THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY
2011, 64 (6), 1048–1055

Psychology Press
Taylor & Francis Group

Rapid communication

Integrating working memory capacity and context-processing views of cognitive control

Thomas S. Redick and Randall W. Engle

School of Psychology, Georgia Institute of Technology, Atlanta, GA, USA

Individuals low in working memory capacity (WMC) exhibit impaired performance on a variety of cognitive control tasks. The executive-attention theory of WMC (Engle & Kane, 2004) accounts for these findings as failures of goal maintenance and response conflict resolution. Similarly, the context-processing view (Braver et al., 2001) provides an explanation of cognitive control deficits observed in schizophrenia patients and older adults that is based on the ability to maintain context information. Instead of maintenance deficits, the inhibition view (Hasher, Lustig, & Zacks, 2007) states that older adults and individuals low in WMC primarily have an impairment in the ability to inhibit information. In the current experiment, we explored the relationships among these theories. Individuals differing in performance on complex span measures of WMC performed the AX-Continuous Performance Test to measure context-processing performance. High-WMC individuals were predicted to maintain the context afforded by the cue, whereas low-WMC individuals were predicted to fail to maintain the context information. Low-WMC individuals made more errors on AX and BX trials and were slower to respond correctly on AX, BX, and BY trials. The overall pattern of results is most consistent with both the executive-attention and context-processing theories of cognitive control.

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

Numerous studies have demonstrated that individual differences in working memory capacity (WMC) are important for higher order cognition. In the Operation Span (Unsworth, Heitz, Schrock, & Engle, 2005), a typical WMC measure, participants must mentally solve maths problems while also remembering letters for later recall. High-WMC individuals outperform those low in WMC on memory and cognitive control tasks. Engle and Kane (2004) interpreted individual differences in WMC as reflecting variation in *executive-attention* ability. High-WMC individuals are better at maintaining goal-related information and resolving response conflict in interference-rich situations.

However, most evidence for the executive-attention account is also consistent with an

Correspondence should be addressed to Thomas S. Redick School of Psychology, Georgia Institute of Technology, 654 Cherry Street, Atlanta, GA 30332, USA. E-mail: thomas.redick@gatech.edu

We thank Nash Unsworth, Whitney Hansen, and the members of the Attention & Working Memory Lab for feedback on an earlier version of this manuscript.

http://www.psypress.com/qjep
DOI:10.1080/17470218.2011.577226

inhibition theory of WMC (Hasher, Lustig, & Zacks, 2007), leading to a "theoretical 'chicken-egg' dilemma" (Kane, Bleckley, Conway, & Engle, 2001, p. 180). For example, in Experiment 1 of Unsworth, Schrock, and Engle (2004), high- and low-WMC participants completed prosaccade (look toward) and antisaccade (look away) blocks of trials. Because participants can quickly respond on prosaccade trials in a reflexive manner, there is little cognitive control or inhibition necessary to respond quickly and accurately. Consequently, there were no WMC differences in prosaccade performance. However, low-WMC individuals were slower and made more errors during the antisaccade block of trials. Antisaccade errors reflect a failure to maintain the goal to look away from the flashing stimulus (executive attention) or a failure to suppress the automatic orienting response (inhibition). Similar explanations could be applied to previous research with the Stroop task (Kane & Engle, 2003)—poorer low-WMC performance could be due to failure to maintain the goal of naming the ink colour (executive attention) or inability to suppress the automatic word-reading response (inhibition).

However, a different pattern of results was obtained in Experiment 2 of Unsworth et al. (2004). The only change was to add a cue 1,200 ms before the stimulus to indicate whether each trial required a pro- or antisaccade response. Failure to maintain the cue information in an active state during the cue–stimulus interval would result in slower performance and more errors for both pro- and antisaccade trials; this is the pattern that the low-WMC group exhibited. The inhibition theory would not predict that low-WMC individuals would go against the prepotent response and produce prosaccade errors. The faster responses by the high-WMC group also indicate that they were more likely to maintain the cue than the low-WMC group.

Context-processing view of cognitive control

While the executive-attention theory has focused on variation within healthy young adults, the context-processing view was developed to account for impaired cognitive control exhibited in schizophrenia patients (Cohen, Barch, Carter, & Servan-Schreiber, 1999) and older adults (Braver et al., 2001; Braver, Satpute, Rush, Racine, & Barch, 2005). The main tenet of the context-processing view is that individuals vary in their ability to maintain context (e.g., task instructions, previous stimuli, cues) to guide future behaviour. This is similar to the role that goal maintenance plays in the executive-attention theory.

Just as complex span tasks have been used as the primary measures of WMC, the AX-Continuous Performance Test (AX-CPT) has been the principal task used to assess context processing. In the AX-CPT, individual letters are presented sequentially, and participants are required to make a target response when the letter X follows the letter A (AX trial). AX targets occur on 70% of all letter sequences, so an expectancy to make a target response is created when the letter A is presented. However, on 10% of trials, the A is not followed by an X (AY trial, where Y stands for all non-X letters), and the expectancy information actually hurts performance. In addition, on 10% of trials, the X will follow a letter other than A (BX trial, where B stands for all non-A letters). In this case, because the previous letter was not an A, the following letter does not require a target response. However, because the letter X is so frequently associated with a target response, the individual must maintain the cue information to avoid making an error. Finally, on 10% of trials, letters other than A and X are presented sequentially (BY trial) to serve as a baseline condition; neither the first nor the second letter in this sequence signals a target response.

The design of the AX-CPT is used to study context processing according to the following logic. Individuals maintaining context (controls, young adults, high-WMC individuals) will use the information obtained from the cue to prepare either a target or a nontarget response to the upcoming probe letter. Thus, intact context maintenance will lead to fewer errors specifically on AX and BX trials and will also speed correct responses on AX, BX, and BY trials. However, AY trials should be more error prone, and slower for correct trials, because the expected target stimulus does not occur. In contrast, individuals with impaired context maintenance (schizophrenia patients, older adults, low-WMC individuals) do not actively maintain the cue information during the cue–probe delay. Therefore, impaired context maintenance will be demonstrated by more errors on AX and BX trials and slower correct response times (RTs) on AX, BX, and possibly BY trials. However, on AY trials, not maintaining the A cue should actually help performance, because a target response has not been prepared before the probe appears.

CURRENT EXPERIMENT

Despite the similarities between the executive-attention and context-processing views, these theories have operated largely independently of each other. In the current study, individuals who had been previously classified as high- or low-WMC completed the AX-CPT. In addition, performance on the AX-CPT can discriminate between the inhibition and executive-attention theories of individual differences in WMC. More specifically, impaired BX performance by the low-WMC group is consistent with both the executive-attention and inhibition theories. However, more AX errors by the low-WMC group would indicate that they are overriding the prepotent target response to the X probe and instead making a nontarget response. This would not be predicted by the inhibition view, but is consistent with a goal-maintenance failure in the executive-attention theory. In fact, this pattern of results would be very similar to the cued antisaccade and prosaccade results in Unsworth et al. (2004). In addition, the ability to maintain the cue information would lead to faster responses on AX, BX, and BY trials. For example, if high-WMC individuals use the B cue to prepare a nontarget response before the probe appears, then they should be faster than the low-WMC individuals who are less likely to maintain the cue.

In addition, we manipulated the interval between the cue and probe letter in the AX-CPT (e.g., Braver et al., 2005). Previous AX-CPT studies have found that individuals with schizophrenia (Cohen et al., 1999) and Alzheimer's disease (Braver et al., 2005) exhibit even worse AX and BX performance as the delay between the cue and probe is lengthened. Thus, one prediction is that the low-WMC deficits may be exacerbated with a longer delay as the context information is maintained longer in working memory. In contrast, healthy older adults are not differentially impacted by a longer cue–probe interval (Braver et al., 2005; Paxton, Barch, Storandt, & Braver, 2006), and so the delay effect may be specific to patients. The effect of delay is secondary compared to the main investigation of the WMC × Trial Type interaction.

Method

Participants

All participants were healthy young adults. Participants included students recruited from colleges and nonstudents within the metropolitan Atlanta area. Participants were compensated with their choice of one research credit or $20. Demographic information about the final sample of 33 high-WMC and 32 low-WMC participants is presented in Table 1.[1]

WMC screening

In the first session, all participants completed automated versions of Operation, Symmetry, and

[1] Nine low-WMC participants were eliminated from the final sample. Four participants could not achieve 75% probe accuracy after three practice blocks and therefore did not complete any experimental blocks. Two participants did not complete the task (one due to experimenter error, the other due to a fire alarm). One participant had an overall accuracy of 66%, largely a result of near-chance performance (54%) on long AX targets. Finally, 2 participants made errors on all long BX nontargets; these individuals had no correct responses to contribute to the RT analyses and may not have understood the task instructions. Note that eliminating these last 3 low-WMC participants weakened our ability to detect the predicted WMC differences in the AX and BX conditions. In addition, including these 3 participants in the analyses did not change any of the results.

Table 1. Demographic information for the high- and low-WMC participants

WMC group	*M/F*	*Age*	*WMC z-score*	*Operation*	*Symmetry*	*Reading*
High	17/16	21.5 (2.0)	0.99 (0.20)	70.0 (3.1)	34.6 (4.5)	66.6 (4.9)
Low	14/18	24.6 (4.8)	−1.02 (0.59)	38.8 (12.2)	17.2 (6.5)	35.3 (14.7)

Note: WMC = working memory capacity. M = male. F = female. Standard deviations in parentheses.

Reading Span in order to assess their WMC. The WMC score was the total number of items recalled in the correct serial position. Performance on each task was transformed into a *z* score based on a database of thousands of scores from our laboratory. A WMC composite was created by averaging across the complex span tasks for each participant. If a participant's WMC composite score fell within the upper or lower quartiles compared to our database, the individual was invited to participate in a second session in which the AX-CPT was administered. For further task descriptions and information about construct validity and test–retest reliability, see Barch et al. (2009), Unsworth et al. (2005), and Unsworth, Redick, Heitz, Broadway, and Engle (2009).

AX-CPT

The AX-CPT used in the current study was based on Braver et al. (2005) and was as described above. Participants used their right hand to make target responses to the letter X when it followed an A (probes on AX trials) with the middle finger and to make nontarget responses to all other stimuli that appeared (all cues and probes on AY, BX, and BY trials) with the index finger. Letters were presented for 300 ms each, and participants had up to 1,000 ms from the onset of each letter to respond. Cues and probes were randomly determined for each nontarget trial, and all letters except K and Y were used.

The cue–probe interval was either 1,000 ms (short) or 5,000 ms (long). The intertrial interval inversely varied with the cue–probe interval to keep all trials the same total duration (8,000 ms). Thus, the intertrial interval was either 5,000 ms (short) or 1,000 ms (long). A fixation point was displayed during the intertrial interval.

Participants completed practice blocks until they had achieved a mean probe accuracy of 75% before proceeding to the experimental blocks. For the final sample, 5 low-WMC participants needed two practice blocks to achieve this criterion, whereas all high-WMC participants needed one block.

Design and analyses

Each of the eight experimental blocks contained 10 long- and 10 short-delay trials. Seven AX targets, one AY nontarget, one BX nontarget, and one BY nontarget were presented within each delay condition in each block.

The study was a 2 (WMC) × 4 (trial type) × 2 (delay) design, with WMC (high, low) as a between-subjects factor, and trial type (AX, AY, BX, BY) and delay (short, long) as within-subjects factors. Probe accuracy was assessed by analysing error rates across trial types and additionally computing signal-detection measures of sensitivity (d'-context) and bias (C) using AX hit rates and BX false alarms (Cohen et al., 1999). Hit and false-alarm rates equal to 0 or 1 were adjusted by .01. The mean of median correct RTs were also analysed. Alpha = .05 was used for all statistical tests. Partial eta-squared (η_p^2) is provided as an index of effect size.[2]

[2] Although the results focus on the performance on probes, cue accuracy was also assessed to ensure general compliance with task instructions. Cue accuracy was 98% for each WMC group. In order to maximize the number of observations, performance was evaluated on all trials regardless of whether the cue was correct or not. Restricting analyses to only those trials in which the cue was responded to correctly did not change the results.

Results

Accuracy

Errors are presented in Figure 1. Both WMC groups made the most errors on AY trials, and errors decreased at the long cue–probe interval. Critically, the low-WMC group committed more errors than the high-WMC group specifically on AX and BX trials and not on AY or BY trials. Significant main effects of WMC, $F(1, 63) = 6.25$, $p = .015$, $\eta_p^2 = .090$, trial type, $F(3, 189) = 59.21$, $p < .001$, $\eta_p^2 = .484$, and interval, $F(1, 63) = 7.69$, $p = .007$, $\eta_p^2 = .109$, were obtained. These main effects were qualified by significant interactions of WMC × Trial Type, $F(3, 189) = 3.18$, $p = .025$, $\eta_p^2 = .048$, and Trial Type × Interval, $F(3, 189) = 5.00$, $p = .002$, $\eta_p^2 = .073$. The WMC × Interval and Trial Type × Interval interactions did not approach significance (both Fs < 1). Follow-up t tests indicated that the low-WMC group committed significantly more errors on short-AX, $t(63) = 2.05$, $p = .044$, long-AX, $t(63) = 2.46$, $p = .017$, short-BX, $t(63) = 2.49$, $p = .016$, and long-BX trials, $t(63) = 3.00$, $p = .004$ (all other ps $> .266$).

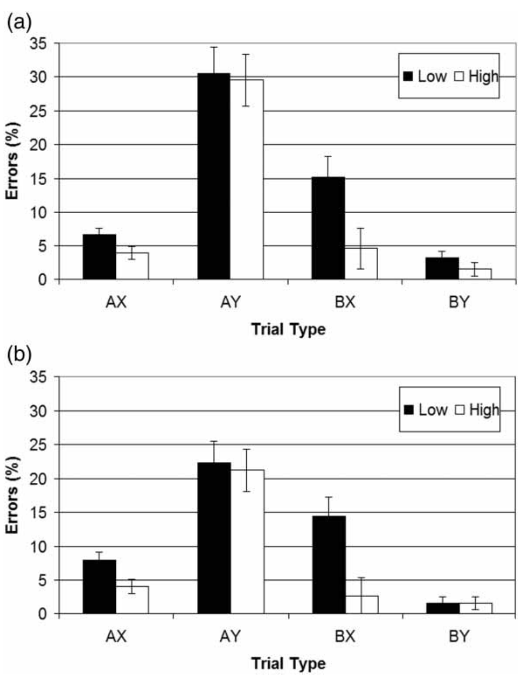

Figure 1. *Errors in Experiment 1 for each WMC (working memory capacity) group as a function of short (A) and long (B) interval between cues and probes. Error bars represent ±1 standard error of the mean.*

Because AY and BX performance has been especially important to the context-processing view, planned interaction contrasts were conducted comparing AY versus BX errors for the high- versus low-WMC groups combined across the interval conditions (Braver et al., 2001; Haarmann, Ashling, Davelaar, & Usher, 2005). The contrast was marginally significant, $F(1, 63) = 3.01$, $p = .088$. The interaction was driven by the greater number of BX errors committed by the low-WMC group than by the high-WMC group (Figure 1).

As can be seen in Table 2, d'-context was larger for the high-WMC individuals across both intervals, indicating greater sensitivity than that for the low-WMC individuals. In contrast, the WMC groups did not differ in response bias at either interval. For d'-context, the main effect of WMC was significant, $F(1, 63) = 9.47$, $p = .003$, $\eta_p^2 = .131$. The main effect of interval ($F < 1$) and the WMC × Interval interaction, $F(1, 63) = 1.58$, $p = .214$, $\eta_p^2 = .024$, were not significant. For C, neither the main effect of WMC, $F(1, 63) = 2.52$, $p = .12$, $\eta_p^2 = .038$, nor the main effect of the interval and the WMC × Interval interaction (both Fs < 1), was significant.

Response times

Mean RTs are presented in Figure 2 as a function of trial type and interval for each WMC group. AY

Table 2. *Signal detection data for high- and low-WMC groups*

WMC group	*Short interval*	*Long interval*
d′-context sensitivity		
High	3.80 (0.76)	3.95 (0.75)
Low	3.22 (1.35)	3.07 (1.27)
C bias		
High	0.04 (0.31)	0.13 (0.25)
Low	−0.05 (0.47)	−0.03 (0.48)

Note: WMC = working memory capacity. Standard deviations in parentheses.

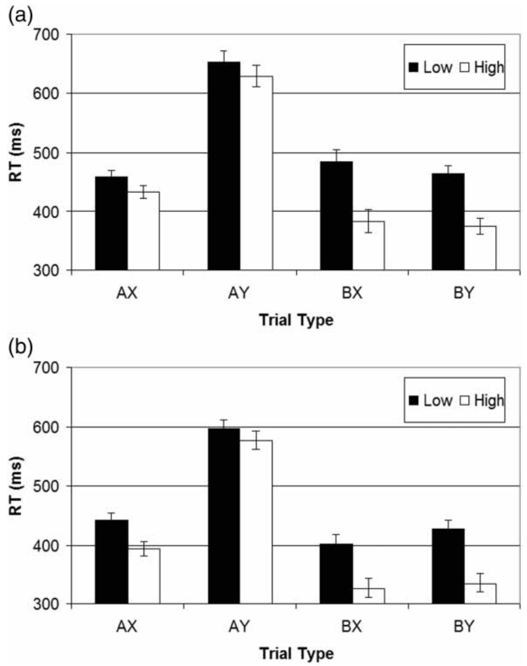

Figure 2. *Mean RTs in Experiment 1 for each WMC (working memory capacity) group as a function of short (A) and long (B) interval between cues and probes. Error bars represent* ±1 *standard error of the mean.*

RTs were slowest, compared to the other trial types, and short-interval trials were slower than long-interval trials. In addition, the low-WMC group appeared to be slower than the high-WMC group on all trial types except AY trials.

All main effects were significant: WMC, $F(1, 63) = 12.56$, $p = .001$, $\eta_p^2 = .166$, trial type, $F(3, 189) = 268.33$, $p < .001$, $\eta_p^2 = .810$, and interval, $F(1, 63) = 82.21$, $p < .001$, $\eta_p^2 = .566$. These effects were qualified by significant two-way interactions of WMC × Trial Type, $F(3, 189) = 7.91$, $p < .001$, $\eta_p^2 = .112$, and Trial Type × Interval, $F(3, 189) = 5.33$, $p = .002$, $\eta_p^2 = .078$. The WMC × Interval interaction was not significant ($F < 1$), and neither was the three-way WMC × Trial Type × Interval interaction, $F(3, 189) = 1.63$, $p = .184$, $\eta_p^2 = .025$.

Follow-up *t* tests indicated that the low-WMC group was significantly slower than the high-WMC group on long-AX, $t(63) = 2.91$, $p = .005$, short-BX, $t(63) = 3.68$, $p < .001$, long-BX, $t(63) = 3.23$, $p = .002$, short-BY, $t(63) = 4.63$, $p < .001$, and long-BY trials, $t(63) = 4.12$, $p < .001$. Although the WMC difference approached significance on short-AX trials, $t(63) = 1.67$, $p = .100$, the two groups did not differ in RTs on short- or long-AY trials (both *p*s > .377).

Comparing the WMC groups across intervals, the planned AY versus BX interaction contrast was significant, $F(1, 63) = 8.90$, $p = .004$. The interaction was driven by no WMC differences on AY trials but slower BX performance by the low-WMC group (Figure 2).

Discussion

First, the low-WMC group made more AX and BX errors than the high-WMC group. Because the probe X is sometimes a target (AX), and other times the X is a nontarget (BX), maintaining the cue is critical for choosing the correct response. AY and BY trials can be responded to correctly without using the cue. Although the low-WMC group's increased BX errors are also compatible with the inhibition account (Hasher et al., 2007), the increased AX errors are inconsistent with a strict inhibition interpretation. If low-WMC individuals were only impaired in their ability to inhibit (as could be claimed based on increased BX errors), then the observation that they go against the prepotent target response and instead make more nontarget responses to an X following an A is inconsistent with the idea that inhibition is the primary deficit for low-WMC individuals. Instead, because the probe X almost always follows the cue A, AX errors reflect a failure to maintain the context provided by the cue, more consistent with the executive-attention and context-processing theories.

Second, the low-WMC group was slower than the high-WMC group on AX, BX, and BY trials, but not on AY trials. This finding is consistent with the interpretation that the high-WMC group is disproportionately slowed on AY trials by using the A cue to prepare a target response and then having to quickly execute a competing nontarget response instead. An alternative explanation is that low-WMC individuals have a general processing-speed deficit, because they were slower overall than the high-WMC group. However, the overall pattern of results does not implicate processing speed as the mechanism responsible for the performance of the two WMC groups. A processing-speed explanation would predict that because AY trials were slowest for the high-WMC group, that condition would produce the largest WMC difference (for similar ageing results, see Braver et al., 2001; Haarmann et al., 2005). However, according to the executive-attention and context-processing theories, RT differences would specifically emerge on AX, BX, and BY trials because the high-WMC group is using the cue information to prepare the correct response before the probe appears. In contrast, the low-WMC group is less likely to maintain the context and instead begin the response selection process when the probe appears.

We observed that the interval manipulation did not differentially affect the two WMC groups. This is similar to the results observed in Braver et al. (2005) and Paxton et al. (2006) comparing young adults to healthy older adults. The implication is that the length of the delay between the cue and probe is not critical to produce the observed WMC effects. The low-WMC group showed performance impairments on the AX-CPT even when only 2,000 ms separated the onset of the cue and the probe. One possibility is that low-WMC individuals are unable to maintain context over very minimal delays. Another possible interpretation given recent findings with other tasks is that the two WMC groups might have performed equivalently if a shorter cue–probe delay had been used (Poole & Kane, 2009; Redick, Calvo, Gay, & Engle, 2011).

Limitations and future directions

Although the WMC results are largely compatible with both the executive-attention and context-processing theories, one aspect of the results is noteworthy. As is evident from Figures 1 and 2, both the high- and low-WMC groups performed worst on the AY trials, which is consistent with AX-CPT studies comparing young and older adults (e.g., Paxton et al., 2006). For both WMC groups, the overwhelming proportion of AY errors was choice errors (making a target response) and not misses (failing to make a response). The conclusion, much like the interpretation of WMC effects on the Stroop task (Kane & Engle, 2003), is that low-WMC individuals are capable of maintaining the context conveyed by the cue, but they have more lapses of attention in which they fail to maintain the goal.

The rate of AY errors was higher than is typically observed in other AX-CPT studies with healthy young adults. Braver et al. (2005) reported pilot testing that revealed that manipulating the cue–probe interval within a block led to increased errors relative to manipulating the interval across blocks, which could partially explain this finding. In addition, the interval manipulation, in conjunction with the low frequency of nontargets, produced eight observations for each of the cells of the short- and long-AY, BX, and BY trial types. Although this is consistent with previous studies (e.g. Haarmann et al., 2005), future work should include more observations to facilitate statistical comparisons.

CONCLUSION

The current research investigated individual differences in WMC (Engle & Kane, 2004; Hasher et al., 2007) within the context-processing view of cognitive control (Cohen et al., 1999). The AX-CPT results indicated that high-WMC individuals are more likely to maintain the context information conveyed by a cue to guide future behaviour. Although the inhibition theory can partially account for the data, the overall pattern of performance is most consistent with the executive-attention and context-processing theories of cognitive control.

Original manuscript received 11 January 2011
Accepted revision received 09 March 2011

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