discussed previously, this task requires participants to actively maintain the task goal (look away from the flashing cue) in order to successfully identify the target letter. Thus, we should see that low-WMC individuals are more likely to have a lapse in goal maintenance leading either to an error or to a very slow correct RT. Prior research with this task has provided evidence consistent with these predictions by demonstrating that high- and low-WMC individuals differ in both accuracy and RT with high-WMC individuals outperforming low-WMC individuals (Kane et al., 2001; Unsworth et al., 2004; Unsworth & Spillers, 2010). However, in terms of RT differences, prior research has not explicitly examined RT distributions to determine whether the WMC differences in RT are due to differences exclusively in the slowest responses as the executive attention view would predict. Therefore, if high- and low-WMC individuals differ in goal maintenance abilities, and this is partially indexed by differences in the tail of the distribution, we should see differences primarily in the slowest responses, with few to no differences in the rest of the distribution. Additionally, we used the antisaccade task to better examine potential differences in posterror slowing. Experiment 1 found no evidence for differences in posterror slowing, but this may have been due to the fact that so few errors were made overall, thus resulting in reduced power to find differences. However, error rates in the antisaccade task tend to be quite

high, thus allowing for a better examination of potential differences in posterror slowing between high- and low-WMC individuals.

Method

Participants and WMC screening
New participants were recruited from the participant pool at the University of Georgia. Individuals were selected based on a z score composite of the three complex span tasks. Only participants falling in the upper (high-WMC individuals) and lower (low-WMC individuals) quartiles of the composite distribution were selected.

Operation span. This was the same as that in Experiment 1.

Reading span. This was the same as that in Experiment 1.

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

Composite score
For the composite score, scores for the three complex span tasks were z-transformed for each participant. These z scores were then averaged together, and quartiles were computed from the averaged distribution. Participants were 28 high-WMC individuals (z-WMC = 0.87, SD = 0.32)

and 31 low-WMC individuals (z-WMC = −1.05, $SD = 0.69$), as determined by the composite measure. The mean age for both groups was roughly 18.7 years, which did not differ as a function of WMC, $p > .40$. Both groups were composed of 67% females.

Antisaccade

In this task (Kane et al., 2001), participants were instructed to stare at a fixation point which was onscreen for a variable amount of time (200–2,200 ms). A flashing white " = " was then flashed either to the left or to the right of fixation (11.33° of visual angle) for 100 ms. This was followed by a 50-ms blank screen and a second appearance of the cue for 100 ms, making it appear as though the cue (=) flashed onscreen. Following another 50-ms blank screen, the target stimulus (a B, P, or R) appeared onscreen for 100 ms followed by masking stimuli (an H for 50 ms and an 8, which remained onscreen until a response was given). All stimuli were presented in Courier New with a 12-point font. The participants' task was to identify the target letter by pressing a key for B, P, or R (keys 1, 2, or 3 on the number keypad) as quickly and accurately as possible. In the prosaccade condition, the flashing cue (=) and the target appeared in the same location. In the antisaccade condition, the target appeared in the opposite location as the flashing cue. Participants received, in order, 10 practice trials to learn the response mapping, 15 trials of the prosaccade condition, and 60 trials of the antisaccade condition.

Results

For all the RT results reported, only correct RTs were examined. In addition, RTs that fell below 200 ms or 3 standard deviations below the individual's mean or above 2,000 ms or 3 standard deviations above the individual's mean were excluded from all RT analyses. This resulted in the exclusion of less than 2% of the responses.

Overall effects

As shown in Table 2, and consistent with prior research (Kane et al., 2001; Unsworth et al.,

Table 2. *Mean accuracy and reaction time in the antisaccade task as a function of WMC*

WMC	Accuracy	RT
High	.60 (.02)	763 (26)
Low	.53 (.03)	850 (33)

Note: WMC = working memory capacity. RT = reaction time. Standard errors are in parentheses.

2004), high-WMC individuals outperformed low-WMC individuals on the antisaccade task. Specifically, high-WMC individuals were more accurate than low-WMC individuals, $t(57) = 2.39$, $p < .05$, $\eta^2 = .09$, and had faster correct RTs than low-WMC individuals, $t(57) = 2.01$, $p < .05$, $\eta^2 = .07$. Thus, as expected, high- and low-WMC individuals differed on a task thought to rely heavily on goal maintenance abilities.

Quintile analyses

Next, we more fully examined WMC differences in RT by examining the full distribution of RTs. As noted previously, prior studies have not explicitly examined RT distributions in the antisaccade for high- and low-WMC individuals. Based on a goal maintenance account of WMC, we should see that high- and low-WMC individuals differ primarily in the slowest responses. Similar to Experiment 1, each individual's RTs were rank-ordered from fastest to slowest. Next, these rank-ordered responses were placed into five bins such that 20% of each individual's responses were placed into each bin. These quintiles were then averaged across participants in order to examine potential WMC differences in the distributions. Shown in Figure 2 are the quintile plots as a function of WMC. As can be seen, RT distributions for high- and low-WMC individuals were similar for Quintiles 1–3, but for Quintiles 4 and 5, low-WMC individuals seem to have slower RTs than high-WMC individuals. These observations were supported by a significant WMC by quintile interaction, $F(4, 228) = 5.74$, $MSE = 20,910$, $p < .01$, $\eta^2_p = .09$. Follow-up analyses suggested that high- and low-WMC individuals did not differ for Quintiles 1–3, all $ps > .13$, but there was a slight
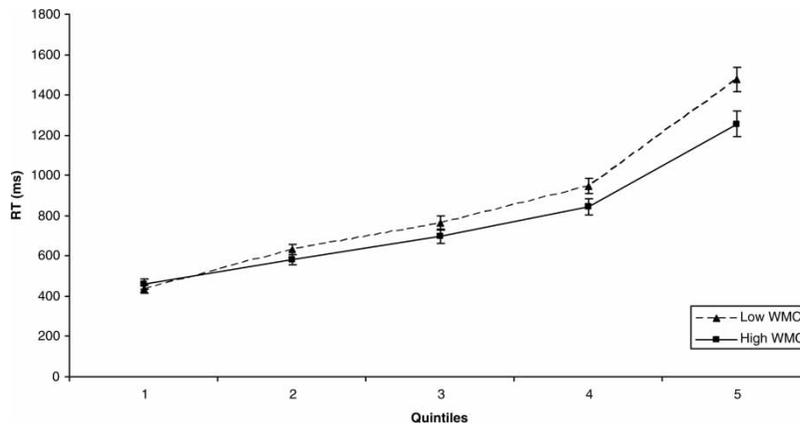
Figure 2. *Quintile plots as a function of working memory capacity (WMC) for the antisaccade task in Experiment 2. RT = reaction time. Note, error bars reflect one standard error of the mean.*

difference between the groups for Quintile 4, $t(57) = 1.87$, $p < .07$, $\eta^2 = .06$, and the groups did differ for Quintile 5, $t(57) = 2.51$, $p < .05$, $\eta^2 = .10$. Thus, overall RT differences between high- and low-WMC individuals seem to be largely due to differences in the slow tail of the distribution rather than due to differences in the overall distribution.

Posterror slowing

Similar to Experiment 1, our final analysis concerned WMC differences in posterror slowing. Unlike Experiment 1, where overall accuracy was high, in the current experiment accuracy was much lower and should allow for a better examination of potential differences in posterror slowing. As with Experiment 1, we compared correct RTs for trials where the preceding response was correct with those for trials where the preceding response was incorrect. Consistent with Experiment 1 and prior research, there was a posterror slowing effect such that following an error, participants were approximately 42 ms ($SE = 16$) slower on the next correct trial. That is, participants were significantly slower when the preceding response was incorrect than when it was correct, $t(58) = 2.63$, $p < .05$. Examining differences between high- and low-WMC individuals suggested that both groups demonstrated a posterror slowing effect, and the posterror slowing effect was of the same magnitude.

Specifically, high-WMC individuals slowed down by 34 ms ($SE = 18$), and low-WMC individuals slowed down by 49 ms ($SE = 25$), and this did not differ between the groups, $t(57) = 0.49$, $p > .63$, $\eta^2 = .01$.

Discussion

Consistent with prior research (Kane et al., 2001; Unsworth et al., 2004), low-WMC individuals were slower and less accurate on the antisaccade than were high-WMC individuals. Novel to the current experiment was the finding that the RT difference between high- and low-WMC individuals was localized to the slow tail of the RT distribution rather than being due to differences in the overall distribution. These results are consistent with the executive attention view of WMC, which suggests that variation in WMC is primarily due to differences in goal maintenance abilities. In the antisaccade task, there is a strong demand to actively maintain the task goal (look away from the flash) in order to respond correctly. Any lapse in goal maintenance should lead to either a fast error or a very slow correct response. The current results are very much in line with these predictions and suggest that high- and low-WMC individuals differ in the ability to actively maintain task goals. Additionally, and similar to Experiment 1, we found a significant posterror slowing effect and the magnitude of this

effect was similar to prior research examining posterror slowing in the antisaccade task (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001). Consistent with Experiment 1, however, high- and low-WMC individuals demonstrated equivalent posterror slowing effects. Thus, although overall error rates were increased, leading to more power than in Experiment 1, high- and low-WMC individuals did not differ in posterror slowing. Again this suggests that high- and low-WMC individuals probably differ in goal maintenance abilities, but they do not differ in microadjustments of control.

EXPERIMENT 3

Experiment 3 was conducted to directly examine the notion that high- and low-WMC individuals differ in cognitive control via differences in goal maintenance abilities but not differences in microadjustments of control. Specifically, we examined performance in a Stroop task to determine whether WMC differences in the Stroop effect (incongruent RT minus congruent RT) that have been reported previously (Kane & Engle, 2003; Long & Prat, 2002; Unsworth & Spillers, 2010) could be localized to the slowest end of the distribution or whether differences resulted from a shift in the overall distribution. Kane and Engle (2003) previously suggested that WMC RT differences in Stroop resulted from both a shift in the distribution due to differences in conflict resolution and differences in the tail of the distribution due to differences in goal maintenance. According to this account of WMC differences in the Stroop effect, we should see that high- and low-WMC individuals differ in both the fast and slow ends of the distribution, with perhaps larger differences occurring in the slow end of the distribution. If, however, WMC differences in the Stroop effect are primarily due to differences in goal maintenance, then we should see that the differences between high- and low-WMC individuals are localized to the slowest end of the distribution. One way to examine potential differences in RT distributions is to examine delta plots (Ridderinkhof, 2002). Delta plots plot the difference between incongruent and congruent trials as a function of RT percentiles. For the Stroop task, this means that the Stroop effect can be examined as function of RT percentile. Prior research has found that the Stroop effect is minimal for the fastest percentiles, but increases for the slowest percentiles (see Pratte, Rouder, Morey, & Feng, 2010, for a review). Thus, the difference between incongruent and congruent trials is largest for the slowest trials. If WMC differences in the Stroop effect are due to differences in goal maintenance, then we would expect no differences in the magnitude of the Stroop effect for the fastest responses, but significant differences for the slowest responses. It should be noted that in the current experiment there were more congruent than incongruent trials. Previous research has suggested that WMC differences only arise in conditions where there is a high proportion of congruent trials relative to incongruent trials (Kane & Engle, 2003; Long & Prat, 2002). Thus, in order to replicate the finding of WMC differences in the magnitude of the Stroop effect, we utilized a procedure where there was a high proportion of congruent trials relative to incongruent trials.

An additional goal of Experiment 3 was to see whether the lack of a relation between WMC and posterror slowing that was found in the first two experiments would generalize to the Stroop task. If posterror slowing reflects a relatively general adjustment of control, then we should find robust posterror slowing effects, but this should not differ as a function of WMC. If, however, posterror slowing is task specific, then perhaps high- and low-WMC individuals might show differences in the Stroop given the high degree of conflict. Finally, as noted earlier, another indicator of microadjustments in control are conflict adaptation effects. These effects have previously been found in the Stroop task (e.g., Kerns et al., 2005), but WMC differences in conflict adaption in the Stroop task have never been investigated. To the extent that posterror slowing and conflict adaption effects reflect the same general microadjustments in control, we would expect high- and low-WMC individuals to demonstrate equivalent conflict adaption effects. However, if posterror slowing

Table 3. *Mean accuracy and reaction time in the Stroop task as a function of trial type and WMC*

	Trial type			
	Congruent		Incongruent	
WMC	Accuracy	RT	Accuracy	RT
High	.96 (.01)	622 (22)	.89 (.02)	742 (30)
Low	.95 (.01)	653 (23)	.88 (.02)	832 (31)

Note: WMC = working memory capacity. RT = reaction time. Standard errors are in parentheses.

and conflict adaption reflect different mechanisms of microadjustments of control, then it is possible that high- and low-WMC individuals may differ in conflict adaption effects but not posterror slowing. In fact, Cohen, Botvinick, and Carter (2000) suggested that posterror slowing effects might reflect different control mechanisms than those present in conflict adaption effects, and that conflict adaptation effects might be reliant on PFC processes whereas posterror effects are not. If this is the case, then one would expect low-WMC individuals to demonstrate diminished conflict adaptation effects compared to high-WMC individuals.

Method

Participants and WMC screening
New participants were recruited from the participant pool at the University of Georgia. Individuals were selected based on a *z* score composite of the three complex span tasks. The three complex span tasks were the same as those in Experiment 2. Only participants falling in the upper (high-WMC individuals) and lower (low-WMC individuals) quartiles of the composite distribution were selected.

Composite score
For the composite score, scores for the three complex span tasks were *z*-transformed for each participant. These *z* scores were then averaged together, and quartiles were computed from the averaged distribution. Participants were 23 high-WMC individuals (z-WMC = 0.82, SD = 0.34) and 22 low-WMC individuals (z-WMC = −1.29,

SD = 0.83), as determined by the composite measure. The mean age for both groups was roughly 18.8 years, which did not differ as a function of WMC, $p > .56$. Both groups were composed of 66% females.

Stroop
Participants were presented with a colour word (red, green, or blue) presented in one of three different font colours (red, green, or blue). All words were presented in Courier New with an 18-point font. The participants' task was to indicate the font colour via key press (red = 1, green = 2, blue = 3). Participants were told to press the corresponding key as quickly and accurately as possible. Participants received 75 trials in total. Of these trials, 67% were congruent such that the word and font colour matched (i.e., red printed in red), and the other 33% were incongruent (i.e., red printed in green). Congruent and incongruent trials were mixed throughout the task.

Results

For all the RT results reported, only correct RTs were examined. In addition, RTs that fell below 200 ms or 3 standard deviations below the individual's mean or above 2,000 ms or 3 standard deviations above the individual's mean were excluded from all RT analyses. This resulted in the exclusion of less than 2% of the responses.

Overall effects
As shown in Table 3, and consistent with prior research (Kane & Engle, 2003; Long & Prat,

2002; Unsworth & Spillers, 2010), high-WMC individuals outperformed low-WMC individuals on the Stroop task, particularly in the RTs. Examining accuracy suggested that incongruent trials were more inaccurate than congruent trials, $F(1, 43) = 28.18$, $MSE = .004$, $p < .01$, $\eta_p^2 = .40$, thus demonstrating a robust Stroop effect in accuracy. However, trial type congruency and WMC did not interact, $F < 1$, and there were no overall differences in accuracy between high- and low-WMC individuals, $F(1, 43) = 1.25$, $MSE = .003$, $p > .27$, $\eta_p^2 = .03$. Examining RTs suggested that incongruent trials were slower than congruent trials, $F(1, 43) = 133.82$, $MSE = 3,730$, $p < .01$, $\eta_p^2 = .76$, thus demonstrating a robust Stroop effect in RTs. Furthermore, there was a significant trial type congruency by WMC interaction, $F(1, 43) = 5.30$, $MSE = 3,730$, $p < .05$, $\eta_p^2 = .11$, suggesting that low-WMC individuals had a significantly larger Stroop effect ($M = 179$ ms, $SE = 18$ ms) than high-WMC individuals ($M = 120$ ms, $SE = 11$ ms). Thus, as expected, high- and low-WMC individuals differed on a task thought to rely heavily on goal maintenance abilities.

Quintile analyses

Next, we more fully examined WMC differences in RT and trial type congruency by examining the full distribution of RTs. As noted previously, prior studies have not explicitly examined RT distributions in the Stroop task for high- and low-WMC individuals. Based on a goal maintenance account of WMC, we should see that high- and low-WMC individuals differ primarily in the slowest responses on incongruent trials. Similar to the prior experiments, each individual's RTs were rank-ordered from fastest to slowest for both congruent and incongruent trials. Next, these rank-ordered responses in each condition were placed into five bins such that 20% of each individual's responses were placed into each bin. These quintiles were then averaged across participants in order to examine potential WMC differences in the distributions across conditions. Shown in Figure 3 are

the quintile plots as a function of trial type congruency and WMC. As can be seen, RT distributions for high- and low-WMC individuals were similar across the board in the congruent condition (Figure 3A), whereas in the incongruent condition (Figure 3B) distributions for high- and low-WMC individuals were similar for Quintiles 1–3, but for Quintiles 4 and 5, low-WMC individuals seemed to have slower RTs than high-WMC individuals. These observations were supported by 2 (trial type congruency) × 2 (WMC) × 5 (quintile) analysis of variance (ANOVA). The results for trial type congruency and WMC were exactly the same as those seen in the overall effects. For differences in quintiles, the ANOVA suggested a significant interaction between WMC and quintile, $F(4, 172) = 4.36$, $MSE = 17,666$, $p < .01$, $\eta_p^2 = .09$, suggesting that WMC differences were largest for the slowest responses. There was also a significant trial type congruency by quintile interaction, $F(4, 172) = 31.08$, $MSE = 5,997$, $p < .01$, $\eta_p^2 = .42$, suggesting that the difference between congruent and incongruent trials was largest for the slowest responses. Finally, these effects were qualified by a significant WMC by trial type congruency by quintile interaction, $F(4, 172) = 3.07$, $MSE = 5,997$, $p < .05$, $\eta_p^2 = .07$. As shown in Figures 3A and 3B, this interaction suggested that there were no WMC differences in the congruent trials, but in the incongruent trials, WMC differences were largest for the slowest quintile.

Another way of examining this effect is to examine delta plots of the difference between incongruent and congruent trials as a function of quintile and WMC.[2] Typically it has been found that the Stroop effect increases as RT increases (e.g., Pratte et al., 2010). As shown in Figure 3C, this same pattern of results was obtained in the current study, such that the Stroop effect was fairly small for the fastest responses, but increased substantially as RT increased, $F(4, 172) = 31.08$, $MSE = 11,994$, $p < .01$, $\eta_p^2 = .42$. Furthermore, as shown in Figure 3C, high- and low-WMC individuals have similar magnitudes of the Stroop effect in the

---

[2] Note that delta plots were examined in Experiments 3 and 4 because delta plots represent the difference between congruent and incongruent trials. Because there are not congruent and incongruent trials in Experiments 1 and 2 delta plots could not be constructed.
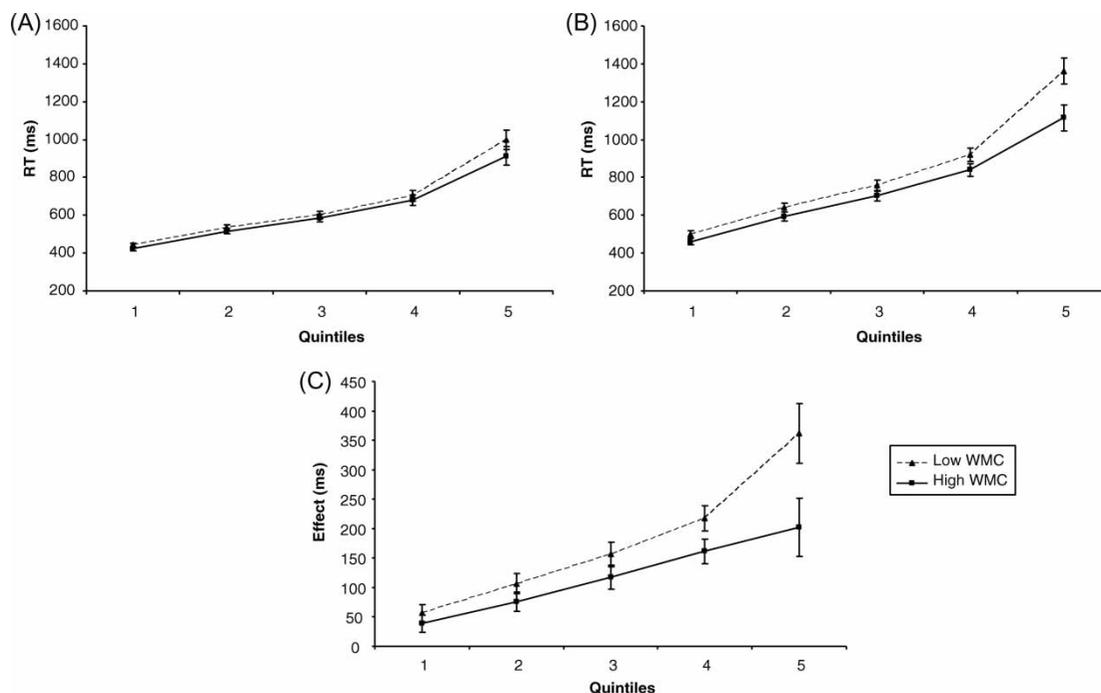
Figure 3. *(A) Quintile plots as a function of working memory capacity (WMC) for the congruent trials on the Stroop task in Experiment 3. (B) Quintile plots as a function of working memory capacity for the incongruent trials on the Stroop task in Experiment 3. (C) Delta plots of the Stroop effect as a function of working memory capacity in Experiment 3. RT = reaction time. Note, error bars reflect one standard error of the mean.*

first three quintiles (all $ts < 1.33$, all $ps > .19$), but for Quintiles 4 ($p < .07$) and 5 ($p < .05$), low-WMC individuals have a larger Stroop effect. Thus, WMC differences in the Stroop effect seemed to be localized to the slowest responses.

Posterror slowing

Similar to the prior experiments, we next examined WMC differences in posterror slowing. As with the prior experiments, we compared correct RTs for trials where the preceding response was correct with trials where the preceding response was incorrect. Consistent with the prior experiments and prior research, there was a posterror slowing effect such that following an error participants were approximately 145 ms ($SE = 28$) slower on the next correct trial. This effect was significantly different from zero, $t(44) = 5.12$, $p < .01$. Next, we examined posterror slowing as a function of trial type congruency and WMC in a 2×2

ANOVA. The ANOVA suggested a significant effect of trial type congruency, $F(1, 43) = 5.84$, $MSE = 50,393$, $p < .05$, $\eta_p^2 = .12$, such that posterror slowing was greater in the incongruent ($M = 202$ ms, $SE = 43$ ms) trials than in the congruent trials ($M = 88$ ms, $SE = 30$ ms). Examining differences between high- and low-WMC individuals suggested that both groups demonstrated a posterror slowing effect, and the posterror slowing effect was of the same magnitude, $F(1, 43) = 0.13$, $MSE = 73,322$, $p > .72$, $\eta_p^2 = .003$. Specifically, high-WMC individuals slowed down by 135 ms ($SE = 40$), and low-WMC individuals slowed down by 155 ms ($SE = 41$), and this did not differ as a function of trial type congruency, $F(1, 43) = 0.76$, $MSE = 50,393$, $p > .39$, $\eta_p^2 = .01$. Thus, there was more posterror slowing on high-conflict incongruent trials, but there were no differences between high- and low-WMC individuals.

Conflict adaptation

Our final analysis examined potential WMC differences in conflict adaptation effects. Specifically, we examined RT as a function of current trial type congruency, prior trial type congruency, and WMC. As shown in Figure 4, we found the standard conflict adaptation effect with a significant prior trial type by current trial type interaction, $F(1, 43) = 5.16$, $MSE = 8,893$, $p < .05$, $\eta_p^2 = .11$, suggesting that the Stroop effect was larger when the prior trial was congruent ($M = 165$ ms, $SE = 15$ ms) than when the prior trial was incongruent ($M = 101$ ms, $SE = 23$ ms). Importantly, high- and low-WMC individuals did not differ in their conflict adaptation effects as indicated by the lack of a significant prior trial by current trial by WMC interaction, $F(1, 43) = 1.66$, $MSE = 8,893$, $p > .20$, $\eta_p^2 = .03$.

Discussion

Consistent with prior research (Kane & Engle, 2003; Long & Prat, 2002; Unsworth & Spillers, 2010), high- and low-WMC individuals differed in the magnitude of the Stroop effect, with low-WMC individuals demonstrating a much larger Stroop effect in RTs than high-WMC individuals. Novel to the current experiment was the finding that the RT difference in the magnitude of the Stroop effect between high- and low-WMC individuals was localized to the slow tail of the RT distribution rather than being to differences in the overall distribution. As suggested by Kane and Engle (2003), these results are consistent with the executive attention view of WMC, which suggests that variation in WMC is primarily due to differences in goal maintenance abilities, which can be seen in the tail of RT distributions. Furthermore, the fact that differences in the magnitude of the Stroop effect were localized to the tail of the distribution would seem to argue against Kane and Engle's suggestion that the other reason for WMC differences in Stroop is due to conflict resolution as seen in a shift in the overall distribution. The current results demonstrated differences in the tail of the distribution only, suggesting that conflict resolution may not have been the primary

mechanism leading to WMC differences in the Stroop, at least in the current study. More work is needed to examine when WMC differences in the Stroop (as well as other tasks) can lead to both a shift in the distribution as well as an increase in the tail of the distribution.

Consistent with prior experiments, we found significant posterror slowing, but found that high- and low-WMC individuals demonstrated equivalent posterror slowing. Finally, we examined another putative index of microadjustments of control in terms of conflict adaptation effects. Consistent with prior research (e.g., Kerns et al., 2005) we found significant conflict adaptation effects, but these did not differ as a function of WMC. Again these results suggest that high- and low-WMC individuals seem to differ in goal maintenance abilities, but do not differ in conflict monitoring and microadjustments of control.

EXPERIMENT 4

The fourth and final experiment was conducted to replicate and extend our prior findings in another attention control task. Specifically, in Experiments 2 and 3 we examined WMC variation in attention control tasks that require the *restraint* of attention such that participants prevent themselves from responding habitually and instead respond in a novel and goal directed manner (Poole & Kane, 2009). Recent work has also suggested that WMC variation exists in attention control tasks that require the *constraint* of attention such that participants must constrain their attention to target items in the presence of distractors (Poole & Kane, 2009). This constraint function is most readily apparent in flanker tasks where a central target item (a letter or arrow) must be selected amongst distractor items (other letters or arrows). When the target items are different from the distractors performance is usually slower and more inaccurate compared to when the target items and distractors match (Eriksen & Eriksen, 1974). In terms of WMC differences, prior research has found that low-WMC individuals have larger flanker effects (incongruent minus congruent RTs) than high-WMC
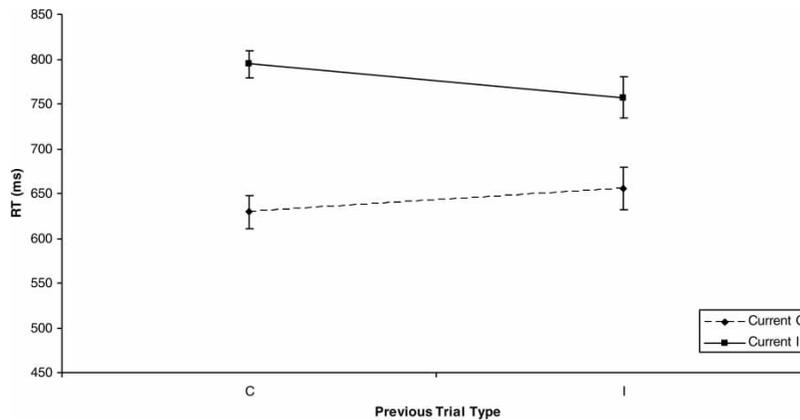
Figure 4. *Mean correct reaction time (RT) as a function of current trial type and previous trial type for the Stroop task in Experiment 3. C = congruent; I = incongruent. Note, error bars reflect one standard error of the mean.*

individuals (Heitz & Engle, 2007; Redick & Engle, 2006; Unsworth & Spillers, 2010). According to Heitz and Engle (2007), WMC differences in the flanker task reflect differences in the rate of attentional constraint. That is, in their model, high- and low-WMC individuals start off with a broad focus of attention that encapsulates both the target item and the flankers. Over time, participants constrain their focus to only the central target letter. However, the rate of attentional constraint differs as a function of WMC such that high-WMC individuals are faster to constrain their attention than low-WMC individuals. Accordingly this predicts that high- and low-WMC individuals should differ by a relatively constant amount on incongruent trials leading to an overall shift in the distributions rather than a lengthening of the tail of the distribution. That is, we can assume that high- and low-WMC individuals differ by a constant amount in the rate of constraint leading to an overall shift in the distribution. Recently, however, Poole and Kane (2009) have suggested that part of the differences found in constraint tasks may also be due to differences in attention control needed for goal maintenance. Specifically, Poole and Kane suggested that WMC is related to the ability to use attention control to actively maintain a constrained attentional focus over time. Thus, this predicts that not only should high- and low-WMC individuals differ in the tail of the distribution (as the previous

experiments showed), but that low-WMC individuals should also have a distribution that is shifted over compared to high-WMC individuals (which was not shown in the previous experiments). Similar to the prior experiments, we examined these predictions by examining the RT distributions via quintile analyses and an examination of delta plots.

In addition to examining overall RT distributions, we were also interested in examining microadjustments of control in the flanker task. Specifically, given that there are some differences between the flanker task (a constraint task) and antisaccade and Stroop tasks (restraint tasks) it is possible that differences in microadjustments in control (posterror slowing and conflict adaptation effects) might arise in the flanker task. Furthermore, given that conflict adaptation effects were originally found in a flanker task (Gratton et al., 1992) and the fact that the majority of the work on conflict adaptation effects have been done with the flanker task, we wanted to examine the extent to which our prior conflict adaptation findings would generalize to the flanker task.

Method

Participants and WMC screening
New participants were recruited from the participant-pool at the University of Georgia.

Individuals were selected based on a z score composite of the three complex span tasks. The three complex span tasks were the same as those in Experiment 2. Only participants falling in the upper (high-WMC individuals) and lower (low-WMC individuals) quartiles of the composite distribution were selected.

Composite score

For the composite score, scores for the three complex span tasks were z-transformed for each participant. These z scores were then averaged together, and quartiles were computed from the averaged distribution. Participants were 33 high-WMC individuals (z-WMC = 0.77, $SD = 0.18$) and 32 low-WMC individuals (z-WMC = −1.04, $SD = 0.72$), as determined by the composite measure. The mean age for both groups was roughly 18.8 years, which did not differ as a function of WMC, $p > .29$. Both groups were composed of 65% females.

Flanker

Participants were presented with a fixation point for 400 ms. This was followed by an arrow directly above the fixation point for 1,700 ms. The arrow consisted of both an arrowhead and a horizontal line (stimuli are from Redick & Engle, 2006). The participants' task was to indicate the direction the arrow was pointing (pressing the F for left-pointing arrows and pressing J for right-pointing arrows) as quickly and accurately as possible. On 50 neutral trials the arrow was flanked by two horizontal lines on each side. On 50 congruent trials the arrow was flanked by two arrows pointing in the same direction as the target arrow on each side. Finally, on 50 incongruent trials the target arrow was flanked by two arrows pointing in the opposite direction to the target arrow on each side. All three trial types were randomly mixed in the same block of trials.

Results

For all the RT results reported, only correct RTs were examined. In addition, RTs that fell below 200 ms or 3 standard deviations below the

individual's mean or above 2,000 ms or 3 standard deviations above the individual's mean were excluded from all RT analyses. This resulted in the exclusion of less than 2% of the responses.

Overall effects

As shown in Figure 5, there was a significant flanker effect, $F(2, 126) = 165.85$, $MSE = 1,847$, $p < .01$, $\eta_p^2 = .73$, such that incongruent trials were slower than both congruent and neutral trials. Overall RTs were slower for low-WMC individuals (687 ms) than for high-WMC individuals (618 ms), $F(1, 63) = 5.81$, $MSE = 40,831$, $p < .05$, $\eta_p^2 = .08$. Importantly, the WMC by flanker condition interaction was significant, $F(2, 126) = 5.41$, $MSE = 1,847$, $p < .01$, $\eta_p^2 = .08$, suggesting that low-WMC individuals had larger flanker effects ($M = 130$ ms, $SE = 14$ ms) than high-WMC individuals ($M = 88$ ms, $SE = 10$ ms). There were no group differences in accuracy (high-WMC, $M = .95$, $SE = .02$, vs. low-WMC, $M = .92$, $SE = .02$), $F(1, 63) = 2.35$, $MSE = 40,831$, $p > .13$, $\eta_p^2 = .03$, but there was a significant effect of flanker condition on accuracy, $F(2, 126) = 27.45$, $MSE = .003$, $p < .01$, $\eta_p^2 = .30$. Accuracy was lower for incongruent ($M = .89$, $SE = .02$) flankers than for either congruent ($M = .96$, $SE = .01$) or neutral ($M = .96$, $SE = .01$) flankers, and this did not differ as a function of WMC, $F(2, 126) = 0.86$, $MSE = .003$, $p > .42$, $\eta_p^2 = .01$. Thus, consistent with prior research, high- and low-WMC individuals differed on a task thought to rely on the ability to constrain attention to target items (Heitz & Engle, 2007; Redick & Engle, 2006; Unsworth & Spillers, 2010).

Quintile analyses

Next, we more fully examined WMC differences in RT and flanker condition by examining the full distribution of RTs. Based on a rate of constraint account of WMC, we should see that high- and low-WMC individuals differ in nearly all quintiles. Additionally, based on a goal maintenance account of WMC, we should see that the RT differences between high- and low-WMC individuals should be largest for the slowest quintiles to the extent
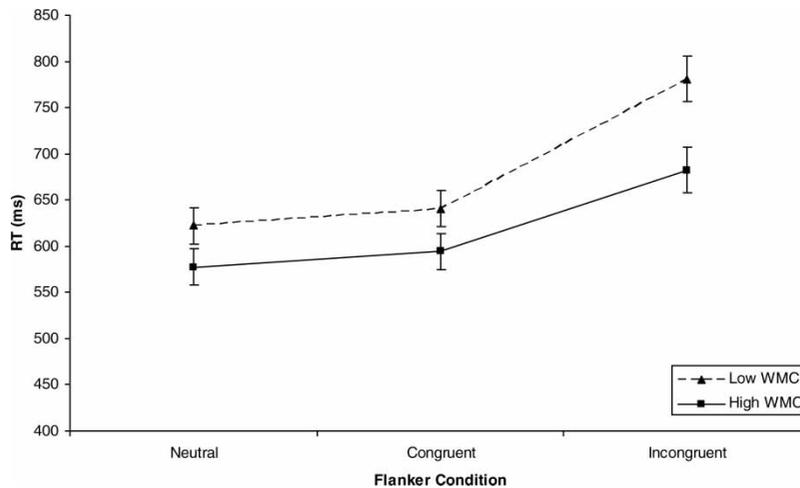
Figure 5. *Mean correct reaction times (RTs) as a function of flanker condition and working memory capacity (WMC). Note, error bars reflect one standard error of the mean.*

that lapses in goal maintenance also contribute to performance differences. Similar to the prior experiments, each individual's RTs were ranked ordered from fastest to slowest for both congruent and incongruent trials. Next, these rank-ordered responses in each condition were placed into five bins such that 20% of each individual's responses were placed into each bin. These quintiles were then averaged across participants in order to examine potential WMC differences in the distributions across conditions. Shown in Figure 6 are the quintile plots as a function of flanker condition (congruent and incongruent trials) and WMC. As can be seen, RT distributions for high- and low-WMC individuals were similar in the congruent condition (Figure 6A) although small differences were apparent. In the incongruent condition (Figure 6B), distributions for high- and low-WMC individuals were different across the board such that low-WMC individuals seemed to have slower RTs than high-WMC individuals in nearly all quintiles (Quintile 1, $p < .07$; Quintiles 2–5, $p < .05$). These observations were supported by a 2 (flanker condition) × 2 (WMC) × 5 (quintile) ANOVA. The results for flanker condition and WMC were similar to those seen in the overall effects. For differences in quintiles, the ANOVA suggested a significant interaction

between WMC and quintile, $F(4, 252) = 4.30$, $MSE = 13,094$, $p < .01$, $\eta_p^2 = .06$, suggesting that WMC differences were largest for the slowest responses. There was also a significant flanker condition by quintile interaction, $F(4, 252) = 4.56$, $MSE = 1,440$, $p < .01$, $\eta_p^2 = .07$, suggesting that the difference between congruent and incongruent trials was largest for the slowest responses. Finally, these effects were qualified by a significant WMC by flanker condition by quintile interaction, $F(4, 252) = 2.81$, $MSE = 1,440$, $p < .05$, $\eta_p^2 = .04$. As shown in Figures 6A and 6B, this interaction suggested that there were slight WMC differences in the congruent trials, but in the incongruent trials, WMC differences were largest for the slowest quintile.

To further examine this effect, we examined delta plots of the difference between incongruent and congruent trials as a function of quintile and WMC. As shown in Figure 6C, the magnitude of the flanker effect seemed to increase as RT increased, similar to what was found with the Stroop task, $F(4, 252) = 4.56$, $MSE = 2,880$, $p < .01$, $\eta_p^2 = .07$. Furthermore, as shown in Figure 6C, high- and low-WMC individuals had similar magnitudes of the flanker effect in the first quintile ($p > .19$), but differed in all other quintiles (all ps $< .05$), with low-WMC individuals
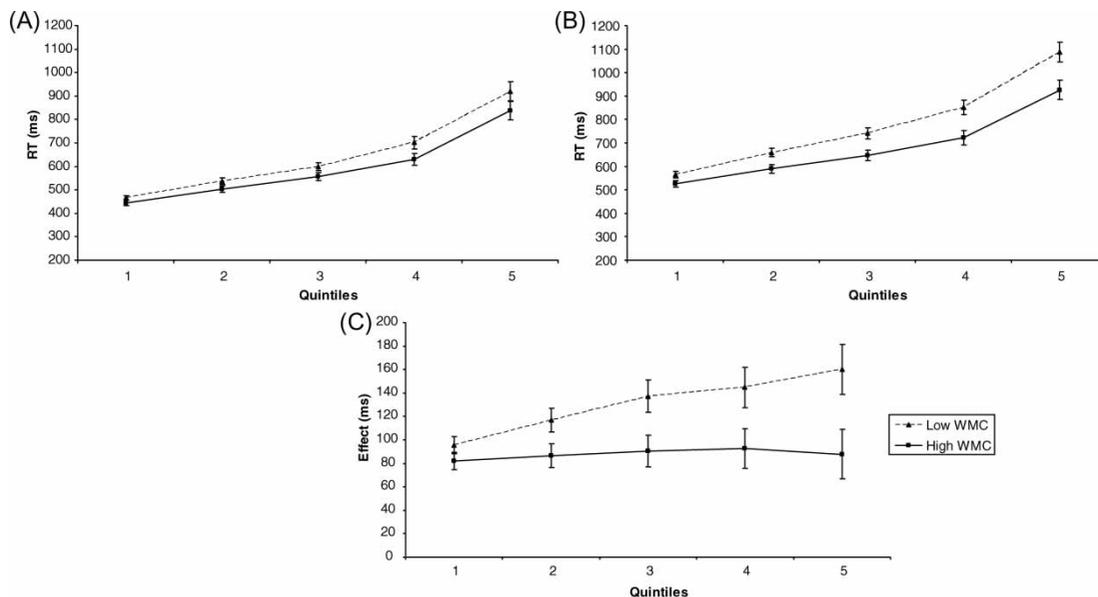
Figure 6. *(A) Quintile plots as a function of working memory capacity (WMC) for the congruent trials on the flanker task in Experiment 4. (B) Quintile plots as a function of working memory capacity for the incongruent trials on the flanker task in Experiment 4. (C) Delta plots of the flanker effect as a function of working memory capacity in Experiment 4. RT = reaction time. Note, error bars reflect one standard error of the mean.*

having larger flanker effects than high-WMC individuals. Specifically, low-WMC individuals' flanker effects increased as RT increased ($p < .01$), but high-WMC individuals' flanker effect stayed the same regardless of RT ($p > .94$). Thus, although WMC differences in the flanker effect were largest for the slowest responses, differences also occurred for other responses as well. This suggests the possibility that high- and low-WMC differences in the flanker task are due to both differences in the rate of constraining attention (Heitz & Engle, 2007) and the differences in maintaining a constrained focus (Poole & Kane, 2009).

Posterror slowing
Similar to the prior experiments, we next examined WMC differences in posterror slowing. As with the prior experiments, we compared correct RTs for trials where the preceding response was correct with trials where the preceding response was incorrect. Consistent with the prior experiments and prior research, there was a posterror

slowing effect such that following an error participants were approximately 40 ms ($SE = 10$) slower on the next correct trial. That is, participants were significantly slower when the preceding response was incorrect than when it was correct, $t(64) = 3.98$, $p < .01$. Examining differences between high- and low-WMC individuals suggested that both groups demonstrated a posterror slowing effect, and the posterror slowing effect was of the same magnitude, $t(63) = 0.61$, $p > .54$. Specifically, high-WMC individuals slowed down by 34 ms ($SE = 13$), and low-WMC individuals slowed down by 47 ms ($SE = 16$). We also examined posterror slowing as a function of flanker condition and WMC. Given that overall accuracy was quite high, there were only 23 low-WMC individuals and 17 high-WMC individuals who had errors in both congruent and incongruent trials and who could contribute to the analysis. These analyses suggested no effect of flanker condition or WMC and no interaction (all ps > .12). Similar to the other three experiments, these results suggest no WMC differences in posterror slowing.
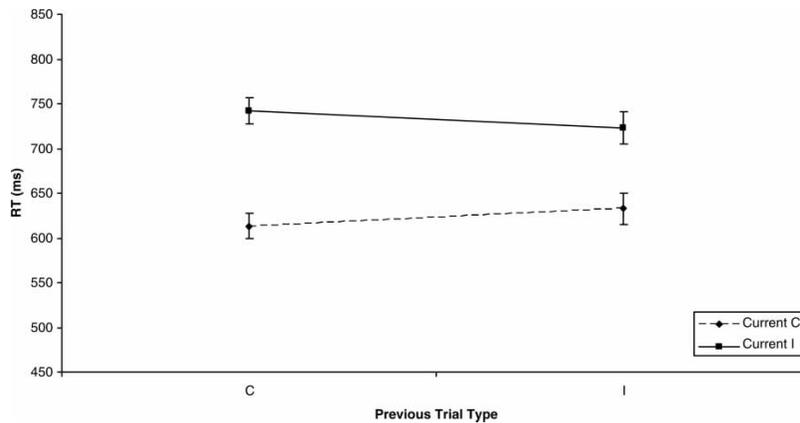
Figure 7. *Mean correct reaction time (RT) as a function of current trial type and previous trial type for the flanker task in Experiment 4. C = congruent; I = incongruent. Note, error bars reflect one standard error of the mean.*

Conflict adaptation

Our final analysis examined potential WMC differences in conflict adaptation effects in the flanker task. Specifically, we examined RT as a function of current trial type congruency, prior trial type congruency, and WMC. As shown in Figure 7, we found the standard conflict adaptation effect with a significant prior trial type by current trial type interaction, $F(1, 63) = 9.76$, $MSE = 2,499$, $p < .01$, $\eta_p^2 = .13$, suggesting that the flanker effect was larger when the prior trial was congruent ($M = 129$ ms, $SE = 11$ ms) than when the prior trial was incongruent ($M = 90$ ms, $SE = 11$ ms). Importantly, high- and low-WMC individuals did not differ in their conflict adaptation effects as indicated by the lack of a significant prior trial by current trial by WMC interaction, $F(1, 43) = 0.12$, $MSE = 2,499$, $p > .73$, $\eta_p^2 = .01$.

Discussion

Consistent with prior research (Heitz & Engle, 2007; Redick & Engle, 2006; Unsworth & Spillers, 2010), high- and low-WMC individuals differed in the magnitude of the flanker effect with low-WMC individuals demonstrating a much larger flanker effect in RTs than high-WMC individuals. Novel to the current experiment was an examination of these differences in terms of overall RT distributions. Quintile analyses suggested

WMC differences in nearly all quintiles on incongruent trials, but the WMC differences were largest for the slowest responses, consistent with the prior experiments. An examination of the delta plot suggested that the differences in the magnitude of the flanker effect for high- and low-WMC individuals were apparent at nearly all quintiles, consistent with the rate of attentional constraint view (Heitz & Engle, 2007). However, the largest differences in the flanker effect were found for the slowest responses. This is consistent with Poole and Kane's (2009) suggestion that perhaps differences in flanker type tasks result from differences in the ability to maintain a constrained focus of attention. That is, attention control and goal maintenance abilities allow one to maintain a constrained focus, and any lapse in attention not only will result in slower overall RTs but will also result in a delay in the constraint of attention, which will increase the difference between incongruent and congruent trials.

Furthermore, the delta plots suggested that high-WMC individuals demonstrated a consistent flanker effect across all quintiles, whereas low-WMC individuals' flanker effect increased across quintiles. This finding potentially helps resolve conflicting findings in the literature regarding the nature of flanker effects in terms of differences in the underlying RT distributions. Specifically, prior work has suggested that the RT difference between incongruent and congruent trials reflects

a constant shift in the RT distribution for incongruent trials compared to congruent trials, with no differences in the tail of the distribution (e.g., Spieler, Balota, & Faust, 2000). Such a shift in the distribution with no difference in the tails of the distributions should lead to a relatively flat delta plot. However, other work has suggested that differences between congruent and incongruent trials are due to both a shift in the distribution and a lengthening of the tail of the incongruent RT distribution (e.g., Blanco & Alvarez, 1994), leading to a linearly increasing delta plot (e.g., Wylie, Ridderinkhof, Eckerle, & Manning, 2007). The fact that high-WMC individuals demonstrate a flat delta plot whereas low-WMC individuals demonstrate an increasing delta plot suggests that prior discrepancies in the literature may be the result of differences in participant characteristics whereby some studies have primarily examined participants high in cognitive control abilities (high in WMC), whereas other studies either have examined a wider range of cognitive control abilities, or have primarily examined participants low in cognitive control abilities (low WMC). Future work should examine the role that individual differences in the cognitive abilities of the samples play in producing the discrepancies observed in the literature.

Finally, and consistent with prior experiments, we found significant posterror slowing, but found that high- and low-WMC individuals demonstrated equivalent posterror slowing. Additionally, and consistent with prior research (Gratton et al., 1992), we found significant conflict adaptation effects, but these did not differ as a function of WMC. Again these results suggest that high- and low-WMC individuals seem to differ in goal maintenance abilities (as well as rate of attentional constraint), but do not differ in conflict monitoring and microadjustments of control.

GENERAL DISCUSSION

In four experiments, we examined variation in WMC and cognitive control via analyses of RT distributions. Specifically, we examined RT differences in a four-choice RT task, a version of the

antisaccade task, a version of the Stroop task, and an arrow version of the flanker task. Based on the executive attention view of WMC (Engle & Kane, 2004), we expected that RT differences between high- and low-WMC individuals would primarily be found in the slowest responses, indicating differences in goal maintenance abilities. Additionally, we examined WMC differences in microadjustments of control via analyses of posterror slowing and conflict adaptation effects. If WMC differences reflect broad differences in cognitive control, we expected to see WMC differences in microadjustments of control.

Across all four experiments the results suggested that high- and low-WMC individuals differ primarily in the slow end of the distribution with little to no differences occurring for the fastest responses. That is, WMC differences in the four-choice RT task and the antisaccade task were only found for the slowest responses. Furthermore, in the Stroop task, WMC differences in RT on incongruent trials only occurred for the slowest responses, resulting in WMC differences in the Stroop effect being localized to the slowest responses. The only task that demonstrated differences across the board in RTs was the flanker task. In this task, high- and low-WMC individuals differed in both fast and slow responses, although differences were maximal for the slowest responses. Overall these results are consistent with the notion that high- and low-WMC individuals differ in goal maintenance abilities in which task goals have to be actively maintained. Lapses in attention control and goal maintenance result in a lengthening of the tail of the RT distribution (i.e., an increase in the number of very slow responses), and these lapses occur more frequently for low-WMC individuals than for high-WMC individuals. In addition, the findings from the flanker task suggest that high- and low-WMC individuals also differ in their ability to rapidly constrain attention to target items (Heitz & Engle, 2007), leading to differences in the ability to maintain a constrained focus of attention (Poole & Kane, 2009). Thus, these experiments, along with prior research (e.g., Unsworth et al., 2010), demonstrate a consistent pattern of results, whereby high- and low-

WMC individuals differ primarily in the slowest responses in a wide range of RT tasks.

Across all four experiments we also found consistent posterror slowing effects where RTs on trials following an error were slower than RTs on trials following a correct response. These results are consistent with many prior studies demonstrating posterror slowing effects on basic choice RT tasks (e.g., Laming, 1979; Rabbitt, 1966) as well as attention control tasks with a high degree of conflict (Kerns et al., 2005; Nieuwenhuis et al., 2001). Consistent with the conflict-monitoring theory (Botvinick et al., 2001), these results suggest that following an error, participants slowed down significantly in order to ensure that the subsequent response was correct, therefore engaging in dynamic microadjustments of control. Despite consistent and robust posterror slowing effects, in all four experiments high- and low-WMC individuals demonstrated equivalent posterror slowing. That is, both high- and low-WMC individuals slowed down following an error, and they slowed down by roughly the same amount. In fact, in all four experiments low-WMC individuals had numerically larger posterror slowing effects than high-WMC individuals. These results are consistent with other research suggesting that low-ability participants demonstrate equivalent or slightly more posterror slowing than high-ability participants (Brewer & Smith, 1984, 1989; Gehring & Knight, 2000; Smith & Brewer, 1995; West & Moore, 2005).

In addition to examining posterror slowing in each experiment, we also examined conflict adaptation effects in both the Stroop and flanker tasks to examine WMC variation in another indicator of microadjustments of control. Consistent with prior research, we found robust conflict adaption effects in both the Stroop (Kerns et al., 2005) and flanker (Gratton et al., 1992) tasks. These results are consistent with the conflict-monitoring theory (Botvinick et al., 2001), which suggests that following an incongruent trial participants make a microadjustment of control such that attention is more tightly focused on the next trial, leading to smaller conflict effects. Despite robust conflict adaptation effects, high- and low-WMC individuals did not differ in conflict adaptation in either the Stroop or the flanker task. These results are

consistent with prior research that found that high- and low-WMC individuals do not differ in conflict adaptation in the flanker task (Heitz, 2003), and variation in WMC was not related to conflict adaptation in either the flanker task or the Simon task (Keye et al., 2008). Thus, if conflict adaptation effects reflect microadjustments of control, it would seem that high- and low-WMC individuals do not differ in those microadjustments of control. Alternatively, it has been argued that conflict adaptation effects partially reflect repetition priming given that many trials are stimulus/response repetitions (Mayr & Awh, 2009; Mayr, Awh, & Laurey, 2003). Thus, at least part of the conflict adaption effect might be due to automatic repetition priming rather than microadjustments of control. Furthermore, there is some evidence that trial-to-trial adjustments can occur without awareness suggesting that conscious control is not necessary to explain these effects (Blais et al., in press). If this is correct, the fact that high- and low-WMC individuals do not differ is perhaps not surprising given the theoretical and empirical link between WMC and control. In the current study, there were not enough trials to examine conflict adaptation in the absence of repetition trials, thus it is possible that with these trials eliminated, a better measure of microadjustments of control can be obtained, which may demonstrate WMC differences. For now, the results suggest that high- and low-WMC individuals do not differ in conflict adaptation effects in at least two attention control tasks.

A strength of the current research is the diversity of the tasks used. In these tasks, performance varied from very accurate (96%) and fast responses (440 ms) to inaccurate (56%) and slow responses (805 ms). Tasks required selection from two, three, or four response options, which varied in prepotency across experiments. Despite these task differences, the basic pattern of results involving WMC were found—differences in the slowest trials, and no relationship with either posterror slowing or conflict adaptation. Future work could bolster this pattern of results via more experimental demonstrations in which WMC is directly manipulated with various load manipulations.

Implications for theories of working memory capacity and cognitive control

Overall, the results of the current study suggest that WMC variation in a number of RT tasks is primarily localized to the slowest responses. These results are consistent with the notion that high- and low-WMC individuals probably differ in goal mainten-ance abilities whereby low-WMC individuals have difficulty actively maintaining task goals and are more likely to have lapses in maintenance than are high-WMC individuals. At the same time, the results suggest that high- and low-WMC indi-viduals do not differ on two putative indicators of microadjustments of control. These results are con-sistent with the executive attention view of WMC (Engle & Kane, 2004) suggesting that variation in WMC is primarily due to differences in goal main-tenance. High-WMC individuals are better able to actively maintain task goals, leading to fast and accurate performance compared to low-WMC individuals. The inability of low-WMC individuals to actively maintain tasks goals leads to periodic lapses in maintenance where the goal was lost but then recovered, leading to much slower responses than on trials on which the goal was actively main-tained and immediately implemented. High-WMC individuals also experience these lapses, but far less frequently than low-WMC individuals. When low-WMC individuals do not have goal maintenance failures on these attention tasks, their performance is indistinguishable from high-WMC individuals' performance. It is argued that these lapses in goal maintenance (i.e., goal neglect) are the primary reason why high- and low-WMC individuals differ on low-level RT tasks. Thus, the current results are consistent with a basic tenet of the executive attention view. At the same time, the fact that high- and low-WMC individuals did not differ in microadjust-ments in control suggests that variation in WMC is not due to global differences in cognitive control, but rather the variation is localized to more specific mechanisms (goal maintenance). Thus, the current results provide a boundary con-dition (e.g., Kane, Poole, Tuholski, & Engle, 2006) for the executive attention view suggesting

that variation in WMC is related to some, but not all, cognitive control functions.

The current results are also consistent with inhibitory accounts of variation in WMC (e.g., Hasher, Lustig, & Zacks, 2007). These accounts suggest that variation in WMC is largely due to differences in the controlled use of inhibition. Thus, the reason that high- and low-WMC indi-viduals differ on tasks like antisaccade, Stroop, and flankers is because high-WMC individuals are better than low-WMC individuals at actively suppressing the incorrect response, thus biasing the probability that the correct response will be generated. Many of the current results are in line with this view in that slower responses may be the result of inefficient inhibitory processes that take time to fully suppress the competing response. Ridderinkhof (2002) has recently advanced such a model in which the incorrect response is actively suppressed. This suppression, however, is variable across trials and participants. When suppression is strong, participants will be minimally influenced by the competing response leading to small conflict effects (as in the Stroop and flanker tasks). When suppression is weak, participants will be more influ-enced by the competing response, and this effect will occur more for slower responses. Using delta plots, several studies have argued that participants who differ in the efficiency of inhibitory control differ in the slowest RTs, with larger conflict effects in those RTs (e.g., Wylie et al., 2007). Thus, the current results (especially the delta plots for the Stroop and flanker tasks) are very much in line with the inhibitory control view. Importantly, like the executive view, the current results suggest a boundary condition for the inhibitory control view by suggesting that not all forms of control are related to variation in WMC.

Although the current results are broadly consist-ent with several views of WMC that suggest that differences are largely due to various control pro-cesses, the current results are not consistent with other views of WMC variation. In particular, the current results argue strongly against the notion that variation in WMC is due simply to differences in speed of processing. According to this view, high-ability individuals (high cognitive control,

high WMC) are faster at processing information, leading to faster overall RTs in a number of tasks (e.g., Jensen, 1998). A similar view has been advocated in the developmental (Hale, 1990) and ageing (Salthouse, 1996) literatures to explain age differences in cognitive processes. In these views, it is the ability to rapidly process information that accounts for differences in RT rather than differences in lapses of goal maintenance. Accordingly, in these speed of processing views, high- and low-WMC individuals should differ at nearly all RTs including both the fastest and the slowest RTs. However, as shown in the current study, high- and low-WMC individuals only differed in the fastest RTs indexed by the first quintile in the flanker task. In all other tasks, there were no differences between high- and low-WMC individuals in the fastest RT quintiles. In fact, WMC differences were largely localized to only the slowest quintile. Thus, it seems very unlikely that variation in WMC as found in RT tasks is due to differences in basic speed of processing.

Finally, the current results are largely inconsistent with views that suggest that variation in WMC is simply due to motivational differences or differences in global processing. That is, alternative theories of variation in WMC would assume that high- and low-WMC individuals simply differ in everything, with high-WMC individuals outperforming low-WMC individuals on every task because of differences in motivation or global processing. Clearly the current results are inconsistent with such a view. In the first three experiments, WMC differences in RT were localized to only the slowest responses, with no differences in the other quintiles. Furthermore, high- and low-WMC individuals did not differ in either posterror slowing or conflict adaption effects, despite the fact that these effects are thought to be indicators of controlled processes. Thus, as we have argued previously (e.g., Unsworth & Engle, 2007), there is overwhelming evidence that high- and low-WMC individuals do not simply differ on every task. Rather, variation in WMC seems to be localized to very specific situations where task goals have to be actively maintained in the face of distraction or when information has to be retrieved from

secondary memory via the self-generation of cues (Unsworth & Engle, 2007).

Before concluding, it would be remiss not to point out some limitations of the current study. In particular, in all four experiments we essentially report null results in terms of the relation between WMC and posterror slowing. Arguing for the null is, of course, quite problematic when relying on traditional null hypothesis testing. Therefore, to give some clarity to our results we utilized a Bayesian analysis suggested by Rouder, Speckman, Sun, Morey, and Iverson (2009) and Gallistel (2009). In particular, for all four experiments we computed Bayes factors for the difference between high- and low-WMC individuals in posterror slowing. Bayes factor provides a means of inferring evidence in favour of the null over evidence in favour of the alternative. That is, Bayes factors represent the odds ratio of evidence in favour of one hypothesis (in this case the null) over the alternative (i.e., the hypothesis that a difference actually exists). For instance, a Bayes factor of 3 suggests that the odds are 3:1 in favour of the null over the alternative (i.e., the null is three times more likely than the alternative) given the data. Computation of Bayes factors represents a significant step over traditional null hypothesis significance testing in that in traditional null hypothesis significance testing a nonsignificant p-value simply indicates a failure to reject the null. Use of Bayes factors, however, allows one to examine the extent to which there is evidence in favour of the null over the alternative (see Gallistel, 2009; Rouder et al., 2009, for excellent arguments on this point). Relying on Bayes factors suggests that in all four experiments the estimated Bayes factors suggested that the odds were always more than 3.7:1 in favour of the null. That is, the null hypothesis was more than three times more likely than the alternative. Thus, it would seem that there are probably few to no differences between high- and low-WMC individuals in posterror slowing.

An additional limitation is the fact that for the quintile analyses there are relatively few trials per bin in each experiment. In particular, in Experiments 2–4 there are on average 5 usable trials per bin. Such a small number of trials could

possibly lead to large standard errors and unreliable results. However, we are confident in our results given that prior research not only by us (e.g., Unsworth et al., 2010) but by others as well (e.g., Tse, Balota, Duchek, Yap, & McCabe, 2010; Yap, Balota, Tse, & Besner, 2008) has used a similar number of trials per bin and found consistent results not only in terms of individual differences in cognitive abilities, but in age differences as well. Furthermore, reanalysing the results in terms of quartiles (i.e., 25% of responses per bin) rather than quintiles (i.e., 20% of responses per bin) resulted in exactly the same pattern of results in all experiments as that in the reported quintile analyses. Thus, although there are a small number of trials, the results seem to be quite reliable in that the same general pattern is observed across experiments, and several of the overall results replicate prior work (e.g., Spieler et al., 2000; Unsworth et al., 2010).

CONCLUSION

In the current study, we examined variation in WMC and cognitive control. It was found that high- and low-WMC individuals differ primarily in the slowest RTs in a number of RT tasks. Furthermore, although significant posterror slowing and conflict adaptation effects were found, these were unrelated to variation in WMC. These results suggest that variation in WMC is related to some cognitive control operations (e.g., active maintenance) but not to others (e.g., microadjustments of control), thus constraining current theories of WMC. Future work is needed to better delineate the nature of WMC differences in cognitive control.

REFERENCES

Blais, C., Harris, M. B., Guerrero, J. V., & Bunge, S. (in press). Rethinking the role of automaticity in cognitive control. *Quarterly Journal of Experimental Psychology*.

Blanco, M. J., & Alvarez, A. A. (1994). Psychometric intelligence and visual focused attention: Relationships in nonsearch tasks. *Intelligence*, 18, 77–106.

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 & Review*, 10, 884–889.

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

Brewer, N., & Smith, G. A. (1984). How normal and retarded individuals monitor and regulate speed and accuracy of responding in serial choice tasks. *Journal of Experimental Psychology: General*, 113, 71–93.

Brewer, N., & Smith, G. A. (1989). Developmental changes in processing speed: Influence of speed–accuracy regulation. *Journal of Experimental Psychology: General*, 118, 298–310.

Carter, C. S., & Van Veen, V. (2007). Anterior cingulate cortex and conflict detection: An update of theory and data. *Cognitive, Affective, & Behavioral Neuroscience*, 7, 367–379.

Cohen, J. D., Aston-Jones, G., & Gilzenrat, M. S. (2004). A systems-level perspective on attention and cognitive control: Guided activation, adaptive gating, conflict monitoring, and exploitation vs. exploration. In M. I. Posner (Ed.), *Cognitive neuroscience of attention* (pp. 71–90). New York, NY: Guilford Press.

Cohen, J. D., Botvinick, M., & Carter, C. S. (2000). Anterior cingulate and prefrontal cortex: Who's in control? *Nature Neuroscience*, 3, 421–423.

Cohen, J. D., Dunbar, K., & Mcclelland, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review*, 97, 332–361.

Colflesh, G. J. H., & Conway, A. R. A. (2007). Individual differences in working memory capacity and divided attention in dichotic listening. *Psychonomic Bulletin & Review*, 14, 699–703.

Conway, A. R. A., Cowan, N., & Bunting, M. F. (2001). The cocktail party phenomenon revisited: The importance of working memory capacity. *Psychonomic Bulletin and Review*, 8, 331–335.

Debener, S., Ullsperger, M., Siegel, M., Fiehler, K., von Cramon, D. Y., & Engel, A. K. (2005). Trial-by-trial coupling of concurrent electroencephalogram and functional magnetic resonance imaging identifies the dynamics of performance monitoring. *Journal of Neuroscience*, 25, 11730–11737.

De Jong, R., Berendsen, E., & Cools, R. (1999). Goal neglect and inhibitory limitations: Dissociable causes of interference effects in conflict situations. *Acta Psychologica*, *101*, 379–394.

Dinges, D. F., & Powell, J. W. (1985). Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. *Behavior Research Methods, Instruments, & Computers*, *17*, 652–655.

di Pellegrino, G., Ciaramelli, E., & Làdavas, E. (2007). The regulation of cognitive control following rostral anterior cingulate cortex lesion in humans. *Journal of Cognitive Neuroscience*, *19*, 275–286.

Duncan, J. (1995). Attention, intelligence, and the frontal lobes. In M. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 721–733). Cambridge, MA: MIT Press.

Egner, T., & Hirsch, J. (2005). Cognitive control mechanisms resolve conflict through cortical amplification of task-relevant information. *Nature Neuroscience*, *8*, 1784–1790.

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. In B. Ross (Ed.), *The psychology of learning and motivation* (Vol. 44, pp. 145–199). New York, NY: Elsevier.

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 letter in a non-search task. *Perception & Psychophysics*, *16*, 143–149.

Everling, S., & Fischer, B. (1998). The antisaccade: A review of basic research and clinical studies. *Neuropsychologia*, *36*, 885–899.

Fukuda, K., & Vogel, E. K. (2009). Human variation in overriding attentional capture. *Journal of Neuroscience*, *29*, 8726–8733.

Gallistel, C. R. (2009). The importance of proving the null. *Psychological Review*, *116*, 439–453.

Gehring, W. J., & Knight, R. T. (2000). Prefrontal-cingulate interactions in action monitoring. *Nature Neuroscience*, *3*, 516–520.

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

Hale, S. (1990). A global developmental trend in cognitive processing speed. *Child Development*, *61*, 653–663.

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

Hasher, L., Lustig, C., & Zacks, R. T. (2007). Inhibitory mechanisms and the control of attention. In A. R. A. Conway. C. Jarrold, M. Kane J., A. Miyake, & J. N. Towse (Eds.), *Variation in working memory*. New York, NY: Oxford.

Heitz, R. P. (2003). *Individual differences in working memory capacity and visual attention*, Unpublished master's thesis, Georgia Institute of Technology, Atlanta, GA.

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

Jensen, A. R. (1998). *The g factor*. Westport, CT: Praeger.

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*(2), 169–183.

Kane, M. J., Conway, A. R. A., Hambrick, D. Z., & Engle, R. W. (2007). Variation in working memory capacity 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*. New York, NY: 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*, 47–70.

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.

Kerns, J. G., Cohen, J. D., Macdonald, A. W., III, Johnson, M. K., & Stenger, V.A., Aizenstein, H., et al. (2005). Decreased conflict- and error-related activity in the anterior cingulate cortex in subjects with schizophrenia. *American Journal of Psychiatry*, *162*, 1833–1839.

Keye, D., Wilhelm, O., Oberauer, K., & van Ravenzwaaij, D. (2008). Individual differences in conflict monitoring: Testing means and covariance hypothesis about the Simon and the Eriksen Flanker task. *Psychological Research*, *73*, 762–776.

Laming, D. (1979). Choice reaction performance following an error. *Acta Psychologica*, *43*, 199–224.

Larson, M. J., Kaufman, D. A. S., & Perlstein, W. M. (2009). Conflict adaptation and cognitive control adjustments following traumatic brain injury. *Journal of International Neuropsychological Society*, *15*, 927–937.

Long, D. L., & Prat, C. S. (2002). Working memory and Stroop interference: An individual differences investigation. *Memory & Cognition*, *30*, 294–301.

Mayr, U., & Awh, E. (2009). The elusive link between conflict and conflict adaptation. *Psychological Research*, *73*, 794–802.

Mayr, U., Awh, E., & Laurey, P. (2003). Conflict adaptation effects in the absence of executive control. *Nature Neuroscience*, *6*, 450–452.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex functioning. *Annual Review of Neuroscience*, *24*, 167–202.

Nieuwenhuis, S., Ridderinkhof, K. R., Blom, J., Band, G. P. H., & Kok, A. (2001). Error-related brain potentials are differentially related to awareness of response errors: Evidence from an antisaccade task. *Psychophysiology*, *38*, 752–760.

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

Pratte, M. S., Rouder, J. N., Morey, R. D., & Feng, C. (2010). Exploring the differences in the distributional properties between Stroop and Simon effects using delta plots. *Attention, Perception, & Psychophysics*, *72*, 2013–2025.

Rabbitt, P. M. A. (1966). Errors and error-correction in choice-response tasks. *Journal of Experimental Psychology*, *71*, 264–272.

Redick, T. S., & Engle, R. W. (2006). Working memory capacity and attention network test performance. *Applied Cognitive Psychology*, *20*, 713–721.

Ridderinkhof, K. R. (2002). Micro- and macro-adjustments of task set: Activation and suppression in conflict tasks. *Psychological Research*, *66*, 312–323.

Roberts, R. J., & Pennington, B. F. (1996). An integrative framework for examining prefrontal cognitive processes. *Developmental Neuropsychology*, *12*, 105–126.

Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian *t* tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review*, *16*, 225–237.

Salthouse, T. A. (1996). The processing speed theory of adult age differences in cognition. *Psychological Review*, *103*, 403–428.

Schachar, R. J., Chen, S., Logan, G. D., Ornstein, T. J., Crosbie, J., Ickowicz, A., et al. (2004). Evidence for an error monitoring deficit in attention deficit hyperactivity disorder. *Journal of Abnormal Child Psychology*, *32*, 285–293.

Schmiedek, F., Oberauer, K., Wilhelm, O., Süß, H. M., & Wittmann, W. W. (2007). Individual differences in components of reaction time distributions and their relations to working memory and intelligence. *Journal of Experimental Psychology: General*, *136*, 414–429.

Smith, G. A., & Brewer, N. (1995). Slowness and age: Speed–accuracy mechanisms. *Psychology and Aging*, *10*, 238–247.

Spieler, D. H., Balota, D. A., & Faust, M. E. (2000). Levels of selective attention revealed through analyses of response time distributions. *Journal of Experimental Psychology: Human Perception and Performance*, *26*, 506–526.

Stürmer, B., Leuthold, H., Soetens, E., Schröter, H., & Sommer, W. (2002). Control over location-based response activation in the Simon task: Behavioral and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception & Performance*, *28*, 1345–1363.

Tse, C., Balota, D. A., Duchek, J. M., Yap, M. J., & Mccabe, D. P. (2010). Effects of healthy aging and early stage dementia of the Alzheimer's type on components of response time distributions in three attention tasks. *Neuropsychology*, *24*, 300–315.

Unsworth, N., & Engle, R. W. (2007). The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory. *Psychological Review*, *114*, 104–132.

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

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

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.

Unsworth, N., & Spillers, G. J. (2010). Working memory capacity: Attention, memory, or both? A direct test of the dual-component model. *Journal of Memory and Language*, *62*, 392–406.

West, R., & Moore, K. (2005). Adjustments of cognitive control in younger and older adults. *Cortex*, *41*, 447–616.

Wylie, S. A., Ridderinkhof, K. R., Eckerle, M. K., & Manning, C. A. (2007). Inefficient response inhibition in individuals with mild cognitive impairment. *Neuropsychologia*, *45,* 1408–1419.

Yap, M. J., Balota, D. A., Tse, C. S., & Besner, D. (2008). On the additive effects of stimulus quality and word frequency in lexical decision: Evidence for opposing interactive influences revealed by RT distributional analyses. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *34,* 495–513.

APPENDIX

Mean total correct for each task by WMC

		Task		
Experiment	WMC	Ospan	Symspan	Rspan
Experiment 1	High	71.19 (2.74)	—	69.73 (3.84)
	Low	55.73 (6.71)	—	48.54 (6.59)
Experiment 2	High	69.13 (4.65)	36.40 (3.06)	68.47 (5.33)
	Low	44.09 (10.65)	21.97 (6.32)	43.50 (11.50)
Experiment 3	High	68.78 (4.70)	36.13 (2.79)	67.52 (5.55)
	Low	40.91 (9.79)	19.59 (6.73)	40.55 (10.09)
Experiment 4	High	69.21 (4.24)	36.48 (3.56)	69.42 (4.15)
	Low	45.38 (12.57)	22.94 (7.20)	42.51 (9.27)

Note: WMC = working memory capacity. Ospan = operation span; Symspan = symmetry span; Rspan = reading span; Ospan and Rspan are out of 75, and Symspan is out of 42. Standard deviations in parentheses.