INDIVIDUAL DIFFERENCES IN WORKING MEMORY CAPACITY AND THE DISTINCTION BETWEEN PROACTIVE AND REACTIVE CONTROL

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INDIVIDUAL DIFFERENCES IN WORKING MEMORY CAPACITY AND THE DISTINCTION BETWEEN PROACTIVE AND REACTIVE CONTROL

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LIST OF SYMBOLS AND ABBREVIATIONS

WMC	working memory capacity
AX-CPT	AX version of the continuous performance test
AX	letter A as cue followed by letter X as probe
AY	letter A as cue followed by non-X letter as probe
BX	non-A letter as cue followed by letter X as probe
BY	non-A letter as cue followed by non-X letter as probe
RT	response time
ms	milliseconds
PFC	prefrontal cortex
ACC	anterior cingulate cortex
fMRI	functional magnetic resonance imaging
ANOVA	analysis of variance

SUMMARY

The construct of cognitive control is often invoked to provide a mechanism responsible for information-processing in ill-defined situations. However, the dual-mechanism theory of cognitive control distinguishes between proactive and reactive varieties, and provides a more concrete framework for explaining behavior across various conditions. Importantly, although proactive and reactive control have been theorized to apply to differential performance observed in various clinical and aging populations, no empirical work has been conducted examining how this theory may apply to individual differences in working memory capacity within a young, healthy population. The current research directly assessed proactive versus reactive control by administering three versions of the AX version of the continuous performance test to individuals varying in working memory capacity. Across the task versions, specific trial type frequencies were manipulated to examine whether this variable interacted with WMC to cause individuals to engage in one control type over the other. In addition, the current work investigated whether individuals can change their mode of control on a trial-to-trial basis, something that had not previously been examined. Individuals low in working memory capacity exhibited specific performance deficits relative to the individuals high in working memory capacity. The results extend the application of the dual-mechanism theory to individual differences in working memory capacity and provide a theoretical framework to explain previous findings in the working memory capacity literature.

CHAPTER 1

INTRODUCTION

The notion of cognitive control has been invoked to explain performance in a number of activities. Broadly defined, cognitive control is the set of mental processes by which information is maintained in a temporary format to guide behavior in a manner consistent with fulfilling a goal or achieving task success. Cognitive control will be necessary to the extent that there are competing alternative actions that could be selected instead of the desired target behavior. The construct of cognitive control is conceptually similar or identical to several other terms used in the psychological literature, including executive attention, executive control, supervisory attention system, context-processing, selection-for-action, top-down processing, and goal maintenance.

While many researchers agree that there must be a mechanism responsible for dealing with competing representations within the information-processing system, notions of cognitive control are unavoidably criticized as homuncular in nature. Can theories of human behavior account for the ability to deal with interference in a variety of situations and paradigms without yielding to the need to invoke a "ghost in the machine" (Ryle, 1949/1966) to explain performance? In addition, how can the seemingly disparate pattern of results throughout the executive control literature be explained in a parsimonious manner? Finally, can this account be implemented in such a way to explain variations in cognitive control that are observed within a certain age range and when comparing individuals of different ages?

Braver, Gray, and Burgess (2007) have recently proposed a mechanistic account of cognitive control that aims to answer all three of these questions. Specifically, they

argue that their dual-mechanism theory of control provides a framework for understanding both person- and task-related variations in controlled behavior, based on knowledge of neurotransmitter and neuroanatomical properties of the human cortex. I begin by briefly reviewing existing theories of cognitive control before moving into a more detailed description of this new cognitive control model.

Cognitive Control

Various theories of cognitive control have guided the field of psychology since the cognitive revolution nearly 50 years ago. Some of the earliest theories focused on interpreting behavior as either automatic or controlled (Posner & Snyder, 1975; Shiffrin & Schneider, 1977). Subsequent theories couched control in terms of a high-level homunculus responsible for supervising and coordinating other lower cognitive components (Baddeley, 1986; Norman & Shallice, 1986). More recent models have focused on using knowledge of the anatomical and chemical substrates of cognitive control to constrain theories in biologically plausible ways (Desimone & Duncan, 1995; Miller & Cohen, 2001). Finally, other theories have focused on capturing variations in cognitive control reflected as differential performance with specific task characteristics (Meyer & Kieras, 1997; Roberts, Hager, & Heron, 1994), or as variations due to individual differences, aging, or psychopathology (Braver, Cohen, & Barch, 2002; Engle & Kane, 2004).

In particular, the work of Engle and colleagues (Engle & Kane, 2004; Kane, Conway, Hambrick, & Engle, 2007; Unsworth & Engle, 2007) is important to the notion of cognitive control used here. Engle and colleagues have provided evidence that performance on complex memory span tasks is predictive of behavior in a variety of

situations. In a typical complex span task, such as Operation Span (Unsworth, Heitz, Schrock, & Engle, 2005), participants must mentally solve math problems while also remembering letters for later recall. Variation in the ability to complete these types of tasks is taken to reflect individual differences in working memory capacity (WMC). Not only do individuals high in WMC outperform those low in WMC on a variety of memory tasks, but they also show improved performance on several attention and inhibition tasks (for review, see Engle & Kane, 2004). In fact, Engle and Kane interpreted individual differences in WMC as reflecting a more general executive control ability, whereby individuals high in WMC are better at maintaining goal-related information and also resolving response conflict in interference-rich situations. Thus, individuals differing in WMC are used in the current research as a crucible (Underwood, 1975) to explore the dual-mechanism theory of cognitive control proposed by Braver et al. (2007).

Dual-Mechanism Theory of Control

Building on these existing models, Braver et al. (2007) proposed a general theory of executive control to account for patterns of behavior observed in a variety of tasks within the cognitive literature. In addition, Braver and colleagues argued that their theory can potentially account for variations in behavior due to normal aging, psychopathology, and individual differences. One of the key aspects of this theory is the ability to account for the temporal dynamics of control in a biologically plausible way that is missing from most existing cognitive control theories. I begin by outlining the specific aspects of the theory, and then provide examples of applications of this framework that are relevant to the current research.

The dual-mechanism theory derives its name from the two modes of control that are assumed to be responsible for flexible behavior. The properties of each mode are given in Table 1. *Proactive* control involves the active maintenance of information that will help to respond appropriately to upcoming stimulus events. This information could be general task instructions, the identity of previous stimuli, or the relevant information conveyed by previous stimuli or cues that are salient for later behavior. The second mode of processing outlined by Braver and colleagues is *reactive* control. Reactive control involves the reactivation or retrieval of information that is imperative for the current decision-making; however, reactive control is only engaged in response to the probe or critical stimulus.

Table 1
Properties of Proactive and Reactive Control (Braver et al., 2007)

	Proactive Control	Reactive Control
Computational properties	Future-oriented, early selection, preparatory attention	Past-oriented, late correction, interference resolution
Information processing	Strong goal-relevant focus, global control effects	Increased goal-irrelevant processing, item-specific control
Temporal dynamics	Sustained, activation prior to imperative stimulus	Transient, activation after imperative stimulus
Neural substrates	Lateral PFC, midbrain DA (phasic activity)	ACC, lateral PFC (transient response), MTL, others

ACC = anterior cingulate cortex; DA = dopamine; MTL = medial temporal lobe; PFC = prefrontal cortex.

Next, I describe the AX version of the continuous performance test (AX-CPT) in detail, because this specific task has been the predominant method used by Braver and colleagues to study proactive and reactive control. In addition, variations on this task form the basis of the current research. The AX-CPT is based on continuous performance tests that have been used in the literature to study cognitive processes associated with vigilance and stimulus detection (Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956).

In the typical version of the AX-CPT (see Figure 1), individual letters are presented one at a time and participants are required to make a target response when the letter X immediately follows the letter A (AX trial).

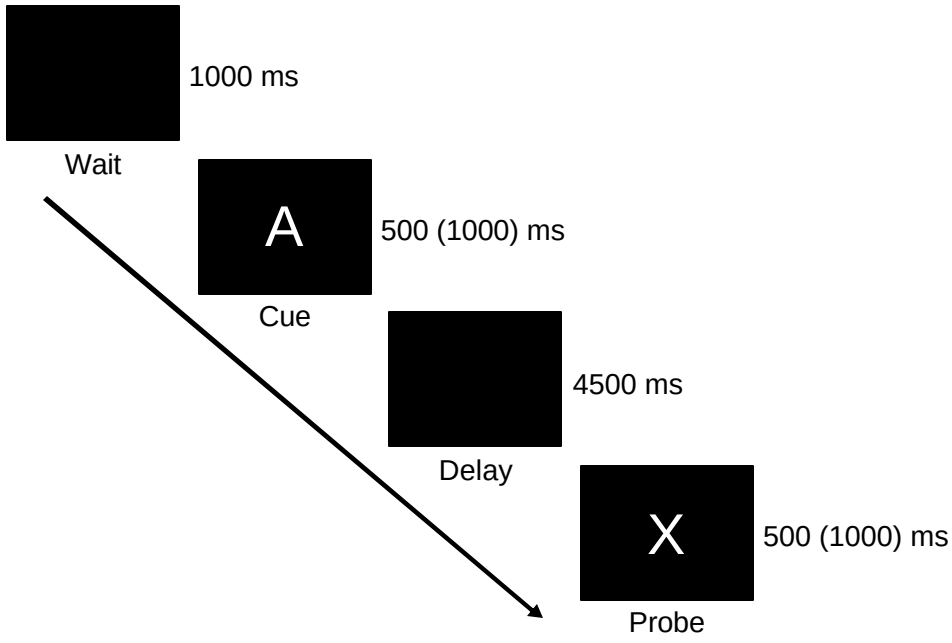


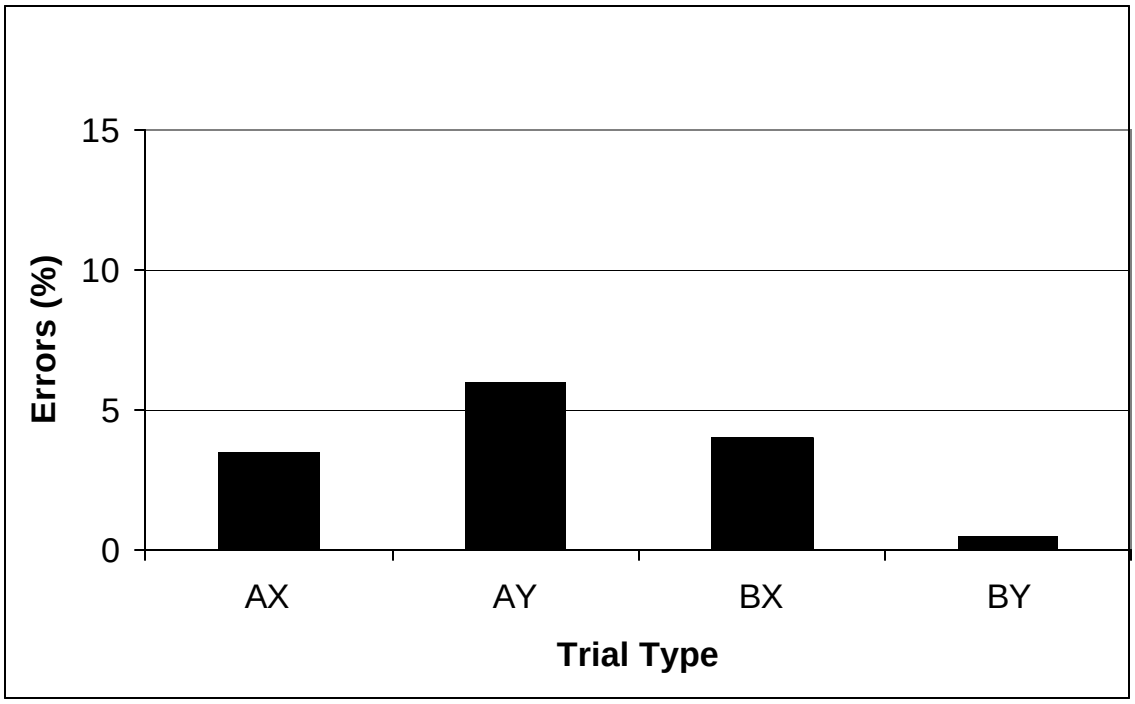
Figure 1. Example trial sequence from the AX-CPT. The numbers in parentheses indicate the total amount of time given to the participant to respond to each letter.

These target sequences occur on the majority of trials (usually 70% of all letter sequences), so an expectancy to make a target response is created when the letter A is presented. However, on a small proportion of trials, the A will not be followed by an X (AY trial, where Y stands for all non-X letters), and the expectancy information will actually hurt performance. In addition, on a small proportion of trials the letter X will follow a letter other than A (BX trial, where B stands for all non-A letters). In this case, the participant should realize that because the letter was not an A, the following letter

does not require a target response. Because the letter X is so frequently responded to with a target response, the individual must maintain the biasing information from the preceding letter to avoid making an incorrect target response. Finally, 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 typical error and mean response time (RT) results from a large sample of healthy young adults are presented in Figures 2a and 2b as a point of reference.

Braver and colleagues have used the AX-CPT to study proactive and reactive control according to the following logic. Individuals engaging in proactive control will sustain the information obtained from the cue to prepare either a target or nontarget response to the upcoming probe letter. Thus, proactive control will lead to fewer errors specifically on BX trials, but 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 engaging in reactive control do not actively maintain the cue information during the cue-probe delay, and thus must rely upon a transient reactivation of the cue information when the probe appears. Therefore, reactive control will be demonstrated by more errors specifically on BX trials, and slower correct RTs on AX, BX, and possibly BY trials. However, on AY trials, not maintaining the A cue information should actually help performance, in that a target response has not been prepared. Thus, when a letter such as F appears as the probe, the participant can relatively quickly and accurately respond that it is not a target. As Braver et al. (2007) state, "In the AX-CPT, proactive control means control engaged by the cue, whereas reactive control means control driven by the probe" (p. 81).

A



B

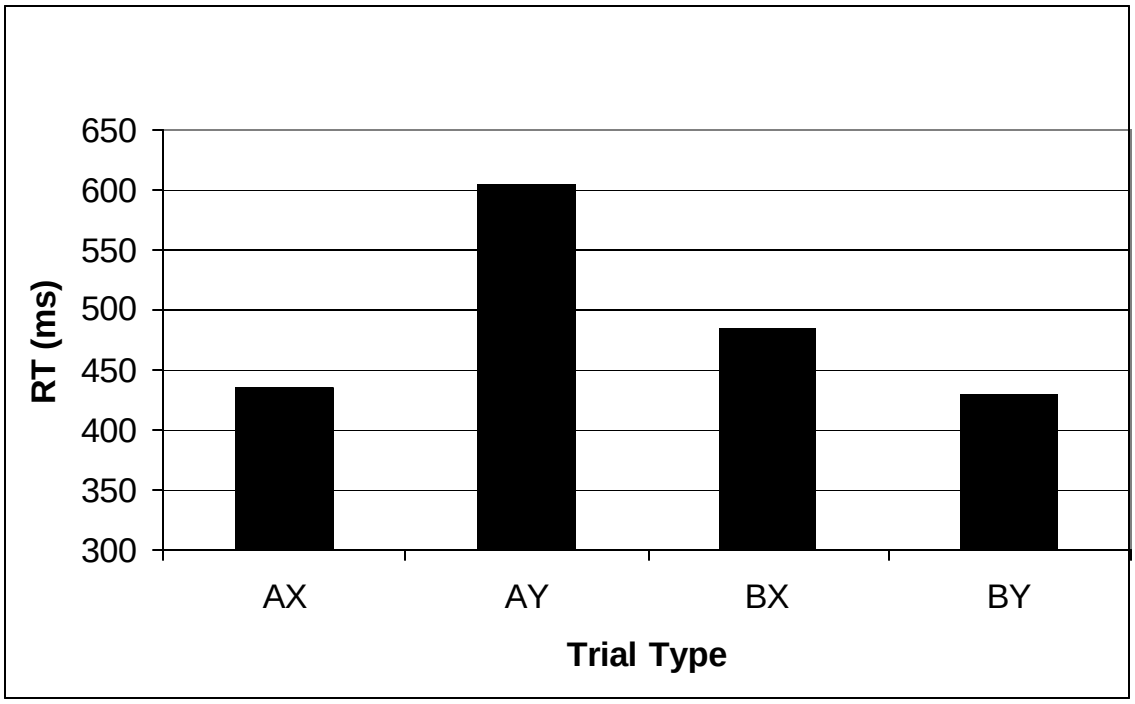


Figure 2. Representative error rate (A) and correct mean RT (B) data from 175 young adults on the AX-CPT as presented in Braver et al. (2001).

The cued-Stroop (1935) task used by MacDonald, Cohen, Stenger, and Carter (2000) also illustrates the proactive and reactive control distinction. In this task, a cue at the beginning of each trial informs the participant to either read the word or name the ink color in which the word is printed. Thus, the cue "word" or the cue "color" is important because in the subsequent incongruent stimulus (e.g., the word RED printed in green), the two dimensions provide evidence for different, conflicting responses. Note that the participant may not necessarily hold the representation "word" during the delay between the cue and the stimulus, but instead may translate this cue into a task goal such as "read the word". Importantly, the signature of proactive control is the use of information to prepare the system to respond *before* the imperative stimulus occurs. In this example given above, reactive control would manifest as attempting to remember which cue had just been presented only after seeing the incongruent stimulus. Note that reactive control may be as likely to lead to trial success as proactive control, but there are situations where one or the other form of control may be best-suited for achieving task goals. For example, if the word RED was presented in red ink as occurs on congruent trials, presumably either proactive or reactive control would lead to the correct response of "red". However, if the participant was to make an overt response before a fast response deadline, the reactive control mode may be too slow to produce an accurate response in the time necessary.

Manipulations that Affect the Usage of Proactive and Reactive Control

In addition, the overall task context may encourage one form of control over another. Stroop tasks that use only the color-naming condition produce varying degrees of interference according to the proportion of incongruent trials within an experimental

block (Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982; Tzelgov, Henik, & Berger, 1992). Stroop interference is commonly measured by comparing the performance on incongruent versus neutral or congruent trials, with typically slower RTs on incongruent trials. The standard observation is that as the relative frequency of incongruent trials increases, the Stroop RT interference effect decreases. When incongruent trials rarely occur, performance on these trials is typically much slower than blocks in which incongruent trials are high-frequency events. In addition, more errors tend to be made on incongruent trials within mostly-congruent Stroop blocks. Braver and Hoyer (2008) recently argued that these proportion congruency effects reflect the overall task context influencing either a proactive or reactive mode of control. Specifically, the increase in RT and errors on incongruent trials within mostly-congruent Stroop blocks reflects a reactive mode, as the majority of trials can be successfully responded to by reading the word or naming the ink color. It is only on the infrequent incongruent trials that the cost of not sustaining the task goal of color naming is observed. In contrast, Braver and Hoyer argued that performance on incongruent trials within mostly-incongruent blocks reflects the proactive mode of control. Because word-reading is a faster process than color-naming for most literate individuals (Lindsay & Jacoby, 1994), optimal performance is more easily achieved by establishing the task set before the stimulus appears onscreen.

In support of these arguments, Braver and Hoyer (2008) found that the Stroop RT interference effect and the percentage of incongruent errors were indeed greater in the mostly-congruent block compared to the mostly-incongruent block, replicating earlier work. Previous Stroop studies with older adults (West & Baylis, 1998) and low-WMC young adults (Daniels, 2003; Kane & Engle, 2003) indicate that these two groups are

particularly affected by proportion congruency effects, by making substantially more incongruent errors when these trial types are particularly rare (Table 2). However, the older adults' and low-WMC individuals' performance on mostly-incongruent blocks was not consistent with strictly a proactive mode of control, given that the RT interference effect and number of errors on incongruent trials were still substantial. Thus, manipulations of overall task context can push participants to use a proactive or reactive mode of control, although some populations appear less likely to use proactive control even when the situational constraints call for it.

Table 2
Comparison of Stroop RT Facilitation and Interference Effects and Incongruent Errors as a Function of Proportion Congruency

	Mostly Congruent			Mostly Incongruent		
	Facil RT	Interf RT	Inc Err	Facil RT	Interf RT	Inc Err
			Braver & Hoyer (2008)			
Young	84 ms	90 ms	7%	14 ms	40 ms	2%
			West & Baylis (1998)			
Young	100 ms	164 ms	4%	6 ms	41 ms	4%
Older	229 ms	268 ms	14%	27 ms	165 ms	8%
			Daniels (2003)			
High	19 ms	78 ms	8%	-8 ms	43 ms	3%
Low	33 ms	114 ms	18%	14 ms	75 ms	7%

Note. Facil: Facilitation; Interf: Interference; RT: Response Time; Inc Err: Incongruent Errors.

Locke and Braver (2008) also manipulated overall task context by having participants perform a standard version of the AX-CPT first, and then perform the task

again with an incentive for speeded performance. The participants were told that they would be additionally compensated by 25 cents for each trial that they responded to faster than their median RT in the standard version. By encouraging participants to make faster responses, Locke and Braver argued they also increased the likelihood of the participants using a proactive strategy. By preparing to respond before the critical probe stimulus appeared, the RTs should be faster when compared to a reactive control mode that begins the response process after the probe letter occurs. They found that participants were faster on all trial types in the incentive compared to the standard version. Critically, they only observed an increase in error rate on AY nontarget trials. This is consistent with the idea that participants were engaged in a proactive control mode, as increased AY errors reflect preparing a target response based on the A cue, and here maintaining the cue information actually impairs performance. In addition, because the B cue perfectly predicts a nontarget response to the upcoming probe, translating this information into a preparation for a nontarget response decreases RTs without an increase in errors. Again, the manipulation of overall task context shifted the participants' into a proactive control mode (see Meyer & Kieras, 1997, for similar arguments regarding daring versus cautious strategies).

These are but a few of the examples of the research that has been conducted examining the dual-mechanism theory of control (see Braver et al., 2007, for other work). As seen in the examples above, when a premium is placed on responding quickly, proactive control is important for sustaining pre-target information to bias future responding in a way consistent with expectancies and the schedule of rewards and punishments. However, there may be instances where there is either no predictive

information available to help prepare one action versus another, or the cue or warning information that is available for use is unreliable. Another variable that will affect the use of proactive or reactive control is the amount of time expected before the critical behavior will have to be performed. If the imperative event is merely seconds away, proactive control may be the logical mode to use. However, if the event is expected to occur 12 hours in the future, engaging in proactive control over this interval will be resource-demanding from both an attentional and a metabolic standpoint. Finally, there might be some populations that are either unable or unlikely to engage in proactive control, even when success depends upon using this mode of control.

A more familiar example may help solidify the main properties of the proactive versus reactive control distinction. Imagine that you are driving your vehicle at a high speed when you notice that a car appears ready to pull out from a side street into your lane of traffic. In order to avoid an accident, you could engage in proactive control by preparing to swerve into the other lane if the car does in fact turn in front of you. It is possible that you could mentally note that the car is about to pull out without actually translating that to an avoidant maneuver. Even if you have not prepared to swerve in advance, it may still be possible to use reactive control to switch lanes at the last second. However, it is likely that there is more of a chance of an accident in this latter case, as you would need to react very quickly to avoid hitting the turning car. Other variables may influence the likelihood of engaging in proactive or reactive control in this situation. For example, if you are driving a motorcycle, the consequences for not using predictive information from the driving environment could be more hazardous. In addition, you may have driven on this stretch of road previously and had an accident or near-accident in a

similar situation. Accessing this previous event history may bias you to engage in proactive control mode to ensure that an error (an accident) does not occur.

Neural Mechanisms of Proactive and Reactive Control

Another property that distinguishes between proactive and reactive control is not only whether neural activity is sustained or transient, but also which brain regions and neurotransmitter systems are responsible for these dissociable control modes (Table 1). Braver et al. (2007) argued that a network of frontal and medial temporal regions is responsible for implementing cognitive control. Specifically, lateral prefrontal cortex (PFC) is the region that maintains cue-related contextual information during the delay period between the cue and probe. In contrast, anterior cingulate cortex (ACC) may signal the need for control when a conflicting stimulus is encountered, especially if the cue information was not maintained in an active state (e.g., an X following a B in the AX-CPT). In these situations, the medial temporal lobe and hippocampal areas may initiate a retrieval process to locate within memory the identity of the last-presented cue letter. Interestingly, the lateral PFC should also show increased activity when reactive control is used, but only transiently after the probe stimulus has been presented.

Evidence for these areas working in concert to determine performance comes from several functional magnetic resonance imaging (fMRI) studies. In the cued-Stroop study described earlier (MacDonald et al., 2000), increased activity during the cue-probe delay was observed within left lateral PFC when the upcoming word stimulus required a color-naming decision and not the stronger word-reading response. However, ACC activity was increased in response to the presentation of an incongruent word stimulus. Consistent with the idea that these areas are part of a control network, the level of cue-

related activity in lateral PFC observed *before* the stimulus was highly correlated with the level of probe-related activity in ACC *after* the stimulus was presented. Other examples of this relationship between lateral PFC activity and ACC activity have also been observed in the flankers task (Kerns et al., 2004) and the AX-CPT (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999).

Braver and Hoyer (2008) also compared neural activity across the manipulations of proportion congruency within the Stroop task described earlier. In the mostly-incongruent condition, which was argued to reflect proactive control, right lateral PFC was observed to display sustained increased activity throughout the run, regardless of trial type. In contrast, performance consistent with a reactive mode of control was observed within bilateral ACC and lateral PFC regions, among others. In the mostly-congruent condition, no sustained activity was observed, but instead these areas showed transient increased activity specifically in response to incongruent stimuli. Other studies examining the effect of Stroop proportion congruency manipulations have produced the same pattern of results implicating the PFC and ACC (Carter et al., 2000; Leung, Skudlarski, Gatenby, Peterson, & Gore, 2000).

Neuroimaging studies using the AX-CPT have also isolated the dorsolateral PFC as being specifically activated in healthy young adults (Barch et al., 1997; Barch et al., 2001; Holmes et al., 2005; MacDonald & Carter, 2003; Perlstein, Dixit, Carter, Noll, & Cohen, 2003). In addition, event-related fMRI studies identified dorsolateral PFC and ACC as showing increased activity specifically on BX and BY trials (MacDonald & Carter, 2003; MacDonald et al., 2005; Perlstein et al., 2003). These findings indicate that the dorsolateral PFC and ACC are important in holding cue information in active

memory, consistent with a series of rat lesion studies (for review, see Haddon & Kilcross, 2007) in the animal literature. Finally, electrophysiological studies have identified a frontocentrally-based positive waveform that has a larger amplitude during the cue-probe delay in response to B cues compared to A cues (Dias, Foxe, & Javitt, 2003; Javitt, Shelley, Silipo, & Lieberman, 2000). These results identify the lateral PFC and ACC as being critically involved in the implementation of proactive control.

In addition to specific brain regions, Braver et al. (2007) have proposed that different aspects of the dopaminergic system are responsible for proactive vs. reactive control. Based on research showing that there are both phasic and tonic changes in the level of dopamine present in the frontal-midbrain loop (Grace, 1991), Braver et al. (2007) argued that dopamine serves as a gating function to the PFC neurons. Specifically, phasic dopamine activity is argued to be important in updating processes, while tonic dopamine activity is responsible for maintenance. Braver et al. (2007) argued that the phasic changes in dopamine level in response to the presentation of a cue or other predictive information only occur if the individual is using proactive control. Therefore, although the dopaminergic system within the PFC and midbrain is largely responsible for these updating and maintenance processes, different modes of control will alter dopamine's effect upon the network of cognitive control areas.

Similarity to Other Theories

Although the dual-mechanism theory is unique in its ability to instantiate cognitive control according to differences in the temporal dynamics and location of neural activity, there are similarities to other existing models of control. Most notably, Jacoby, Kelley, and McElree (1999) proposed a memory model that distinguished

between early-selection and late-correction cognitive control processes. Similar to the dual-mechanism theory, Jacoby et al. argue that early-selection is used to override automatic processing that may lead to errors, although late-correction may lead to task success in certain conditions. Likewise, the model recently proposed by Unsworth and Engle (2007) includes a flexible primary memory buffer to protect information from interference, and a secondary memory component whereby a controlled search process is used to locate the appropriate memory traces or stimulus-response mappings among other memory representations. Each theory uses two functions to account for behavior in interference-rich situations, and each has attempted to account for variations in control exhibited by either aging (Jacoby et al., 1999) or individual differences in WMC (Unsworth & Engle, 2007).

Age Differences as Variation in Proactive and Reactive Control

Braver, Satpute, Rush, Racine, and Barch (2005) initially proposed the proactive and reactive control distinctions based on the pattern of errors and correct RTs exhibited by healthy older adults on the AX-CPT (Table 3), and so I will briefly review the evidence for this idea. In Braver et al. (2001), older adults did not produce statistically more errors across the various trial types compared to young adults, in contrast to previous research with schizophrenia patients. However, the pattern of RTs for the two age groups revealed interesting differences on AY and BX trials. Specifically, the older adults were numerically *faster* than young adults on AY trials, whereas older adults displayed proportionally greater slowing than young adults on BX trials. This pattern of equivalent error rates and slowed BX RTs has been generally replicated in subsequent aging studies (Braver et al., 2005; Paxton, Barch, Racine, & Braver, 2008; Paxton, Barch,

Storandt, & Braver, 2006), although young adults have been shown to produce more errors than the older adults on AY trials in a couple of the latter studies. If young adults are more likely to use proactive control than older adults, than they would be expected to make more AY false alarms than older adults. If older adults are more likely to use reactive control than younger adults, they should be slower to respond on AX and even BY trials, because they are not preparing a response before the probe appears. However, this would specifically impair older adults' speed to respond on BX trials, where the probe information is strongly associated with a target response, and the cue identity must be reactivated in order to respond correctly. Examining Table 3, the age difference (older minus young) in BX RTs was +150, + 195, +251, and +75 ms across the four studies. In comparison, the age difference in AY RTs was -10, +50, +140, and +79 ms across the four studies. Note the larger age RT differences were found on BX trials, even though young adults responded to these quicker than AY trials. This is inconsistent with much of the aging literature indicating that older adults' RTs can be predicted as a constant multiplier of young adults' observed RTs in various conditions (e.g., Brinley, 1965). However, this pattern is consistent with the argument that older adults use a reactive control mode, and young adults more often use a proactive control mode in performing the AX-CPT.

In a similar vein, Mayr (2001) argued that older adults have difficulty using a preparatory cue to make the appropriate response during a cued task-switching paradigm. He found that older adults were slowed specifically when the stimulus was ambiguous as to the correct response, and proposed that older adults were not using the cue-stimulus interval to engage the appropriate mental set during the delay period. Instead, older adults

Table 3
Young vs. Older Adults' and High- vs. Low-WMC Groups' Performance on AX-CPT

	Errors				Correct RTs			
	AX	AY	BX	BY	AX	AY	BX	BY
Braver et al. (2001)								
Young	3.5%	6.0%	4.0%	0.5%	435	605	485	430
Older	5.0%	5.0%	5.8%	0.0%	475	595	635	505
Braver et al. (2005)								
Young	4.0%	13.0%	6.0%	1.0%	390	555	375	370
Older	4.5%	4.8%	3.6%	0.5%	490	605	570	490
Paxton et al. (2006)								
Young	2.0%	11.0%	4.0%	0.0%	405	560	423	381
Older	1.0%	2.0%	3.0%	0.0%	554	700	674	523
Paxton et al. (2008)								
Young	2.0%	2.0%	6.0%	1.0%	552	696	530	547
Older	0.0%	4.0%	7.0%	1.0%	592	775	605	610
Redick and Engle (2008)								
High	3.3%	21.7%	2.0%	1.2%	393	580	326	331
Low	7.1%	22.5%	14.1%	1.8%	442	598	395	426

Note. Only long cue-probe delay data presented; Target/nontarget decision for each letter.

may have been attempting to retrieve the current task and corresponding stimulus-response pairings after the critical stimulus was presented. Despite the differences in the processes assumed to account for aging performance on the AX-CPT and in the task-switching literature, conceptualizing the older adults as engaging in reactive control provides a parsimonious account for the data in both cases.

In addition, there is evidence suggesting that older adults have impairments in PFC functioning (e.g., West, 1996), along with concomitant declines in cognitive abilities that are related to decreases in dopaminergic functioning (Volkow et al., 1998). Indeed, Braver et al. (2005) speculated that the phasic dopamine bursts that serve as the PFC gating signal to implement updating may be more sensitive to aging than tonic dopamine activity, which would lead older adults to be more likely to engage in reactive control. Important for the study proposed here, Bopp and Verhaeghen (2005) have shown that older adults show specific declines on WMC measures as compared to other memory span tasks. More direct support indicating that young and older adults differ in performing the AX-CPT comes from a neuroimaging study conducted by Paxton et al. (2008). In this study, the authors selectively isolated regions that met certain criteria to reflect reactive control within the older adults. Given previous research that demonstrated that young adults exhibit more cue-related activity to B cues compared to A cues (MacDonald & Carter, 2003; MacDonald et al., 2005; Perlstein et al., 2003), Paxton et al. (2008) identified right dorsolateral PFC as the only region showing increased activity during the cue-probe delay in the young adults relative to older adults. This result suggests older adults were not actively maintaining the cue information during the delay period. In addition, the dual-mechanism theory predicts that individuals engaging in reactive control will show increased probe-related activity when the cue information must be reactivated to make the appropriate response (viz., BX trials). Therefore, Paxton et al. identified the right dorsolateral PFC and right middle frontal gyrus as areas that showed increase probe-related activity in older adults compared to young adults. Thus, by separating neural activity during different parts of each trial, Paxton et al. provided strong

evidence that older adults were engaging in reactive control, as exhibited both by their behavioral performance and by the different temporal dynamics of their activation.

Individual Differences in WMC as Variation in Proactive and Reactive Control

Although the dual-mechanism theory can account for the aging data observed in the AX-CPT and other tasks, Braver et al. (2007) also proposed that the proactive versus reactive distinction might be able to account for individual differences in behavior as well. Although they have primarily focused on personality variables (e.g., Locke and Braver, 2008), Braver et al. (2007) speculated that "individuals with high-WM span and high gF should thus show an increased tendency to use proactive control strategies, but only in the task demands that most require and benefit from such strategies" (p. 89). That is, although young adults are expected to use proactive control more often than older adults, variation in WMC may explain variation in cognitive control observed within young adults. For example, low-WMC individuals exhibit a pattern of Stroop performance consistent with reactive control. In addition to the WMC results discussed previously and given in Table 2, Kane and Engle (2003) found that low-WMC individuals were more likely to read the word during the Stroop task. In Experiment 4, Kane and Engle (2003) examined error latencies, with the expectation that fast errors on incongruent trials largely represent forgetting the goal of naming the ink color in favor of reading the word. They found that the error latencies for incongruent trials were equivalent to correct congruent trials, and not statistically different between WMC groups. The main observation was that low-WMC individuals produced dramatically more of these types of errors than the high-WMC individuals. Thus, WMC group was diagnostic of the frequency of engaging in reactive control.

Redick and Engle (2008) administered a version of the AX-CPT that intermixed short (1000 ms) and long (5000 ms) intervals between the cue and probe letters. The results for the long-delay condition are presented in Table 3. The low-WMC group made more errors on AX and BX trials, but did not differ on AY or BY error rates. This finding is consistent with most of the schizophrenia patient literature with the AX-CPT, and suggests that low-WMC individuals were hurt by not maintaining the cue information to respond appropriately to X probes. Although the low-WMC group was slower overall, they were not statistically slower than the high-WMC group on AY trials. Consistent with the aging data described earlier, the WMC group (low minus high) difference in BX RTs was +65 ms, whereas the difference on AY RTs was +18 ms.

Although the overall pattern of errors and correct RTs across trial types is consistent with the notion that high-WMC individuals are engaged in proactive control, and low-WMC individuals are less likely to use proactive control, further analyses help to support this interpretation. First, we examined the difference in performance on AY and BX trials for each WMC group. If AY errors are due to preparing a target response, and BX errors are due to not maintaining the cue information, then the group with the larger error difference (AY minus BX) is more proactive. In addition, if AY RTs are slower because an individual has to overcome the prepared and expected target response, and BX RTs are faster due to preparing a nontarget response based on the B cue information, then the group with the larger RT difference (AY minus BX) is more proactive. In both cases, the high-WMC groups had a statistically greater AY-BX difference score, indicating that as a group, high-WMC individuals were more likely to use proactive control. In addition, although performance on the AY and BX trials are typically the

focus of Braver and colleagues, valuable information can be gained from examining the time to respond to AX targets that occur on 70% of the trials. If an individual is actively maintaining the cue and preparing a target response during the cue-probe delay, that individual would be expected to both be faster and more consistent in their RT to the X when it appears. By calculating each participant's individual standard deviation for AX trials, we found that the low-WMC group showed more variability when correctly responding to targets, compared to the high-WMC group. Again, this evidence suggests that, as Braver et al. (2007) predicted, high-WMC individuals are using proactive control more often than low-WMC individuals.

Another recent study is also indicative of a relationship between WMC and proactive control. Redick, Calvo, Gay, and Engle (2009) compared high- and low-WMC groups on two versions of a go/no-go task. In the standard version of the task, participants were instructed to make a simple button press to any letter except X (go). On 20% of the trials, the letter X occurred, and participants were instructed to withhold responses (no-go). In this version, there were no WMC group differences in accuracy or RTs. Previous research on a similar go/no-go task failed to find age differences as well (Rush, Barch, & Braver, 2006). In the second version of the task, which we have labeled a conditional go/no-go task, participants were instructed to respond only to the letter M or the letter W and withhold responding to any other letters. However, there was an additional rule such that the letters M or W had to alternate from the last presentation in order to be a go trial. For example, a participant might see the following five letters on consecutive trials: *F…M…W…J…W*. In this example, the first instance of M and W would be go trials, but the second instance of W would be classified as a no-go trial

because it had not alternated since the last presentation of either an M or W. As opposed to the standard go/no-go version that used a consistent rule for responding, the conditional go/no-go version required using the previous go stimulus in order to respond correctly when the next M or W was presented. The no-go trials here are similar to BX trials in the AX-CPT – if the participant has not maintained previous stimulus (cue) information, then it will be difficult to not respond to the X (M or W) as a target.

In contrast to the standard version, WMC group differences were observed on the conditional go/no-go task. A WMC by trial type interaction revealed that the low-WMC group made slightly more omission errors than the high-WMC group on go trials, and many more commission errors than the high-WMC group on no-go trials. In addition, when they correctly responded on go trials, the low-WMC group was more variable but not slower than the high-WMC group. These results corroborate the AX-CPT results, in that the low-WMC individuals appeared less likely to actively maintain the previous go stimulus information, consistent with the idea that they were less likely to be using proactive control.

Finally, results from the antisaccade task provide additional information about the ways that high- and low-WMC individuals use cues to guide behavior in demanding situations (Unsworth, Schrock, & Engle, 2004). In Experiment 1, high- and low-WMC participants were presented with prosaccade and antisaccade blocks of trials in which the task instruction was to either look toward or away from the box that flashed on the left or right side of the screen. Because participants can quickly respond on prosaccade trials in a reflexive manner, reactive control should have been the mode employed by both WMC groups. In line with this idea, there were no WMC differences in errors or correct

latencies during the prosaccade blocks. However, and consistent with previous research (Kane, Bleckley, Conway, & Engle, 2001), low-WMC individuals were slower and made more errors during the antisaccade block of trials. The antisaccade block of trials requires proactive control, in order to keep the task goal or response rule (e.g., *look away from the flashing stimulus*) active to guide behavior and prevent the reflexive but incorrect response of looking toward the flashing box. The data suggest that the low-WMC individuals were more frequently engaging in reactive control instead, as evidenced by the reflexive errors and slower responses even when correct.

In Experiment 2, Unsworth et al. (2004) changed to a cued-saccade version of the task. Here, a cue 1200 ms before the critical stimulus indicated whether each trial required a pro- or antisaccade as the correct response. Given this manipulation, one might expect that the participants can use the cue to prepare a general response rule for the upcoming stimulus (*look toward stimulus / look away from stimulus*), but preparation of a specific response is not possible until the actual stimulus is presented. In this way, the cued-saccade task is similar to the cued-Stroop task and cued-task-switching paradigm described earlier, and different from the AX-CPT task in which a specific target or nontarget response can be prepared based on the cue. Critically, not maintaining the cue information in an active state during the cue-stimulus interval will result in slower performance on more errors for both types of trials in the cued-saccade task. That is, in the cued-Stroop task, if the word RED is presented in red ink, then accurate performance can be achieved even if the task cue to name the ink or read the word was not maintained. However, in the cued-saccade task, the correct response is dependent upon remembering the task cue (except for guessing). Importantly, Unsworth et al. (2004) found that the

low-WMC group was slower and more error-prone than the high-WMC group on both prosaccade and antisaccade trials. Note that this finding is somewhat at odds with the executive attention framework (Kane et al., 2007), as that theory would not necessarily predict that low-WMC individuals would go against the prepotent response and produce prosaccade errors. However, if the low-WMC individuals are construed as engaging in reactive control, and the high-WMC individuals as using proactive control, then the pattern of results is consistent. The low-WMC group was less likely to use the task cue to ready the information-processing system prior to the onset of the target stimulus, and thus attempted to retrieve the cue information and stimulus-response mappings after the stimulus appeared. This search process is more vulnerable to proactive interference from previous trials (Unsworth & Engle, 2007), and thus low-WMC individuals would make errors on both prosaccade and antisaccade trials. In addition, the fact that the high-WMC group was also faster to correctly respond on both types of trials is consistent with the idea that they were using proactive control.

There have been a number of recent investigations into the neural mechanisms responsible for individual differences in WMC that are relevant to the dual-mechanism theory. Kane and Engle's (2002) review of the neuroscience literature suggests that low-WMC individuals have impaired dorsolateral PFC functioning. Osaka, Kondo, and colleagues (Kondo et al., 2004; Kondo, Osaka, & Osaka, 2004; Osaka et al., 2003; Osaka et al., 2004) have demonstrated across several fMRI studies that PFC and ACC activity, and the connectivity between these regions, are critical in accounting for neural differences between high- and low-WMC individuals while performing measures of WMC. Several other theories of working memory indicate an important role for

dorsolateral PFC (Chein, Fiez, & Ravizza, 2002; D'Esposito, Postle, Ballard, & Lease, 1998). In addition, recent research has demonstrated that individuals low in WMC have lower levels of dopamine present in the striatum compared to high-WMC individuals (Cools, Gibbs, Miyakawa, Jagust, & D'Esposito, 2008). Similar to the neural evidence in older adults, the profile of low-WMC individuals is consistent with what Braver et al. (2007) predict for a reactive control mode.

Current Research

Despite the evidence just reviewed, there are still several unanswered questions in regard to specific applications and tests of the dual-mechanism theory of cognitive control. The current research was designed to answer some of these unresolved questions, as well as provide tests of new predictions of this model. For example, the evidence reviewed thus far suggests that in healthy young adults, proactive control best accounts for the pattern of behavioral data and neural activity during performance of the AX-CPT and other tasks. However, the research just reviewed indicates that there are individual differences in the use of proactive and reactive control within young adults. Thus, the current study examined high- and low-WMC young adults in a series of tests of the dual-mechanism theory. Although the evidence suggests that low-WMC young adults are less likely to use proactive control than high-WMC young adults, perhaps this ability is intact in these participants and they instead choose not to use proactive control. I have discussed proactive and reactive control as being an either/or distinction that describes the behavior of an individual, but Braver et al. (2007) speculated that "it may be the case that the two systems are fully independent, and thus may be engaged in both simultaneously" (p. 85). If this is true, it may be possible for high-WMC individuals to

engage in both a proactive and reactive control mode better than low-WMC individuals, depending on the situation. This might explain the discrepancy between AY and BX errors observed in Redick and Engle (2008). Although the high-WMC individuals' high AY error rate and low BX error rate is consistent with proactive control alone, the low-WMC individuals produced high rates of AY and BX errors. This suggests a combined proactive and reactive control style across various trials. Thus, a more complete evaluation of proactive and reactive control will allow these ideas to be fully examined.

The AX-CPT was used to investigate these issues related to proactive and reactive control, for the following reasons. One reason is to maintain consistency with the existing literature and replicate our previous work. The second reason is that the AX-CPT provides a way to systematically manipulate target frequency, which should produce different results within the proactive versus reactive control framework. Finally, the cue information in the AX-CPT allows biasing of distinct responses to the various probes across the different trial types, and provides a way to measure proactive and reactive control more specifically. In contrast, the Stroop task has provided evidence for the dual-mechanism theory of control, but it is difficult to identify the mode of control being used. If given a cue to name the color of the ink, or presented with a block of mostly incongruent trials that should encourage proactive control, it is not possible for the participant to selectively prepare one response (e.g., red, green, etc.) over another. At best, the participant can sustain the goal information and perhaps activate all possible responses.

Target Frequency Manipulations

This last point is particularly important for the three versions of the AX-CPT used in the current study. The first version is similar to the AX-CPT I have discussed throughout, and is labeled *AX-CPT-70*. As can be seen in Table 4, "70" refers to the percentage of trials in that version of the AX-CPT that are the AX targets. Accordingly, in this version 70% of the trials are AX targets, and the other three nontarget trial types occur 10% each. Thus, this version connects to the existing AX-CPT literature on psychopathology and aging by investigating individual differences in WMC and serving to replicate Redick and Engle (2008). As has been discussed throughout, data obtained via computational simulations and empirical studies indicate that optimal performance on the AX-CPT-70 is produced via a proactive strategy (Braver et al., 2007). Cue information guides the appropriate responding to probes, and maintaining this context over the cue-probe delay will aid participants in responding quickly and accurately on all trial types except for the rare occasion when a Y probe follows an A. Overall, this version of the AX-CPT-70 induces a global context of proactive control (Table 5).

Another version used in the current study is the *AX-CPT-10* (Table 4). This version switches the frequencies for AX and AY trials, such that now AX targets occur on 10% of trials, whereas AY nontargets occur on 70% of all trials. BX and BY trials remain at 10% each of all trials. Participants are still expected to engage in a proactive strategy in the AX-CPT-10, with the exception that the information from the A cue in this version should lead the participant engaging in proactive control to prepare a nontarget response, given that AY trials are 70% of all trials. In this way, the AX targets occur much less frequently than the AX-CPT-70 just discussed, but the information gained

from the cues in these two versions is equivalent. Again, the global context of the AX-CPT-10 should lead to use of proactive control (Table 5).

Table 4
Stimulus Probabilities for the Different Versions of the AX-CPT

Type	Freq	*p*(cue)	*p*(probe)	*p*(probe | cue)	*p*(targ | cue)	*p*(targ | probe)
			AX-CPT-70			
AX	70	.8	.8	.875	.875	.875
AY	10	.8	.2	.125	.875	.000
BX	10	.2	.8	.500	.000	.875
BY	10	.2	.2	.500	.000	.000
			AX-CPT-10			
AX	10	.8	.2	.125	.125	.500
AY	70	.8	.8	.875	.125	.000
BX	10	.2	.2	.500	.000	.500
BY	10	.2	.8	.500	.000	.000
			AX-CPT-40			
AX	40	.8	.5	.500	.500	.800
AY	40	.8	.5	.500	.500	.000
BX	10	.2	.5	.500	.000	.800
BY	10	.2	.5	.500	.000	.000

Note. Freq: Frequency; targ: target.

Finally, the *AX-CPT-40* was used to assess unanswered questions of the dual-mechanism theory. In this version, both AX targets and AY nontargets each occur on 40% of trials, with BX and BY nontargets still occurring on 10% of all trials (Table 4). The advantage of the AX-CPT-40 is that the A cues here carry different predictive validity compared to the previous two versions of the AX-CPT. Here, A cues predict a

Table 5
Predictions of Optimal Proactive versus Reactive Control Usage for Each Version of the AX-CPT

Trial Type	Trial Frequency (%)	Optimal Control Mode
	AXCPT-70	
AX	70	proactive (T)
AY	10	proactive (T)
BX	10	proactive (NT)
BY	10	proactive (NT)
	AXCPT-10	
AX	10	proactive (NT)
AY	70	proactive (NT)
BX	10	proactive (NT)
BY	10	proactive (NT)
	AXCPT-40	
AX	40	reactive
AY	40	reactive
BX	10	proactive (NT)
BY	10	proactive (NT)

Note. T: Target; NT: Nontarget.

target or nontarget response with equal probability. Contrast this with A cues from the previous versions, which served as mostly valid cues, and with B cues in each version, which are 100% predictive of a nontarget response. In this version, there is no consistent control strategy that should be employed to produce optimal performance, and although the frequency of A cues here is the same as in the previous two versions that led to proactive control, now reactive control is expected to be engaged in response to A cues.

This condition critically assesses a speculative idea raised by Braver and Hoyer (2008), namely that participants may alternate "on a trial-by-trial basis between a proactive control state and a reactive control state". In the AX-CPT-40, the cue-probe contingencies are set up to study *within the same task* whether or not cognitive control can dynamically shift between the optimal control states, and whether or not this ability differs for high- and low-WMC individuals.

WMC Predictions Based on the Dual-Mechanism Theory of Control

Several different comparisons to examine the potential relationships among WMC and task context with the use of proactive and reactive control. Comparing the high- and low-WMC young adults on the AX-CPT-70, the following results are predicted by the dual-mechanism theory:

1. The low-WMC group should produce more errors on AX and BX trials than the high-WMC group.
2. The low-WMC group will not differ from the high-WMC group in either accuracy or correct RT for AY trials.
3. The low-WMC group should produce a greater number of slower responses in the slowest part of their RT distribution on AX target trials.

The manipulation of AX and AY frequency was predicted to have the following effects on performance on AX-CPT-10:

1. The low-WMC group should *not* produce more errors on BX trials than the high-WMC group, as the low frequency of targets and X probes will not lead to the same prepotency of a target response to the X that is observed in the AX-CPT-70.

2. The high-WMC group is expected to produce fewer AY errors but more AX target errors than in the AX-CPT-70.
3. The low-WMC group should be slower than the high-WMC group on AY trials specifically in the slowest bins of the RT distributions.

Finally, examining the performance of the high- and low-WMC groups in the AX-CPT-40 leads to following predicted results:

1. The high-WMC group is predicted to be able to use a reactive control mode in response to A cues and a proactive control mode in response to B cues. Thus, the results should show that AX and AY trials do not differ in accuracy or in correct RTs for the high-WMC group, and BX performance should indicate few errors and fast correct RTs.
2. The low-WMC group is predicted to have more difficulty switching between proactive and reactive control as necessary. If the WMC groups are equivalent when using reactive control, the low-WMC group should show performance on AX and AY trials that is qualitatively similar to that of the high-WMC group. However, if the high-WMC group is also better able to use reactive control, the low-WMC group will show impaired performance even after an A cue.
3. The low-WMC group should especially have difficulty engaging in proactive control when the overall task context favors a reactive control mode, such that BX trials should be error-prone and responded to slower than the high-WMC group.

CHAPTER 2

METHOD

Participants

All participants were between 18 and 30 years of age. Out of 120 young adults, 60 high- and 60 low-WMC individuals were included in the current study based on their performance on the automated versions of the Operation and Symmetry Span tasks (see description below) from a previous session in the lab.

All participants were examined for the following exclusionary criteria: (a) currently suffering from a major illness that affects the participant's attention or memory; (b) currently taking medication that impairs the participant's attention or memory; (c) history of head injury or trauma; (d) non-English native speaker; and (e) poor visual acuity (less than 20/50 corrected). In addition, self-report estimates of current health status and years of formal education were also collected.

Tests to Assess WMC

Operation Span. In this task, individuals must mentally compute the results of mathematical problems while also concurrently remembering to-be-presented letters for later recall. Participants first practice the storage portion of the task alone, with individual letters presented on the screen for 800 ms, with 1000 ms between each letter. Participants are then presented with a response grid of all possible letter stimuli from the memory set (12 letters), and the individual must click on the letters in the order they were presented on that trial. Participants then practice the processing portion of the task alone, with arithmetic problems presented on the screen until the participant makes a mouse click to proceed to the answer screen. On the answer screen, the participant must decide whether

the number presented onscreen matches the result of the mental calculation that was performed by clicking the box for either "True" or "False". After 15 such practice problems, the participants then perform three practice items composed of both the processing-and-storage aspects. After completing the practice, the participant completes 15 experimental processing-and-storage trials. Within each trial, between three and seven math problems and letters are presented, with the exact number of items on any given trial unknown to the participant. There are three trials of each list length, for a total of 75 math problems and letters on the task. The main dependent variable for the Operation Span is the total number of letters recalled in the correct serial position across all trials.

Symmetry Span. The task structure is similar to that of the Operation Span just described, with the following exceptions. First, instead of remembering letters, participants are presented with a 4 x 4 matrix of blank squares, with one square colored in red on a given trial. At recall, the participant must indicate the location of the squares within the matrix that were colored for that trial. Second, instead of solving math problems, participants are presented with an 8 x 8 figure composed of black and white squares. The participant must decide whether the figure is symmetrical about its vertical axis by clicking "Yes" or "No" on the answer screen. Finally, the list length can vary between two and five, for a total of 42 symmetry figures and square locations on the task. The main dependent variable for the Symmetry Span is the total number of square locations recalled in the correct sequential order across all trials (for more information about the validity and reliability of the automated versions of the Operation and Symmetry Span, see Barch et al., 2009; Unsworth et al., 2005; Unsworth, Redick, Heitz, Broadway, & Engle, in press).

AX-CPT

The general materials and stimuli presentation for the three versions of the AX-CPT utilized are described first, and then the information specific to each version is presented separately. Specifically, individual letters were presented one at a time in the center of the screen. Capital letters were presented in white on a black background in 24-point Arial font. All letters except vowels were used as possible cue and probe stimuli. A serial response box was used to collect responses. Participants used the index fingers of each hand to respond to nontargets and targets, respectively.

As shown in Figure 1, each trial begins with the presentation of a blank screen for 1000 ms, followed by a letter (cue) for 500 ms. Next, a blank interstimulus interval of 4500 ms occurs, followed by another letter (probe) for 500 ms. A beep serves as auditory feedback if the participant does not make a response to stimuli within 1000 ms of the onset of the letter (miss). A trial sequence with *A* as a cue and *X* as a probe defines the target, and the participant is instructed to press the target response button as quickly as possible when this event happens. All other cue-probe sequences are nontargets; these letters are to receive a nontarget response. For each of the different versions of the AX-CPT described below, Table 4 provides information about the probability of each cue, probe, and cue-probe sequence.

AX-CPT-70. This version of the AX-CPT is most similar to the kind used by Barch, Braver, Cohen, and colleagues (for review, see Braver et al., 2002). In this version, *AX* targets occur on 70% of all cue-probe trials. The remaining nontarget trial types (*AY, BX, BY*) all occur on 10% each of cue-probe trials.

AX-CPT-10. This version of the AX-CPT is similar to a version used by Dias et al. (2003). The main difference between this version of the AX-CPT and the version just described is that the frequency of *AX* targets and *AY* nontargets is switched. That is, *AX* targets, along with *BX* and *BY* nontargets, occur on 10% each of all cue-probe trials, whereas *AY* nontargets occur on 70% of cue-probe trials.

AX-CPT-40. This version of the AX-CPT has not been reported in the literature previously. Again, the main difference between this version of the AX-CPT and the versions just described is that the frequencies of AX target and AY nontargets are now equal. That is, AX targets and AY nontargets occur on 40% each of all cue-probe trials, whereas BX and BY nontargets still occur on 10% each of cue-probe trials.

Procedure

Participants were identified as belonging to the high- or low-WMC group according to the average of their z-transformed scores on Operation and Symmetry Span. If their z-score composite fell within the upper or lower quartiles of scores from our database of over 4000 participants, they were assigned to the high- or low-WMC group, respectively. Within each WMC group, participants were randomly assigned to the various versions of the AX-CPT. Thus, 20 high- and 20 low-WMC individuals were each assigned to complete AX-CPT-70, AX-CPT-10, and AX-CPT-40. The different versions of the AX-CPT were administered as a between-subjects factor. Trial type frequencies were kept constant within an individual in order to prevent possible task order effects that would complicate the interpretation of the results (Kane & Engle, 2003; Kane et al., 2001; Unsworth et al., 2004).

Each version of the AX-CPT began with instructions and examples to ensure the participant understood the task goals. Each participant performed a practice block of 40 trials that was constructed to be similar to the experimental blocks that followed. The only exception was that each practice trial was followed by auditory accuracy feedback. At the end of the practice block, participants must achieve 75% accuracy in order to move on to the experimental blocks. All participants in the current studies were able to achieve the criterion accuracy level after one practice block.

Each experimental block contained 40 trials, broken down into the specific target and nontarget trial types according to the version of the AX-CPT being performed. Because each trial was a fixed duration of 6500 ms, each block lasted 4 minutes, 20 seconds. Each block was separated by a minimum of 15 seconds, and each block did not start until the participant instructed the experimenter to begin. A total of 1 practice block and 10 experimental blocks for each version of the AX-CPT, along with time for instructions and breaks, took approximately 60 minutes to complete. Participants were given the option of taking an extended break halfway through the session.

Analyses

For both the probe accuracy and correct mean RT results, an omnibus analysis of variance (ANOVA) was first conducted with WMC (2) and Version (3) as between-subjects factors, and Trial Type (4) as the within-subjects factor. Because the predictions were tailored to examine the effect of manipulating the cue and target frequencies and conditional probabilities as a function of WMC, follow-up split-plot ANOVAs with WMC (2) as the between-subjects factor, and Trial Type (4) as the within-subjects factor, were conducted separately for AX-CPT-70, AX-CPT-10, and AX-CPT-40. In each case,

simple-main-effects independent-samples t-tests (Bonferroni corrected alpha = .0125) were conducted to compare performance *between* the WMC groups on each trial type in each task version. Simple-main-effects analyses were also conducted via paired-samples t-tests (Bonferroni corrected alpha = .0042) to pairwise compare the different trial types *within* each task version for each WMC group separately. In addition, follow-up analyses were conducted for each WMC group separately via split-plot ANOVAs with Version (3) as the between-subjects factor, and Trial Type (4) as the within-subjects factor. Tukey's tests (Bonferroni corrected alpha = .0167) were conducted to examine the relative performance on the different trial types *across* each task version for each WMC group separately. Given the significant effects of practice observed in the current study (see below), the above analyses were also conducted using only the trials from the first five blocks (200 trials) of each task. These results are provided in Tables A.1 and A.2 for archival purposes and to facilitate comparison with the existing AX-CPT-70 literature. Finally, all probe accuracy analyses were additionally conducted using arcsine-transformed accuracy rates.

In addition, analyses of the RT distributions were computed for specific trial types for each task version: (a) AX trials in the AX-CPT-70; (b) AY trials in the AX-CPT-10; and (c) AX and AY trials in the AX-CPT-40. The distribution analyses were conducted by first rank-ordering each individual participant's correct RT for the specific trial type, and then dividing each participant's RT distribution into deciles. Therefore, the fastest 10% of trials assigned to bin one, the next fastest 10% of trials were assigned to bin two, and so on until the slowest 10% of trials were assigned to bin ten. Each individual's mean RT for each bin was then averaged at the group level in order to make comparisons

between the high- and low-WMC groups for each task version. A split-plot ANOVA with WMC (2) as the between-subjects factor and Bin (10) as the within-subjects factor was computed separately for AX-CPT-70 and AX-CPT-10, and a split-plot ANOVA with WMC (2) as the between-subjects factor and Bin (10) and Trial Type (2) as the within-subjects factors was computed for AX-CPT-40.

Performance was additionally examined as a function of the amount of practice. First, recent studies (Paxton et al., 2006; Braver, Paxton, Locke, & Barch, 2009) have shown that older adults' AX-CPT-70 performance varies relative to the amount of practice experienced. Second, the current versions of the AX-CPT presented a total of 400 cue-probe trials. The main reasons for including a higher number of trials were to provide more stable estimates of performance on non-target trial types and have a sufficient number of correct trials to analyze the RT distributions. However, if performance changes are observed on specific trial types early vs. late in the task session, this could be diagnostic about the processes involved in performance. Practice was operationally defined as the first vs. the second half of the task. The first half of the task consisted of averaging blocks one through five, and the second half of the task consisted of averaging blocks six through ten. An omnibus ANOVA was first conducted with WMC (2) and Version (3) as between-subjects factors, and Trial Type (4) and Half (2) as the within-subjects factor. To examine the effects of practice separately for each WMC group on each task version, performance was then evaluated using repeated-measures ANOVAs with Trial Type (4) and Half (2) as the within-subjects factors. Finally, follow-up paired-samples t-tests (Bonferroni corrected alpha = .0125) were used to statistically

evaluate the amount and direction of change in performance indicated by any significant Trial Type x Half interactions from the previous analyses.

CHAPTER 3

RESULTS

Participants

Two low-WMC participants were classified as outliers due to extremely low accuracy on AX trials, which led to an overall accuracy on probe trials of less than 70%. These participants (one in AX-CPT-70, one in AX-CPT-40) were subsequently replaced to achieve equivalent sample sizes across WMC group and version of the AX-CPT. The demographic information for the final sample is presented in Table 6.

Table 6
Demographic Information for the High- and Low-WMC Participants

	Age (years)	Z-WMC	% Female	% College
		AX-CPT-70		
High	23.0 (3.1)	0.88 (0.18)	55	85
Low	23.1 (4.2)	-1.18 (0.55)	75	75
		AX-CPT-10		
High	21.8 (2.6)	0.82 (0.14)	45	70
Low	22.3 (3.1)	-0.97 (0.43)	60	80
		AX-CPT-40		
High	23.3 (3.2)	0.92 (0.16)	65	65
Low	23.7 (3.9)	-1.14 (0.56)	60	55

Note. Standard deviations are in parentheses.

Probe Accuracy

The full omnibus ANOVA output is provided in Table B.1. The three-way interaction was significant, $F(6, 342) = 4.03$, $p = .001$, partial $eta^2 = .066$, and follow-up analyses were conducted by examining performance separately for each level of Version and subsequently for each level of WMC to decompose this interaction.

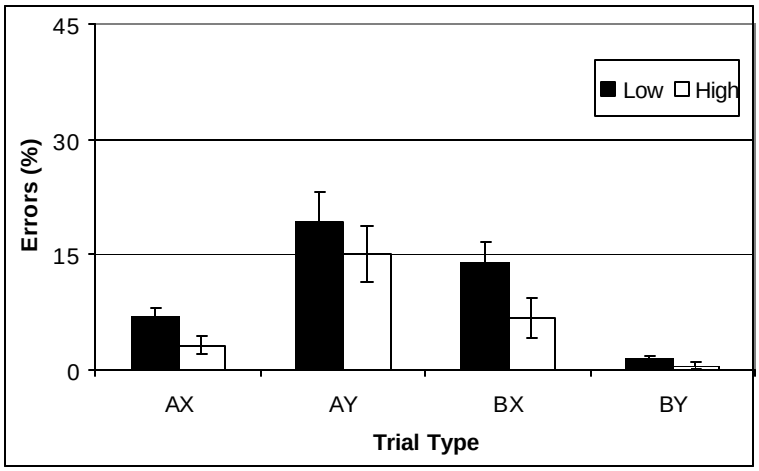
AX-CPT-70

Accuracy results for probe trials on the AX-CPT-70 are presented in Figure 3a. The main effect of Trial Type was significant, $F(3, 114) = 18.77$, $p < .001$, partial $eta^2 = .331$, and although the main effect of WMC was significant, $F(1, 38) = 6.14$, $p < .018$, partial $eta^2 = .139$, the WMC x Trial Type interaction did not approach significance ($F < 1$).

Comparison between high and low WMC. As can be seen in Figure 3a, the follow-up independent-samples t-tests on each trial type indicated that the high-WMC participants were marginally more accurate than low-WMC participants on AX trials, $t(38) = 2.53$, $p = .016$, BX trials, $t(38) = 2.00$, $p = .053$, and BY trials, $t(38) = 2.08$, $p = .044$. However, the WMC groups did not differ in accuracy on AY trials ($t < 1$). Note that the WMC group difference on BY trials, although marginally significant, reflects a total of 12 errors for the low-WMC group and 4 errors for the high-WMC group out of a total of 800 BY trials for each group.

Comparison within high WMC. For the high-WMC group, probe accuracy results were examined via a repeated-measures ANOVA with Trial Type as the within-subjects factor. The main effect of Trial Type was significant, $F(3, 57) = 12.91$, $p < .001$, partial $eta^2 = .404$. Theoretically relevant paired-samples t-tests indicated the high-WMC group:

A



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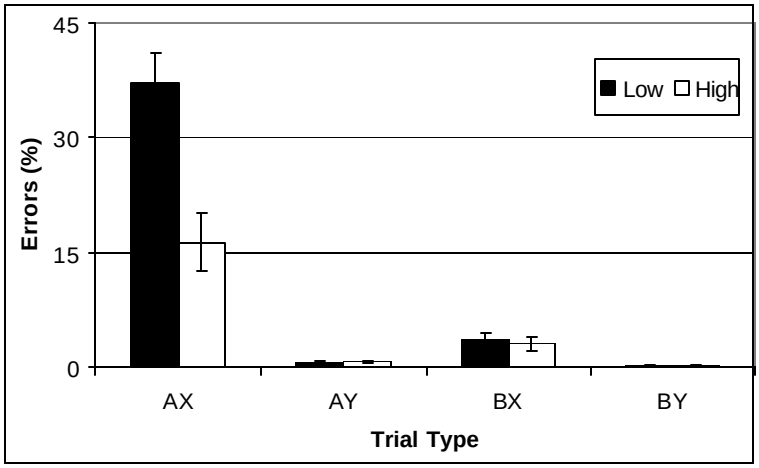

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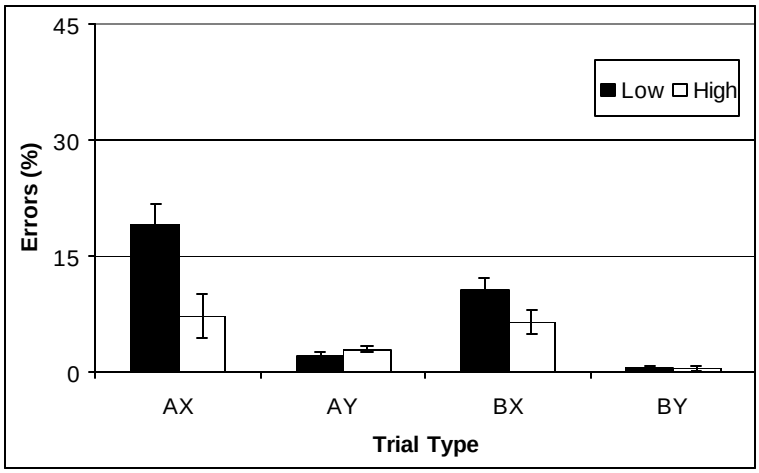


Figure 3. Errors for high- and low-WMC groups on AX-CPT-70 (A), AX-CPT-10 (B), and AX-CPT-40 (C). Error bars represent $\pm$ 1 standard error of the mean.

(a) made more errors on AY vs. AX trials, $t(19) = 3.75$, $p = .001$; and (b) committed more errors on AY vs. BX trials, $t(19) = 2.45$, $p = .024$.

Comparison within low WMC. For the low-WMC group, probe accuracy data were analyzed using a repeated-measures ANOVA with Trial Type as the within-subjects factor. The main effect of Trial Type was significant, $F(3, 57) = 8.33$, $p < .001$, partial $eta^2 = .305$. The same follow-up paired-samples t-tests as above confirmed that the low-WMC group: (a) made more errors on AY vs. AX trials, $t(19) = 2.81$, $p = .011$; and (b) did not differ in accuracy on AY vs. BX trials ($t < 1$).

AX-CPT-10

Accuracy results for probe trials on the AX-CPT-10 are presented in Figure 3b. The main effect of Trial Type was significant, $F(3, 114) = 91.06$, $p < .001$, partial $eta^2 = .706$, as was the main effect of WMC, $F(1, 38) = 13.39$, $p = .001$, partial $eta^2 = .261$. However, these effects were qualified by a significant WMC x Trial Type interaction, $F(3, 114) = 15.04$, $p < .001$, partial $eta^2 = .284$.

Comparison between high and low WMC. As is evident from Figure 3b, follow-up independent-samples t-tests indicated that high-WMC individuals were significantly more accurate than low-WMC individuals on AX trials, $t(38) = 3.93$, $p < .001$. However, the WMC groups did not differ in accuracy on all other trial types (all t's < 1).

Comparison within high WMC. For the high-WMC group, probe accuracy results were examined via a repeated-measures ANOVA with Trial Type as the within-subjects factor. The main effect of Trial Type was significant, $F(3, 57) = 32.73$, $p < .001$, partial $eta^2 = .633$. Theoretically relevant paired-samples t-tests indicated the high-WMC group:

(a) made more errors on AX vs. AY trials, $t(19) = 6.00$, $p < .001$; and (b) committed more errors on AX vs. BX trials, $t(19) = 5.22$, $p < .001$.

Comparison within low WMC. For the low-WMC group, probe accuracy data were analyzed using a repeated-measures ANOVA with Trial Type as the within-subjects factor. The main effect of Trial Type was significant, $F(3, 57) = 59.72$, $p < .001$, partial $eta^2 = .759$. The same follow-up paired-samples t-tests as above confirmed that the low-WMC group: (a) made more errors on AX vs. AY trials, $t(19) = 7.92$, $p < .001$; and (b) committed more errors on AX vs. BX trials $t(19) = 7.37$, $p < .001$.

AX-CPT-40

Accuracy results for probe trials on the AX-CPT-40 are presented in Figure 3c. Significant main effects of Trial Type, $F(3, 114) = 28.17$, $p < .001$, partial $eta^2 = .426$, and WMC, $F(1, 38) = 7.94$, $p = .008$, partial $eta^2 = .173$, were qualified by a significant WMC x Trial Type interaction, $F(3, 114) = 7.13$, $p < .001$, partial $eta^2 = .158$.

Comparison between high and low WMC. As shown in Figure 3c, follow-up independent-samples t-tests indicated that the high-WMC group was significantly more accurate than the low-WMC group on AX trials, $t(38) = 2.91$, $p = .006$, and BX trials (marginally), $t(38) = 2.04$, $p = .048$. However, the two WMC groups did not differ in accuracy on AY trials, $t(38) = 1.35$, $p = .184$, nor on BY trials ($t < 1$).

Comparison within high WMC. For the high-WMC group, probe accuracy results were examined via a repeated-measures ANOVA with Trial Type as the within-subjects factor. The main effect of Trial Type was significant, $F(3, 57) = 13.05$, $p < .001$, partial $eta^2 = .407$. Theoretically relevant paired-samples t-tests indicated the high-WMC group: (a) made more errors on AX vs. AY trials, $t(19) = 3.76$, $p = .001$; (b) did not differ in

accuracy on AX vs. BX trials ($t < 1$); and (c) produced more errors on BX vs. AY trials, $t(19) = 2.62$, $p = .017$.

Comparison within low WMC. For the low-WMC group, probe accuracy data were analyzed using a repeated-measures ANOVA with Trial Type as the within-subjects factor. The main effect of Trial Type was significant, $F(3, 57) = 18.53$, $p < .001$, partial $eta^2 = .494$. The same follow-up paired-samples t-tests as above confirmed that the low-WMC group: (a) made more errors on AX vs. AY trials, $t(19) = 4.43$, $p < .001$; (b) committed more errors on AX vs. BX trials, $t(19) = 2.32$, $p = .031$; and (c) produced more errors on BX vs. AY trials, $t(19) = 5.60$, $p < .001$.

Comparison across Versions

High WMC. Accuracy for the high-WMC group was examined as a function of Version and Trial Type. Although the main effect of Version was not significant, $F(2, 57) = 1.86$, $p = .165$, the main effect of Trial Type was significant, $F(3, 171) = 19.98$, $p < .001$, partial $eta^2 = .260$. Critically, the Version x Trial Type interaction was significant, $F(6, 171) = 18.69$, $p < .001$, partial $eta^2 = .396$.

Tukey's tests were used to examine the effects of Version upon each trial type. For AX trials, AX-CPT-10 accuracy was significantly lower than both AX-CPT-40 and AX-CPT-70 (both p's $< .001$), which did not differ from each other ($p = .231$). For AY trials, AX-CPT-10 accuracy was significantly higher than both AX-CPT-40 and AX-CPT-70 (both p's $< .001$), which did not differ from each other ($p = .653$). For BX trials, accuracy on the three task versions was not significantly different from each other (all p's $> .183$). Finally, on BY trials, accuracy on the three task versions was not significantly different from each other (all p's $> .736$).

Low WMC. Accuracy for the low-WMC group was analyzed as a function of Version and Trial Type. Although the main effect of Version was not significant, $F(2, 57) = 1.12$, $p = .332$, the main effect of Trial Type was significant, $F(3, 171) = 38.40$, $p < .001$, partial $eta^2 = .402$. Again, the Version x Trial Type interaction was significant, $F(6, 171) = 21.77$, $p < .001$, partial $eta^2 = .433$.

Tukey's tests were conducted to examine the effects of Version upon each trial type. For AX trials, AX-CPT-10 accuracy was significantly lower than both AX-CPT-40 ($p = .002$) and AX-CPT-70 ($p < .001$), and the difference between AX-CPT-40 and AX-CPT-70 approached significance ($p = .052$). For AY trials, AX-CPT-10 accuracy was significantly higher than both AX-CPT-40 and AX-CPT-70 (both p's $< .001$), which did not differ from each other ($p = .905$). For BX trials, AX-CPT-10 accuracy was significantly higher than AX-CPT-70 ($p = .002$) and marginally higher than AX-CPT-40 ($p = .048$), and there was no difference between AX-CPT-70 and AX-CPT-40 ($p = .514$). Finally, for BY trials, AX-CPT-70 accuracy was marginally lower than AX-CPT-10 ($p = .019$), but the other comparisons were not significant (both p's $> .134$).

Probe Accuracy Summary

The analyses of the accuracy results produced several significant effects involving WMC. The analyses indicated that the low-WMC group made more: (a) AX errors on AX-CPT-70, AX-CPT-10, and AX-CPT-40; and (b) BX errors on AX-CPT-70 and AX-CPT-40. That is, across the various versions of the task, the significant WMC differences in accuracy occurred when the probe decision involved the letter X. In all task versions, correctly responding to the probe letter X depends upon remembering the most recent cue letter (A or B), whereas the correct response to any other probe letters (Y) can be made

without regard to the specific cue that preceded the probe letter. The implications of these results are explored further in the Discussion.

Probe Mean RT

The full omnibus ANOVA output is provided in Table B.2. The three-way interaction was not significant ($F < 1$). However, the Trial Type x Version interaction was significant, $F(6, 342) = 53.76$, $p < .001$, partial eta^2 = .485, and the WMC x Trial Type interaction was marginally significant, $F(3, 342) = 2.57$, $p = .05$, partial eta^2 = .022. Follow-up analyses were conducted by examining performance separately for each level of Version and subsequently for each level of WMC to decompose these interactions.

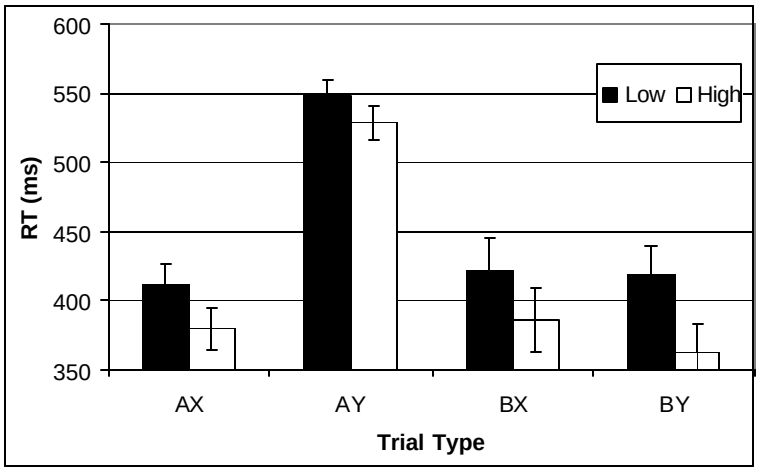
AX-CPT-70

Mean RT results for probe trials on the AX-CPT-70 are presented in Figure 4a. Although the main effect of Trial Type was significant, $F(3, 114) = 125.31$, $p < .001$, partial eta^2 = .767, both effects involving WMC were not significant: WMC, $F(1, 38) = 2.41$, $p = .129$; WMC x Trial Type, $F(3, 114) = 1.47$, $p = .226$.

Comparison between high and low WMC. The follow-up independent-samples t-tests on each trial type indicated that the high-WMC participants were marginally faster than low-WMC participants on BY trials, $t(38) = 2.00$, $p = .053$. However, the WMC groups did not differ in mean RT on AX trials, $t(38) = 1.51$, $p = .140$, AY trials, $t(38) = 1.15$, $p = .256$, or BX trials, $t(38) = 1.09$, $p = .283$.

Comparison within high WMC. For the high-WMC group, probe mean RT results were examined via a repeated-measures ANOVA with Trial Type as the within-subjects factor. The main effect of Trial Type was significant, $F(3, 57) = 92.28$, $p < .001$, partial eta^2 = .829. Theoretically relevant paired-samples t-tests indicated the high-WMC group:

A



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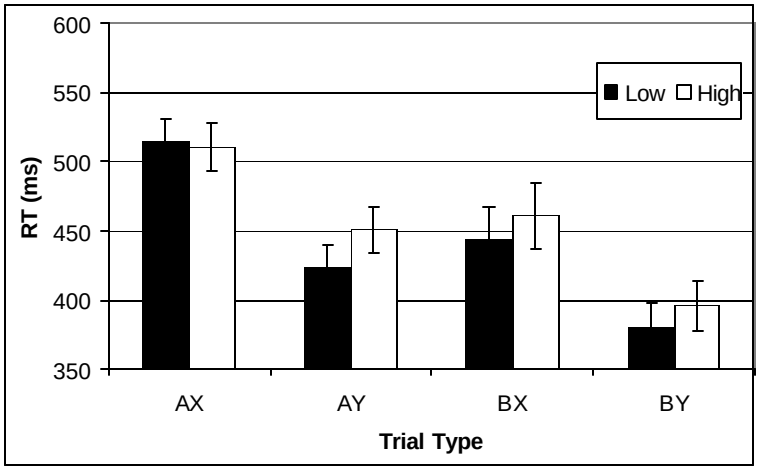

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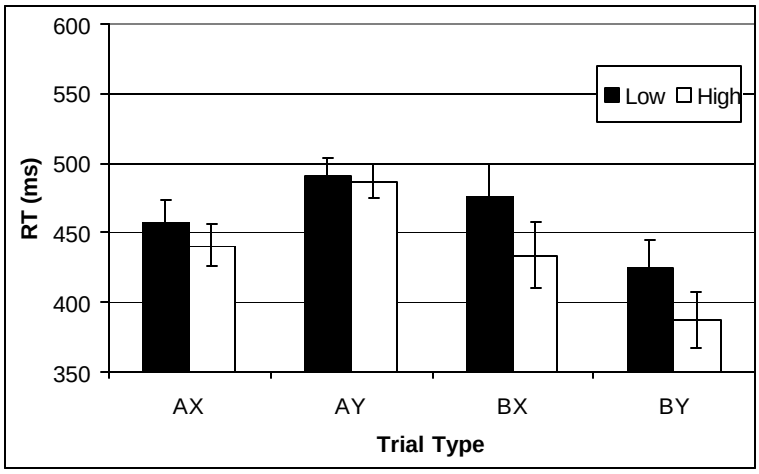


Figure 4. Correct mean RT for high- and low-WMC groups on AX-CPT-70 (A), AX-CPT-10 (B), and AX-CPT-40 (C). Error bars represent $\pm$ 1 standard error of the mean.

(a) was slower on AY vs. AX trials, $t(19) = 16.70$, $p < .001$; and (b) took longer to respond on AY vs. BX trials, $t(19) = 9.27$, $p < .001$.

Comparison within low WMC. For the low-WMC group, probe mean RT data were analyzed using a repeated-measures ANOVA with Trial Type as the within-subjects factor. The main effect of Trial Type was significant, $F(3, 57) = 44.32$, $p < .001$, partial $eta^2 = .700$. The same follow-up paired-samples t-tests as above confirmed that the low-WMC group: (a) was slower on AY vs. AX trials, $t(19) = 12.38$, $p < .001$; and (b) took longer to respond on AY vs. BX trials $t(19) = 6.46$, $p < .001$.

AX-CPT-10

Mean RT results for probe trials on the AX-CPT-10 are presented in Figure 4b. Although the main effect of Trial Type was significant, $F(3, 114) = 69.75$, $p < .001$, partial $eta^2 = .647$, both the main effect of WMC ($F < 1$) and the WMC x Trial Type interaction, $F(3, 114) = 1.15$, $p = .331$, were not significant.

Comparison between high and low WMC. The follow-up independent-samples t-tests on each trial type indicated that the high and low-WMC participants did not significantly differ in mean RT to any of the trial types: AY trials, $t(38) = -1.16$, $p = .253$ (all other t's < 1).

Comparison within high WMC. For the high-WMC group, probe mean RT results were examined via a repeated-measures ANOVA with Trial Type as the within-subjects factor. The main effect of Trial Type was significant, $F(3, 57) = 24.47$, $p < .001$, partial $eta^2 = .563$. Theoretically relevant paired-samples t-tests indicated the high-WMC group: (a) was slower on AX vs. AY trials, $t(19) = 4.30$, $p < .001$; and (b) took longer to respond on AX vs. BX trials, $t(19) = 3.14$, $p = .005$.

Comparison within low WMC. For the low-WMC group, probe mean RT data were analyzed using a repeated-measures ANOVA with Trial Type as the within-subjects factor. The main effect of Trial Type was significant, F(3, 57) = 51.94, p < .001, partial eta^2 = .732. The same follow-up paired-samples t-tests as above confirmed that the low-WMC group: (a) was slower on AX vs. AY trials, $t(19) = 9.57$, $p < .001$; and (b) took longer to respond on AX vs. BX trials $t(19) = 4.79$, $p < .001$.

AX-CPT-40

Mean RT results for probe trials on the AX-CPT-40 are presented in Figure 4c. Although the main effect of Trial Type was significant, $F(3, 114) = 26.47$, $p < .001$, partial eta^2 = .411, both effects involving WMC were not significant: WMC, $F(1, 38) = 1.56$, $p = .219$; WMC x Trial Type, $F(3, 114) = 1.80$, $p = .151$.

Comparison between high and low WMC. The follow-up independent-samples t-tests on each trial type indicated that the high-WMC participants were marginally faster than low-WMC participants on BY trials, $t(38) = 1.94$, $p = .060$. However, the WMC groups did not differ in mean RT on any other trial types: BX trials, $t(38) = 1.27$, $p = .211$ (all other t's < 1).

Comparison within high WMC. For the high-WMC group, probe mean RT results were examined via a repeated-measures ANOVA with Trial Type as the within-subjects factor. The main effect of Trial Type was significant, $F(3, 57) = 15.93$, $p < .001$, partial eta^2 = .456. Theoretically relevant paired-samples t-tests indicated the high-WMC group: (a) was slower on AY vs. AX trials, $t(19) = 6.35$, $p < .001$; (b) did not differ in the time to respond on AX vs. BX trials ($t < 1$); and (c) took longer to respond on AY vs. BX trials, $t(19) = 2.60$, $p = .018$.

Comparison within low WMC. For the low-WMC group, probe mean RT data were analyzed using a repeated-measures ANOVA with Trial Type as the within-subjects factor. The main effect of Trial Type was significant, $F(3, 57) = 11.49$, $p < .001$, partial $eta^2 = .377$. The same follow-up paired-samples t-tests as above confirmed that the low-WMC group: (a) was slower on AY vs. AX trials, $t(19) = 3.75$, $p = .001$; (b) did not differ in the time to respond on AX vs. BX trials, $t(19) = 1.25$, $p = .227$; and (c) did not differ in mean RT to BX vs. AY trials ($t < 1$).

Comparison across Versions

High WMC. Probe mean RT for the high-WMC group was examined as a function of Version and Trial Type. Although the main effect of Version was not significant, $F(2, 57) = 1.53$, $p = .226$, the main effect of Trial Type was significant, $F(3, 171) = 67.71$, $p < .001$, partial $eta^2 = .543$. Critically, the Version x Trial Type interaction was significant, $F(6, 171) = 22.84$, $p < .001$, partial $eta^2 = .445$.

Tukey's tests were used to examine the effects of Version upon each trial type. For AX trials, AX-CPT-10 mean RT was significantly slower than both AX-CPT-70 ($p < .001$) and AX-CPT-40 ($p = .005$), and AX-CPT-40 mean RT was significantly slower than AX-CPT-70 ($p = .015$). For AY trials, AX-CPT-10 mean RT was significantly faster than AX-CPT-70 ($p = .002$), but no other differences were significant (both p's > .136). For BX trials, AX-CPT-70 mean RT was marginally faster than AX-CPT-10 ($p = .069$), but no other differences were significant (both p's > .328). Finally, on BY trials, mean RT on the three task versions was not significantly different from each other (all p's > .393).

Low WMC. Probe mean RT for the low-WMC group was examined as a function of Version and Trial Type. Although the main effect of Version was not significant ($F < 1$), the main effect of Trial Type was significant, $F(3, 171) = 43.43$, $p < .001$, partial $eta^2 = .432$. Critically, the Version x Trial Type interaction was significant, $F(6, 171) = 32.49$, $p < .001$, partial $eta^2 = .533$.

Tukey's tests were used to examine the effects of Version upon each trial type. For AX trials, AX-CPT-10 mean RT was significantly slower than AX-CPT-70 ($p < .001$) and marginally slower AX-CPT-70 ($p = .036$), which did not significantly differ from each other ($p = .105$). For AY trials, AX-CPT-10 mean RT was significantly faster than both AX-CPT-40 ($p = .001$) and AX-CPT-10 ($p < .001$), which were significantly different from each other ($p = .006$). For both BX and BY trials, mean RT on the three task versions was not significantly different from each other (all p's > .240 and .169, respectively).

Probe Mean RT Summary

The analyses conducted on the mean RTs can be summarized rather succinctly, at least in regard to differences between the two WMC groups. In AX-CPT-70 and AX-CPT-40, the high-WMC group was marginally faster than the low-WMC group on BY trials. Otherwise, the WMC groups did not differ in the speed with which they responded to the probe trials across the various trial types. These results are examined further in the Discussion.

RT Distribution Analyses

AX-CPT-70

AX trials in the AX-CPT-70 were used to form RT distributions for the high- and low-WMC groups, which are shown in Figure 5a. The main effect of Bin was significant, $F(9, 342) = 457.48$, $p < .001$, partial $eta^2 = .923$. Although the main effect of WMC was not significant, $F(1, 38) = 2.26$, $p = .141$, the WMC x Bin interaction was significant, $F(9, 342) = 2.41$, $p = .012$, partial $eta^2 = .060$.

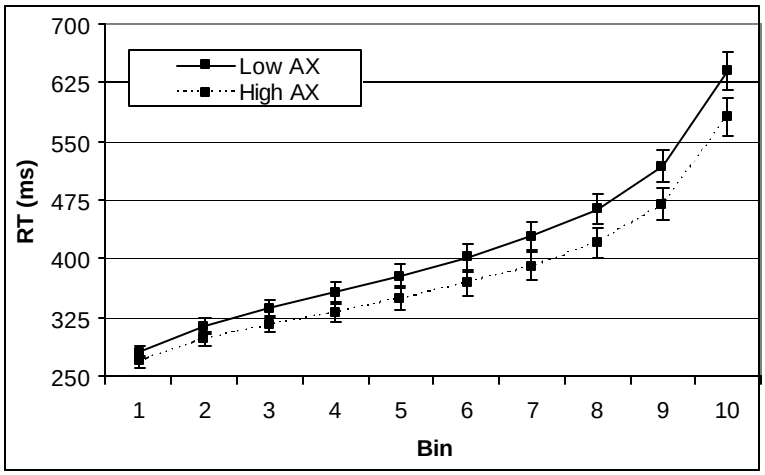
AX-CPT-10

AY trials in the AX-CPT-10 were used to form RT distributions for the high- and low-WMC groups, which are shown in Figure 5b. The main effect of Bin was significant, $F(9, 342) = 618.48$, $p < .001$, partial $eta^2 = .942$, but neither the main effect of WMC, $F(1, 38) = 1.35$, $p = .253$, nor the WMC x Bin interaction ($F < 1$) was significant.

AX-CPT-40

AX and AY trials in the AX-CPT-40 were used to form RT distributions for the high- and low-WMC groups, which are shown in Figure 5c. Significant main effects of Bin, $F(9, 342) = 552.20$, $p < .001$, partial $eta^2 = .936$, and Trial Type, $F(1, 38) = 47.37$, $p < .001$, partial $eta^2 = .555$, were obtained, along with a significant Bin x Trial Type interaction, $F(9, 342) = 27.15$, $p < .001$, partial $eta^2 = .417$. However, neither the main effect of WMC ($F < 1$), nor any of the interactions with WMC were significant: WMC x Bin ($F < 1$); WMC x Trial Type, $F(1, 38) = 1.28$, $p = .265$; WMC x Bin x Trial Type, $F(9, 342) = 1.31$, $p = .230$.

A



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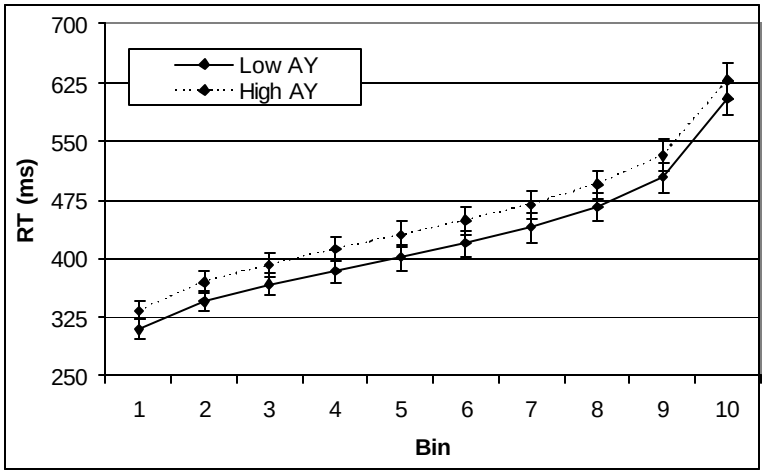

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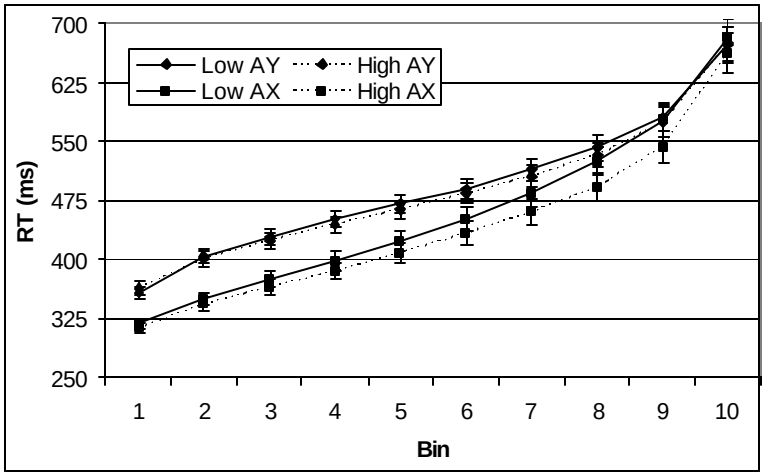


Figure 5. RT distributions for high- and low-WMC groups on AX-CPT-70 (A), AX-CPT-10 (B), and AX-CPT-40 (C). Error bars represent $\pm$ 1 standard error of the mean.

For AX trials, the main effect of Bin was significant, $F(9, 342) = 442.60$, $p < .001$, partial $eta^2 = .921$, but neither the main effect of WMC nor the WMC x Bin interaction was significant (both F's < 1). For AY trials, the main effect of Bin was significant, $F(9, 342) = 523.74$, $p < .001$, partial $eta^2 = .932$, but neither the main effect of WMC nor the WMC x Bin interaction was significant (both F's < 1).

RT Distribution Summary

The analyses of the RT distributions produced mixed results across the three task versions. The only significant difference obtained between the WMC groups was on AX-CPT-70, where there was a significant WMC x Bin interaction. The source of the interaction can be seen in Figure 5a: the RTs for the fastest bin are 269 ms and 281 ms for the high- and low-WMC groups, respectively; in comparison, the RTs for the slowest bin are 583 ms and 639 ms for the high- and low-WMC groups, respectively. However, for both the AX-CPT-10 and AX-CPT-40, the WMC x Bin interaction did not approach significance.

Practice Analyses of Accuracy

The full results of the omnibus ANOVA are provided in Table B.3. Examining the higher-order interactions involving the factor Half, the four-way interaction was marginally significant, $F(6, 342) = 2.06$, $p = .057$, partial $eta^2 = .035$, as was the three-way interaction of WMC x Trial Type x Half, $F(3, 342) = 2.50$, $p = .060$, partial $eta^2 = .021$. In addition, the three-way interaction of Version x Trial Type x Half was significant, $F(6, 342) = 2.85$, $p = .010$, partial $eta^2 = .048$, although the WMC x Version x Half interaction was not significant ($F < 1$).

AX-CPT-70

The probe accuracy results as a function of the first half vs. the second half of trials in the task session are presented in Figure 6. Looking first at the high-WMC group in Figure 6a, both the main effect of Half and the Trial Type x Half interaction were not significant (both F's < 1). Focusing on the low-WMC group in Figure 6b reveals a different pattern of results. Although the main effect of Half was not significant ($F < 1$), the Trial Type x Half interaction was significant $F(3, 57) = 5.98$, $p = .001$, partial eta^2 = .239. Paired-samples t-tests indicated the low-WMC group committed marginally more AY errors ($p = .018$) and fewer BX errors ($p = .079$) during the second half of the AX-CPT-70.

AX-CPT-10

The probe accuracy results as a function of the first half vs. the second half of trials in the task session are presented in Figure 7. Concentrating first on the high-WMC group in Figure 7a, the main effect of Half was marginally significant, $F(1, 19) = 3.77$, $p = .067$, partial eta^2 = .166. This main effect was qualified by a significant Trial Type x Half interaction, $F(3, 57) = 5.93$, $p = .001$, partial eta^2 = .238. Paired-samples t-tests indicated the high-WMC group committed marginally more AX errors ($p = .019$) during the second half of the AX-CPT-10. Inspecting the performance of the low-WMC group in Figure 7b, both the main effect of Half and the Trial Type x Half interaction were not significant (both F's < 1).

AX-CPT-40

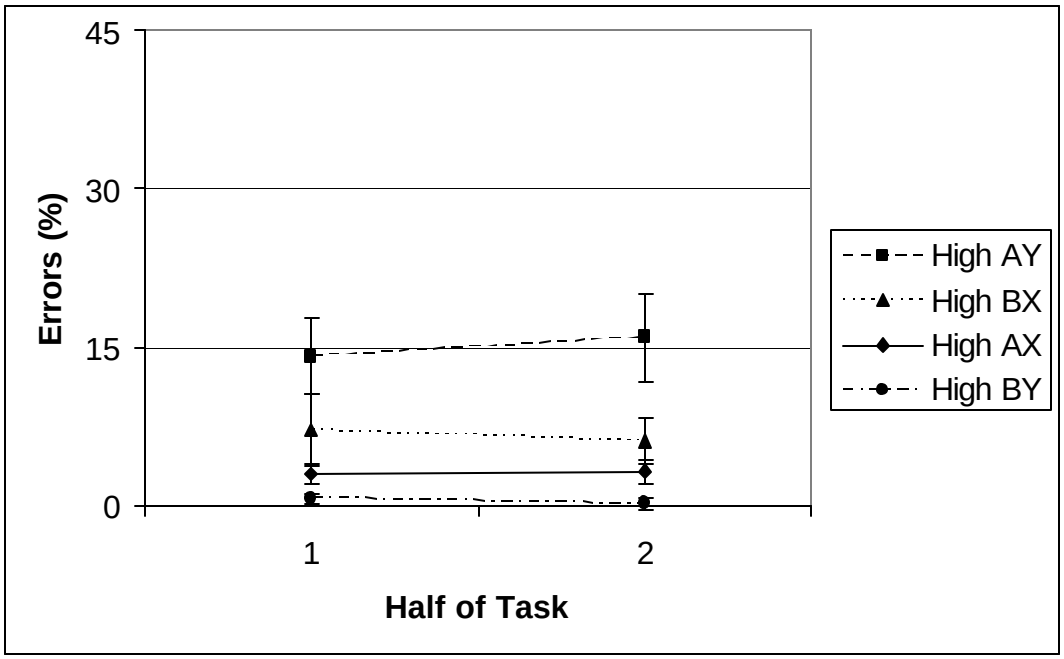
The probe accuracy results as a function of the first half vs. the second half of trials in the task session are presented in Figure 8. Examining the performance of the

high-WMC group in Figure 8a, both the main effect of Half ($F < 1$) and the Trial Type x Half interaction, $F(3, 57) = 1.05$, $p = .377$, were not significant. However, analyzing the performance of the low-WMC group in Figure 8b revealed that although the main effect of Half was not significant ($F < 1$), the Trial Type x Half interaction was significant, $F(3, 57) = 4.06$, $p = .011$. Paired-samples t-tests indicated that the low-WMC group made marginally more AX errors ($p = .054$) during the second half of the AX-CPT-40.

Practice Accuracy Summary

Somewhat surprisingly, including more blocks of trials in order to have more observations for statistical analyses of the rarely occurring nontarget trials had the unintended consequence of producing specific practice effects. On AX-CPT-70, only the low-WMC group showed an effect of practice, by making more AY errors and fewer BX errors later in the task session. On AX-CPT-10, only the high-WMC group showed an effect of practice, by making more AX errors later in the task session. Finally, on AX-CPT-40, only the low-WMC group showed a practice effect, by making marginally more AX errors later in the task session. The changes in performance observed on specific trial types, in specific task versions, and in specific WMC groups, are considered in the Discussion.

A



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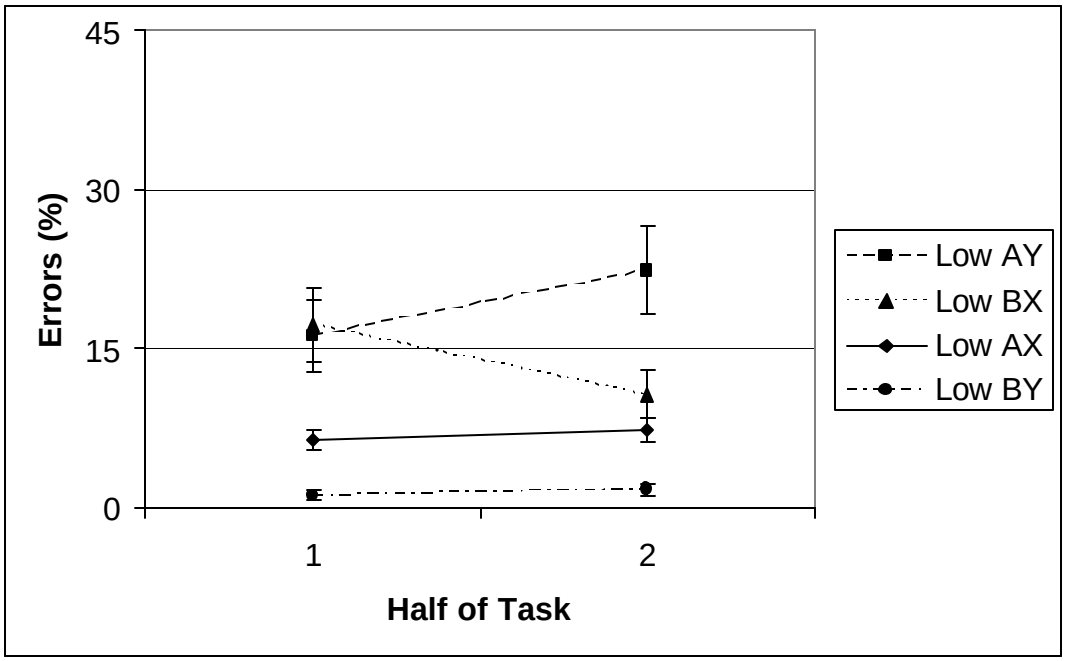
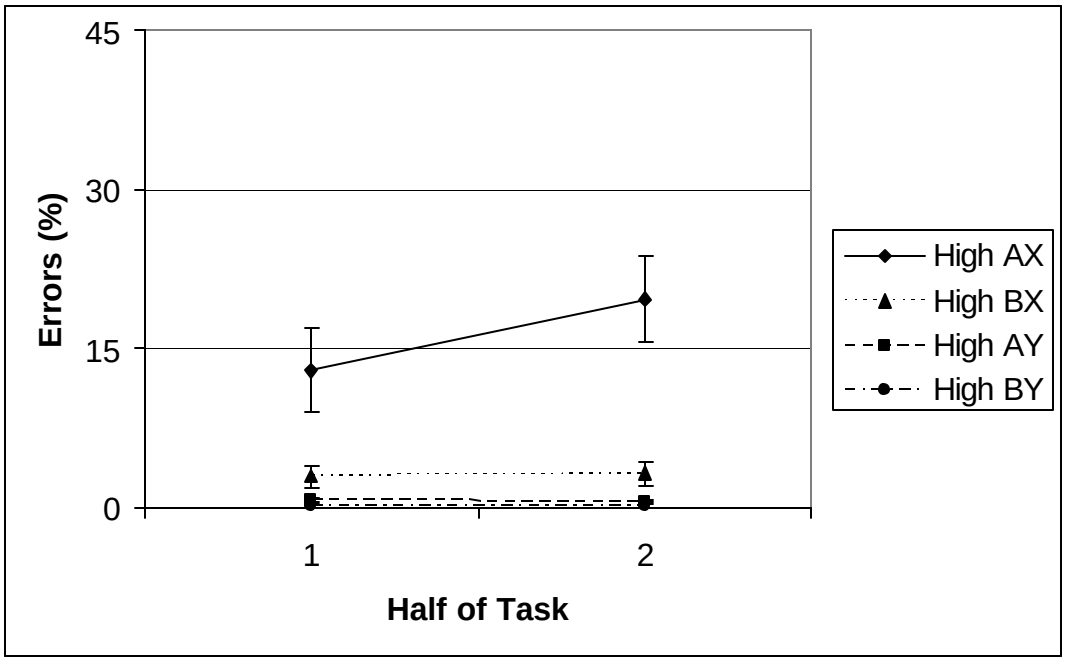


Figure 6. Errors for high-WMC (A) and low-WMC (B) groups as a function of practice on AX-CPT-70. Error bars represent $\pm$ 1 standard error of the mean.

A



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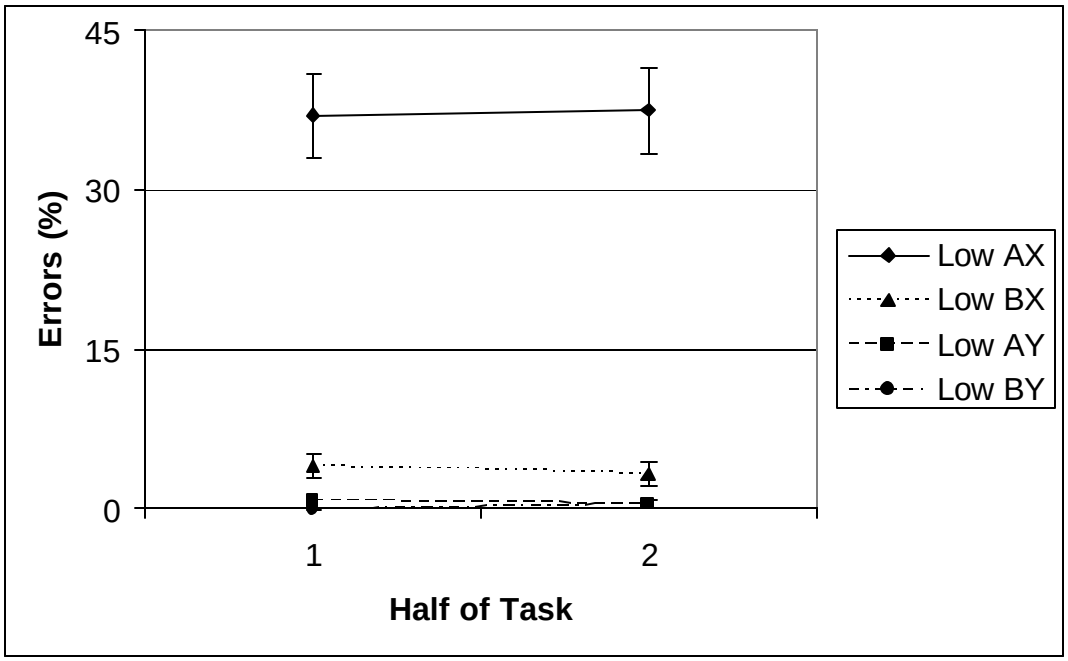
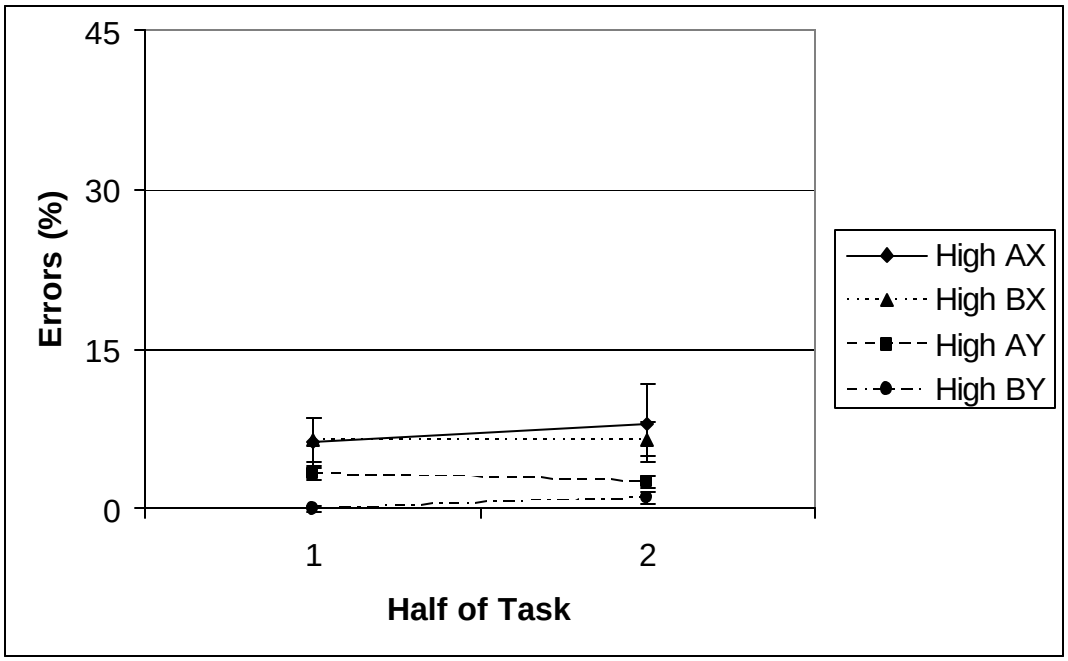


Figure 7. Errors for high-WMC (A) and low-WMC (B) groups as a function of practice on AX-CPT-10. Error bars represent $\pm$ 1 standard error of the mean.

A



B

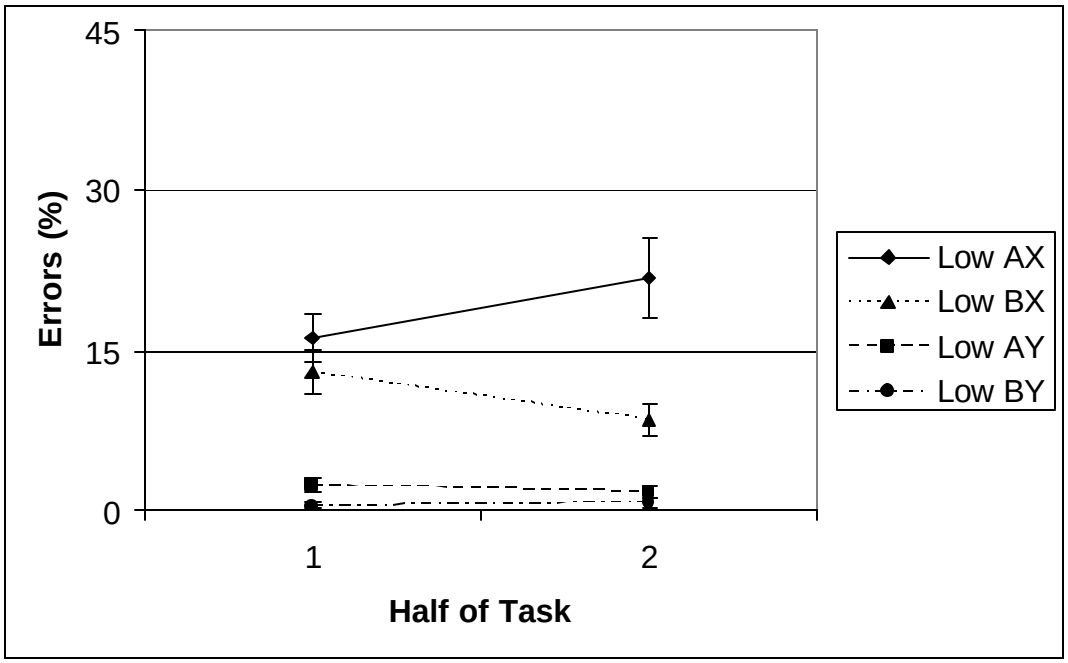


Figure 8. Errors for high-WMC (A) and low-WMC (B) groups as a function of practice on AX-CPT-40. Error bars represent $\pm$ 1 standard error of the mean.

CHAPTER 4

DISCUSSION

Across three versions of the AX-CPT, the WMC level of the participant influenced accuracy specifically on AX and BX trials. As mentioned previously, these are the only trial types where responding correctly to the probe stimulus depends upon the preceding cue stimulus. In contrast, the probe Y on AY and BY trials provided full information as to the correct nontarget response. The implication of this finding is that what differentiates the two WMC groups is the ability to use memory of local cue stimuli to guide behavior according to global task instructions and goals.

AX Performance as an Index of Cue Maintenance

The low-WMC participants made more AX errors than the high-WMC participants across all three task versions. AX errors reflect making an incorrect nontarget response to the probe letter X. Note that if the prepotency of the target response to the letter X was the sole determinant of BX errors, increased AX errors by the low-WMC group would not be expected. In fact, because the probe X almost always follows the cue A in AX-CPT-70, AX errors should reflect not actively maintaining the cue and instead an incorrect retrieval of the cue upon presentation of the probe X. Correct AX trials should reflect a mixture of sometimes using the cue to prepare a target response in advance, other times correctly retrieving the cue upon presentation of the probe, and the influence of guessing based on the high probability of making a target response to an X (Table 4). Thus, correct AX trials should be faster than AX errors on AX-CPT-70. This was the case for both the high-WMC group ($p < .001$) and the low-WMC group ($p = .001$). Note that if instead the AX errors were the result of encoding the cue letter

incorrectly, then the prediction would be that AX errors would be *faster* than correct AX trials – the participant would have been able to prepare a nontarget response, and thus the RTs would be expected to be similar to the RTs obtained on correct BX trials.

This interpretation is additionally strengthened by the analyses of the RT distributions of correct AX trials. Again, assume that the fastest AX trials represent response preparation during the cue-probe interval, whereas the slowest AX trials are more likely situations where the cue was not actively maintained or translated into preparing a target response. On the fastest AX trials, the RT difference between the two WMC groups was 12 ms, whereas on the slowest AX trials, the RT difference was 56 ms. Although the WMC groups did not differ in mean RT on AX trials, the WMC interaction observed with regard to the RT distributions indicates that the low-WMC group engaged in more trials where they had to retrieve the cue representation from secondary memory. This explanation would also apply to the increased AX errors produced by the low-WMC participants – not only does this search process take a varying amount of time, but it also can result in retrieving the incorrect cue representation. Again, the implication is that these errors occurred as a consequence of not maintaining the cue information, and resulted from the imperfect search process.

On AX-CPT-40, the low-WMC group produced more AX errors than the high-WMC group. This occurred despite the fact that the A cue in this task version was equally predictive of the subsequent probe requiring a target or a nontarget response. Thus, although maintaining access to the cue representation is necessary for success on AX trials, selectively preparing either response in advance would not be beneficial for performance in the long run. However, if one was using the A cue to prepare a nontarget

response, or simply preparing a nontarget response given the response frequencies listed in Table 7, then these AX errors should be faster than correct AX trials. In fact, AX errors were *slower* than correct AX trials for both the high-WMC group ($p = .004$) and the low-WMC group ($p = .011$).

Table 7
Target and Nontarget Response Probabilities across the Versions of the AX-CPT

	All Stimuli		Probe Stimuli Only	
Version	*p*(target)	*p*(nontarget)	*p*(target)	*p*(nontarget)
AX-CPT-70	.35	.65	.70	.30
AX-CPT-10	.05	.95	.10	.90
AX-CPT-40	.20	.80	.45	.55

On AX-CPT-10, the low-WMC participants produced over twice as many AX errors as the high-WMC participants. At first glance, the high number of AX errors should reflect the influence of preparing a nontarget response based on the knowledge that the A cue in this task version is strongly predictive of a Y probe letter. However, the high number of AX errors on AX-CPT-10 could also indicate the fact that a nontarget response was made to 95% of all stimuli, and to 90% of all probe stimuli (Table 7). In the Introduction, I outlined that the AX-CPT-70 and AX-CPT-10 task versions were the same, with the exception that the A cue could be used in a proactive manner to prepare a target response in AX-CPT-70 and to prepare a nontarget response in AX-CPT-10. However, this oversimplification ignores the effect that this manipulation had upon the different response probabilities (Table 7). That is, although the cue-probe conditional

probabilities were manipulated, so too were the frequencies of making either a target or nontarget response.

If one is using the cue to prepare a response in the cue-probe interval, as the high-WMC individuals appear to be doing, then they would be primarily affected by the cue validity manipulation. Thus, their performance on BX and BY conditions in AX-CPT-70 and AX-CPT-10 are very similar, and performance on the AX and AY conditions are essentially reversed across the two task versions. This pattern does not hold for the low-WMC group. If instead, the low-WMC group is less likely to use the cue to prepare a response in advance, and they can respond correctly on 95% of all stimuli by making a nontarget response, this would seem to reinforce *not* maintaining the cue. Individuals using this way of responding would perform quickly and accurately on AY, BX, and BY trials in the AX-CPT-10, and would only show impaired performance on the very rare AX trials.

The explanation I have given here is somewhat analogous to the explanation provided by Kane and Engle (2003) to account for the Stroop performance of high- and low-WMC individuals across various proportion congruency manipulations, which was briefly mentioned in the Introduction. In their Experiment 1, Kane and Engle manipulated the frequencies of the various trial types so that the proportion of congruent trials was high (75%) relative to the proportion of incongruent trials (25%). In this condition, the word and color information provided the same correct information on the majority of trials. Thus, although the task instructions were to ignore the word information and respond based upon the color information, simply responding by reading the word would lead to quick and accurate performance on most trials. However, responding in this

manner would lead to inaccurate performance on the rare incongruent trials, as reading the word on these trials would be an error. They found that the low-WMC group committed nearly double the number of incongruent errors as the high-WMC group. In addition, the low-WMC group produced a larger facilitation effect on congruent relative to neutral trials, another indication they were more often reading the word than the high-WMC group was.

The Stroop results are relevant because, as mentioned in the Introduction, Braver and Hoyer (2008) have argued that the mostly-congruent version of the Stroop task induces a reactive control mode. Braver and colleagues would likely argue that the AX-CPT-10 also promotes a reactive mode. Note that this interpretation is slightly different than the way that I have used the term 'reactive' – perhaps the proper label would be 'not-proactive'. Conceptualizing the AX-CPT-10 as having a global context that promotes *not* maintaining the cue can help the WMC effects on this task fit within the proactive and reactive control framework. The high-WMC individuals are performing consistent with the notion they are maintaining the cue and using it to prepare a response in advance of the probe based on the predictive utility of the cue. In contrast, the low-WMC individuals are still not maintaining the cue, and are instead automatically making a nontarget response, given that this response is correct on virtually all trials.

BX Performance as an Index of Cue Maintenance

In addition, the low-WMC individuals made more BX errors than the high-WMC individuals on both the AX-CPT-70 and AX-CPT-40, but not on the AX-CPT-10. Importantly, BX trials are particularly indicative of whether or not an individual is maintaining the cue and/or using the cue to prepare a response in advance of the probe.

As outlined in Table 4, the B cue is perfectly predictive of a nontarget response to be made to the subsequent probe stimulus. Using this information in advance of the probe stimulus is important on BX trials, where the letter X appears as the probe. Across all task versions, the letter X is associated both with making a target and a nontarget response. Thus, there is response uncertainty associated with the letter X, and it is only in conjunction with the cue that there is absolute information to respond correctly. However, across task versions, the amount of response uncertainty varies, which helps explain the specific pattern of BX errors for the high- and low-WMC participants.

On AX-CPT-70, BX errors could be a consequence of either: (a) an inability to maintain or retrieve the representation for the preceding cue; or (b) difficulty in preventing a target response, given that the probability of making a target response to probe stimuli was $p = .70$ (Table 7). Thus, the worse BX performance by the low-WMC group on this task version is insufficient to confirm that they are less likely to maintain or remember the cue. However, as mentioned previously, the low-WMC participants also made more AX errors on AX-CPT-70, which goes against the idea that the BX errors simply reflect an inhibitory impairment. In addition, the low-WMC individuals also made more BX errors than the high-WMC individuals on AX-CPT-40. BX errors on this task version should be specifically due to not maintaining or remembering the cue, because both the overall response frequency and the probe response frequency favored a nontarget response (Table 7).

Why, then, do the high- and low-WMC groups not differ in BX accuracy on AX-CPT-10? If BX errors indicate a failure of maintaining the cue information, one might expect the two WMC groups to differ here as well. The answer appears to again be

related to the response frequencies associated with the various stimuli (Table 7). On AX-CPT-10, a target response is to be produced to only 5% of all stimuli and 10% of all probe stimuli. Thus, the response that is likely to be executed by default would be a nontarget response, even if the B cue information has not been used to specifically prepare a nontarget response in advance.

Further Evidence Supporting the Proactive vs. Reactive Control Framework

Looking solely at the results of AX-CPT-70, one could make an argument that the high-WMC group is engaged in proactive control, and the low-WMC group is engaged in reactive control. In this regard, the results are consistent with the idea that the high-WMC group is more often preparing to respond in advance of the presentation of the probe, whereas the low-WMC group is instead often waiting until the presentation of the probe letter to initiate the response selection process.

On AX-CPT-70, the low-WMC participants made more BX errors than the high-WMC group, indicative that they did not maintain the information that the B cue perfectly predicted that the subsequent letter would require a nontarget response. In addition, whereas the high-WMC group made significantly more AY errors than BX errors, the low-WMC group produced a similar number of errors across the two trial types. Finally, the low-WMC group's increased AX errors can be interpreted as a failure to maintain the A cue until the X probe appeared.

In addition, the accuracy results of the high-WMC group across all three task versions are largely consistent with the idea that these individuals are engaging in control according to the predictive information conveyed by the cue. In AX-CPT-70, the high-WMC group made the most errors on AY trials, consistent with the idea that they used

the A cue to expect an X as the subsequent probe, and thus prepared a target response during the cue-probe interval. In AX-CPT-10, the pattern reversed, with the high-WMC group producing the most errors on AX trials. In this version, the A cue was strongly predictive of a subsequent Y as the probe. Thus, the high-WMC participants appeared to prepare a nontarget response during the cue-probe interval, and the proportion of AX errors committed in the AX-CPT-10 was strikingly similar to the proportion of AY errors committed in the AX-CPT-70. Finally, in AX-CPT-40, the high-WMC group made a similar amount of errors on AX and AY trials. Although the number of AX errors was statistically greater than the number of AY errors, the difference between the two trial types was much smaller compared to AX-CPT-70 and AX-CPT-10. Because the A cue was equally predictive of a subsequent target or nontarget response, differentially preparing one response during the cue-probe interval would be largely counterproductive. This manipulation was introduced to induce a reactive mode in high-WMC individuals, and compared to the performance on AX-CPT-70 and AX-CPT-10, appears consistent with this interpretation.

Evidence against the Proactive vs. Reactive Control Framework?

Despite the results discussed so far, there are data that can be taken as inconsistent with the idea that the high-WMC group is solely influenced by the cue information to guide behavior. First, the difference between AX and AY accuracy on AX-CPT-40 mentioned above was significant – in terms of the predictive utility of the A cue, the performance on the two trial types should be identical. In addition, within each task version, the high-WMC participants made more errors on BX trials compared to BY trials. In each version, the B cue always signaled that the subsequent probe letter would

require a nontarget response regardless of the probe letter's identity. Thus, participants strictly using the cue to guide behavior would be expected to prepare a nontarget response during the cue-probe interval, and performance on the two trial types should be equivalent. Note that these two points are rather minor, and assume the extreme case that *only* the cue is used to guide responding – if this was actually the case, the high-WMC group would make zero errors on AX trials in AX-CPT-70 and AY trials in AX-CPT-10, and make errors on all AY trials in AX-CPT-70 and all AX trials in AX-CPT-10.

By and large, the results on the AX-CPT-70 and the AX-CPT-10 can be interpreted as supporting the proposal that the high-WMC groups primarily used proactive control and the low-WMC groups primarily used reactive control (remember that the low-WMC group's AX-CPT-10 performance is better understood as 'not-proactive'). However, the AX-CPT-40 provides an interesting test of this explanation. Because the A cue is equally predictive of a nontarget and target response, the reactive mode should be favored on these trial types (AX and AY). However, the B cue remains perfectly predictive of a nontarget response, and so the proactive mode should be favored on these trial types (BX and BY). To some extent, the AX-CPT-40 corresponds to the mostly-neutral condition in Braver and Hoyer (2008), which was argued to "lead to a mixture of reactive and proactive control modes" (p. 7). Thus, the results in this task version should provide evidence as to whether the high- and low-WMC groups can switch between the two control modes as necessary for successful task performance.

On the AX-CPT-40, the low-WMC group made more AX and BX errors than the high-WMC group. As a group, the high-WMC participants made slightly over two times more AX errors than AY errors, whereas the low-WMC participants made over nine

times more AX errors than AY errors. In addition, the high-WMC group made a similar proportion of errors on AX and BX trials, whereas the low-WMC group made significantly more AX errors than BX errors.

The substantial increase in AX errors for the low-WMC group compared to the high-WMC group is particularly diagnostic with regard to the strict dichotomous hypothesis that high-WMC individuals use proactive control, and low-WMC individuals use reactive control instead. This is because the A cue in AX-CPT-40 was designed to be equally predictive of a target and a nontarget response. There is no specific response to prepare in advance of the probe stimulus, and so both high- and low-WMC participants should wait until the probe stimulus appears to begin selecting the appropriate response. Note that even when the two WMC groups are assumed to be behaving similarly during the cue-probe interval (i.e., not preparing a response in advance), the low-WMC group still produces many more AX errors than the high-WMC group. This suggests that not only are high-WMC individuals more likely to use proactive control to prepare a response based on cue validity when available (AX-CPT-70 and AX-CPT-10), they are also more likely to effectively use reactive control to select the appropriate response associated with the cue and probe combination.

Practice Effects on AX-CPT

Recent AX-CPT-70 research (Paxton et al., 2006; Braver et al., 2009) identified interesting practice effects upon older adults' AX-CPT performance. In the current research, practice effects on accuracy were also observed. In fact, the four-way WMC x Version x Trial Type x Half interaction was marginally significant ($p = .057$), and there were significant Trial Type x Half interactions on AX-CPT-70 and AX-CPT-40 for the

low-WMC group, and on AX-CPT-10 for the high-WMC group. Interestingly, the AX-CPT-70 practice effects for the low-WMC group were similar to those obtained by Paxton et al. for older adults. The low-WMC participants made fewer BX errors later in the task session, but committed more AY errors in the second part of the session (Figure 6b). This pattern has been labeled the "training-related proactive shift" (Braver et al., 2009, p. 7352). The low-WMC group's specific pattern of performance change in AX-CPT-70 is consistent with the notion that the participants shifted to using the cue to prepare the appropriate responses during the cue-probe interval during the second half of the task. That is, the decrease in BX errors suggests using the B cue to prepare the unambiguous nontarget response, and the increase in AY errors suggests using the A cue to prepare the likely target response. Note that the pattern is inconsistent with an alternative explanation that the low-WMC group simply did not understand the task instructions at the beginning of the task, as the level of AX and BY errors did not change throughout the task.

Looking at AX-CPT-10, the high-WMC group showed the only effect of practice (Figure 7a). The high-WMC participants produced more AX errors in the second half of the task. Although it is not entirely clear why the high-WMC group would commit an increased amount of AX errors with more task experience, the results are still consistent with the idea that they are actively using the A cue to prepare the expected nontarget response. On AX-CPT-40, the low-WMC group showed a marginal increase in AX errors on the second half of the task (Figure 8b). As mentioned previously, the A cue in this task version was equally predictive of an upcoming target and nontarget response. Thus, if the effect of practice is to cause the low-WMC group to shift to using more of a proactive

control mode, they are using the A cue to prepare a nontarget response more often than a target response.

As can be seen in the work of Paxton et al. (2006), the effects do not seem related to any specific training strategy, as the three different training groups produced the same performance changes in their study. In addition, Braver et al. (2009) observed a relationship between the accuracy changes and fMRI activity modulation in bilateral PFC, providing further evidence that the processes involved in performance of AX-CPT-70 differ not only between-subjects (e.g., young vs. older adults), but also within-subjects. Further research is clearly needed in this area to understand more definitively why these practice effects are observed. In addition, specific interventions might be implemented before the task session to improve the identified group's performance.

Lack of WMC Effects Involving Mean RT

Somewhat surprising was the lack of significant between-WMC-group differences in mean RT across the versions of the AX-CPT, except for marginal effects on BY trials. Previous research on AX-CPT-70 found that high-WMC individuals were faster than low-WMC individuals on AX, BX, and BY trials (Redick & Engle, 2008). The previous study used more participants in each WMC group, and although the differences in the current study were not significant, they were in the same direction. In addition, the pattern within each WMC group was similar across studies, with both groups slowest on AY trials. An additional difference was that in Redick and Engle (2008), target and nontarget responses were made with the index and middle fingers of the same hand, whereas in the current research, the two responses were mapped to the index fingers of the left and right hands. Consistent with previous research showing that two-choice RTs

are faster when mapped to separate hands versus separate fingers on the same hand (e.g., Kornblum, 1965), the overall mean RT was faster in the current work. Finally, there was a significant interaction involving WMC when analyzing the RT distributions for AX trials in AX-CPT-70. Although there were too few trials in the previous study to conduct analyses on the RT distributions, the low-WMC group in that study was found to be more variable in their AX responses as indicated by a higher individual standard deviation, consistent with the current results of the RT distribution analyses.

Limitations and Future Directions

Despite the significant effects found across the various versions of the AX-CPT for the WMC groups, future research can help provide further information about the nature of individual differences in WMC and the relationship with proactive and reactive control. One issue is that the identification of behavior as manifesting proactive or reactive control remains a largely inductive process. Although Braver et al. (2009) and Paxton et al. (2008) have used fMRI activation dynamics to segregate specific regions as showing cue-related vs. probe-related activity, these analyses are still conducted at a level of aggregation that prevents identifying on a trial-by-trial (or moment-by-moment) basis the type of control mode in use. Thus, future research should integrate recent development in the neuroimaging and electrophysiological literatures (e.g., Debener et al., 2005) to provide more accurate estimates for the likelihood of engaging in proactive or reactive control.

Different techniques focusing on the behavioral performance can also shed light on the dual-mechanisms account, and manipulations involved in affecting the likelihood of using proactive versus reactive control. Braver et al. (2007) proposed that proactive

control would be more likely to be used in situations emphasizing speeded responses over accurate performance, and Locke and Braver (2008) provided evidence for this idea by rewarding faster performance and punishing errors in separate blocks of AX-CPT-70. However, examination of speed-accuracy functions via manipulations of response deadlines may provide more detailed information about the proactive/reactive control framework. In the current study, the manipulation of AX and AY frequency occurred between-subjects, given previous WMC research showing order effects of proportion congruency in the Stroop task (Kane & Engle, 2003) and trial type in the antisaccade task (Kane et al., 2001). However, manipulation of the AX and AY trial types within participants allows the application of binary mixture distribution analyses (DeJong, 2000) to provide further evidence that task variables affect individuals in a manner that is theoretically consistent with either cue-based or probe-based responding.

Braver and colleagues have also manipulated other aspects of the AX-CPT, including using different durations of the cue-probe interval and presenting irrelevant distractor letters during the cue-probe interval. These manipulations may provide further information about the high- and low-WMC individuals' ability to use the cue information to guide responding. Although a previous AX-CPT study did not find an interaction of WMC with the duration of the interval (Redick & Engle, 2008), other research using a cued-visual search task found that the length of the cue-target interval was influenced by the participant's corresponding level of WMC (Poole & Kane, in press).

An additional factor that should manipulate the mode of control that is optimal for task performance is the type of response format. Instead of the target/nontarget choice response format used in the current research and in most recent studies by Braver, Barch

and colleagues, the target-detection only method of responding may be useful in teasing apart proactive versus reactive control in the AX-CPT. The concept of comparing choice response formats against go/no-go response formats is not new; Donders (1868/1969) argued that response selection time could be measured by subtracting the latter from the former. The original version of the AX-CPT used by Servan-Schreiber, Cohen, and Steingard (1997) and Cohen, Barch, Carter, and Servan-Schreiber (1999) was more consistent with the continuous performance literature, where participants only make responses to a specific target and not a choice response to every stimulus. Although this difference in response format has been largely overlooked within the AX-CPT literature, Braver, Barch, and Cohen (1999) in a technical report noted that this response change did produce some differences in AX-CPT results observed within young adults. Namely, Braver et al. (1999) found that AY trials were more error-prone than BX trials in young adults using the target/nontarget version; this pattern can be observed in Table 3 as well. In contrast, studies using the target-only response method have found more BX errors than AY errors (Cohen et al., 1999; Javitt et al., 2000; Javitt, Rabinowicz, Silipo, & Dias, 2007; Lee & Park, 2006; but see Perlstein et al., 2003; Stratta, Daneluzzo, Bustini, Prosperini, & Rossi, 2000). This is an important discrepancy to clarify, as the pattern of AY and BX errors is a critical part of the proactive versus reactive control classification.

Implications for Theories of WMC

There are several prominent theories of WMC other than the models of Engle and colleagues that have been discussed throughout. Although it was not the goal of the current study to explicitly compare these alternative theories with the dual-mechanism theory endorsed here, the results are largely inconsistent with some of the main accounts.

A first alternative explanation is that the low-WMC individuals are simply less-motivated participants, and so their impaired performance reflects less effort instead of an ability difference. Recent research has provided evidence against the motivation hypothesis (Heitz, Schrock, Payne, & Engle, 2008), and the current research is inconsistent with this idea. The low-WMC participants made more errors than the high-WMC participants only on theoretically-relevant conditions. For example, on AX-CPT-10, the low-WMC group made more AX errors, but achieved the same level of accuracy and RT performance as the high-WMC group on the other 90% of the trials. In addition, both WMC groups exhibited faster RTs later in the task session as compared to earlier, inconsistent with an idea that the low-WMC group was specifically less motivated. Finally, the practice effects on accuracy discussed previously also indicate specific changes in performance, and not a general lack of effort by the low-WMC group.

In addition, the paucity of significant mean RT results between the two WMC groups contradicts a general speed account of WMC differences (Salthouse & Babcock, 1991). That is, if the low-WMC individuals are simply slower processors of information, they would be expected to produce slower RTs. However, this was not the case, even though the mean RTs were over 500 ms in some conditions. Although one may argue via inspection of Figure 4 that the trend toward slower RTs for the low-WMC group is apparent on AX-CPT-70 and AX-CPT-40, the results numerically indicate that the low-WMC group produced faster RTs on AX-CPT-10.

An inhibition account of individual differences in WMC (Lustig, Hasher, & May, 2001) can partially account for the error differences observed across the versions of the AX-CPT administered here, for some of the reasons already mentioned about the

prepotency of certain responses with specific stimuli. Given that that probe X is associated with making a target response on AX-CPT-70 (and perhaps on AX-CPT-40), the data indicating more errors produced by the low-WMC participants is consistent with an inhibitory deficit. However, this account has difficulty explaining why the low-WMC group produces more AX errors in the same two task versions. If the A biases toward a target response, and the X biased toward a target response, why would the low-WMC participants not execute the biased or automatic response? Instead, interpreting the results as differences in the use of proactive and reactive control is more consistent with the overall pattern of results.

What, then, do the current results imply for the theories of Engle and colleagues? As mentioned, the proactive/reactive framework maps onto both the two-factor theory of executive control (Engle & Kane, 2004) and the primary/secondary memory theory (Unsworth & Engle, 2007). Within the terminology of the dual-mechanism theory (Braver et al., 2007), proactive control maps onto goal maintenance and primary-memory capacity, whereas reactive control corresponds to response-conflict resolution and secondary-memory retrieval. The current research serves to more concretely specify ideas about goal maintenance and response prepotency in relation to individual differences in WMC. Manipulating cue-probe contingencies across the versions of the AX-CPT administered in the current studies permits examination of performance as a function of both the global and local context, as opposed to inferences about local performance that are presumed to occur due to global context manipulations (e.g., proportion congruency effects). In addition, there is more experimental control over the goal-related information from trial-to-trial: the information conveyed by the most recent cue as opposed to a general instruction to "name the ink color". The need to constantly update and maintain information temporarily in order to serve task goals seems more consistent with notions

of the function that a working memory module should perform within the information-processing stream.

CHAPTER 5

CONCLUSION

The current research investigated individual differences in WMC within the dual-mechanism theory of control (Braver et al., 2007). The results indicate that high-WMC individuals are more likely to use information conveyed by a cue to prepare a response in advance, but only when the cue information is predictive of subsequent action. When the cue was uninformative as to the subsequent probe, the high-WMC individuals were still better at accessing the cue information in order to select the correct response after the probe was presented. Overall, individuals high in WMC behave in a manner consistent with proactive control when possible, whereas individuals low in WMC are more likely to engage in reactive control.

APPENDIX A

Table A.1
Errors on the First Half of Each AX-CPT for the High- and Low-WMC Groups

WMC Group	AX	AY	BX	BY
		AX-CPT-70		
High	3.1 (3.1)	14.3 (13.1)	7.3 (9.5)	0.8 (1.8)
Low	6.4 (5.6)	16.3 (17.9)	17.3 (20.0)	1.3 (2.2)
		AX-CPT-10		
High	13.0 (11.3)	0.8 (0.9)	3.0 (5.0)	0.3 (1.1)
Low	37.0 (22.7)	0.7 (0.7)	4.0 (4.8)	0.0 (0.0)
		AX-CPT-40		
High	6.3 (4.8)	3.3 (3.0)	6.5 (7.3)	0.0 (0.0)
Low	16.2 (13.2)	2.4 (1.7)	13.0 (11.2)	0.5 (1.5)

Note. Data are percentages. Standard deviations are in parentheses.

Table A.2
Mean RT on the First Half of Each AX-CPT for the High- and Low-WMC Groups

WMC Group	AX	AY	BX	BY
		AX-CPT-70		
High	388 (56)	536 (51)	414 (113)	374 (71)
Low	423 (90)	561 (67)	446 (126)	430 (109)
		AX-CPT-10		
High	521 (104)	464 (101)	496 (138)	411 (115)
Low	535 (70)	441 (52)	469 (107)	393 (60)
		AX-CPT-40		
High	449 (51)	498 (59)	455 (106)	395 (70)
Low	464 (66)	502 (60)	505 (105)	438 (68)

Note. Data are in ms. Standard deviations are in parentheses.

APPENDIX B

Table B.1
Complete Omnibus ANOVA Output for Error Data

Effects and interactions	*F*	partial $?^2$	*p*
Untransformed Error Rates			
Main effects			
WMC	26.24	.187	< .01
Version	2.37	.040	.10
Trial Type	55.75	.328	< .01
2-way interactions			
WMC x Version	0.28	.005	.75
WMC x Trial Type	11.73	.093	< .01
Version x Trial Type	37.95	.400	< .01
3-way interaction			
WMC x Version x Trial Type	4.03	.066	< .01
Arcsine-Transformed Error Rates			
Main effects			
WMC	16.69	.128	< .01
Version	3.65	.060	.03
Trial Type	135.57	.543	< .01
2-way interactions			
WMC x Version	0.11	.000	.99
WMC x Trial Type	10.52	.085	< .01
Version x Trial Type	48.17	.458	< .01
3-way interaction			
WMC x Version x Trial Type	2.10	.035	.05

Table B.2
Complete Omnibus ANOVA Output for Mean RT Data

Effects and interactions	*F*	partial $?^2$	*p*
Main effects			
WMC	1.47	.013	.23
Version	0.70	.012	.50
Trial Type	110.14	.491	< .01
2-way interactions			
WMC x Version	1.33	.023	.27
WMC x Trial Type	2.57	.022	.05
Version x Trial Type	53.76	.485	< .01
3-way interaction			
WMC x Version x Trial Type	0.95	.016	.46

Table B.3
Complete Omnibus ANOVA Output for Practice Analyses of Error Data

Effects and interactions	*F*	partial $?^2$	*p*
Main effects			
WMC	26.24	.187	< .01
Version	2.37	.040	.10
Trial Type	55.75	.328	< .01
Half	1.78	.015	.19
2-way interactions			
WMC x Version	0.28	.005	.75
WMC x Trial Type	11.73	.093	< .01
WMC x Half	0.74	.006	.39
Version x Trial Type	37.95	.400	< .01
Version x Half	0.33	.006	.72
Trial Type x Half	7.82	.064	< .01
3-way interactions			
WMC x Version x Trial Type	4.03	.066	< .01
WMC x Version x Half	0.68	.012	.51
WMC x Trial Type x Half	2.50	.021	.06
Version x Trial Type x Half	2.85	.048	.01
4-way interaction			
WMC x Version x Trial Type x Half	2.06	.035	.06

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