Working memory capacity and intra-individual variability of proactive control

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A B S T R A C T

Two datasets of 110 young adults were examined to investigate the relationship between individual differences in working memory capacity (WMC) and dynamic cognitive control. The results delve into the specific differences between high- and low-WMC individuals’ ability to enact and maintain cognitive control using the AX version of the continuous performance test (AX-CPT). Compared to high-WMC individuals, low-WMC individuals: (a) made more errors, specifically to AX targets; (b) exhibited a partial shift to proactive control with more time-on-task; (c) had more exaggerated slower AX target responses in the tail of the response time distribution; and (d) were equally likely to adjust control after conflict. These results fit with the dual mechanisms of cognitive control theory and goal-maintenance account, and further clarify how individual differences in WMC manifests as intra-individual variability in cognitive control.

1. Introduction

Working memory capacity (WMC), defined as the temporary storage, active manipulation, and retrieval of information (Unsworth & Engle, 2008), is of interest due to its many relationships observed with important behaviors in and out of the lab setting. For example, WMC is positively correlated with attention control (Engle & Kane, 2004). Compared to high-WMC individuals, low-WMC individuals are more prone to interference in Stroop tasks (Kane & Engle, 2003; Long & Prat, 2002; Unsworth, Redick, Spillers, & Brewer, 2012), they are less accurate and make slower saccades on anti-saccade tasks (Kane, Bleckley, Conway, & Engle, 2001; Unsworth et al., 2012; Unsworth, Schrock, & Engle, 2004), and they are disproportionately affected by distractors on visual flankers tasks (Heitz & Engle, 2007; Redick & Engle, 2006).

A goal-maintenance account attributes this worse performance to the inability to maintain consistent cognitive control (Engle & Kane, 2004). Engle and Kane posit that low-WMC individuals are simply less able than are high-WMC individuals to maintain goal-relevant information in working memory during task completion, leading to failures in control such as slower response times (RTs) and more errors in situations when control is vital for performance. Importantly, when control is less crucial for performance, high- and low-WMC individuals do not differ in performance. For example, in the more automatic pro-saccade task, in which participants are asked to look to the side of the screen on which a flashing cue appears, control is less necessary for accurate performance and no WMC differences are found (Kane et al., 2001; Unsworth et al., 2004). However, in an anti-saccade task, participants are asked to look away from the flashing cue. Low-WMC individuals are more likely to lose track of this goal, react more slowly, and make more errors by looking toward the flashing cue (Kane et al., 2001; Unsworth et al., 2004). Failure to maintain the task goal would lead to performing whichever response is more automatic, in this case, looking toward (instead of away from) the flashing cue. Note that the consistency with which an individual can maintain task goals and/or attention seems to be critical; individuals low in WMC exhibit more intra-individual variability in RTs on such cognitive control tasks (McVay & Kane, 2009; Redick, Calvo, Gay, & Engle, 2011; Unsworth et al., 2012; Unsworth, Redick, Lakey, & Young, 2010).

1.1. Proactive and reactive control

Despite implementation of appropriate cognitive control having profound effects on behavior, many cognitive control theories do not specify the temporal dynamics of how cognitive control is used. An exception is the dual mechanisms of control theory (Braver, 2012;...
Braver, Gray, & Burgess, 2007; Braver, Paxton, Locke, & Barch, 2009), in which there are proactive and reactive cognitive control mechanisms. Proactive control, in which available information is used to inform or prepare for a response before the reaction is needed, can lead to higher accuracy and faster RTs. Alternatively, with reactive control, relevant information is not utilized prior to the time to respond. Instead, once the critical stimulus appears, information must then be retrieved to select the appropriate response, which can lead to slower and less accurate responses. The use of proactive or reactive control is influenced by both internal factors such as age (Paxton, Barch, Storandt, & Braver, 2006), patient status (Edwards, Barch, & Braver, 2010), and WMC (Redick, 2014), and external factors such as incentives (Braver et al., 2009), practice (Paxton et al., 2006), and trial type frequency (Redick, 2014).

In the anti-saccade example, those individuals who are implementing proactive control would keep the goal of ‘look away from the flashing cue’ in mind prior to the onset of the cue. However, those using reactive control would wait until the flashing cue appeared, then recall the ‘look away’ goal, maybe in time and maybe not, to override the prepotent (but incorrect) pro-saccade response and enact the controlled (but correct) anti-saccade response. In relation to Kane et al.’s (2001) anti-saccade work, it could be that high- and low-WMC individuals differ in their use of both proactive and reactive control.

### 1.2. AX-CPT: previous research

In the present study, we use the AX version of the continuous performance test (AX-CPT) to examine the differences between high- and low-WMC individuals in the context of dynamic cognitive control. The AX-CPT has been used in many previous studies on proactive and reactive control (for review, see Braver, 2012). The AX-CPT is composed of four trial types, AX, AY, BX, and BY. The first letter in each pair is a cue and the second letter the probe. Of note, despite the name “continuous performance”, the cue-probe pairs are clearly marked. A targetkeypress is only required for an ‘X’ that follows an ‘A’. All other probes should elicit a non-target keypress. Additionally, all cues should elicit a non-target keypress (Fig. 1). Because 70% of trials are target (AX) trials, and only 10% of trials have an ‘A’ cue not followed by an ‘X’ (AY trials), participants would benefit by preparing the specific ‘X’ probe target keypress during the cue-probe interval after an ‘A’ cue is presented. Importantly, proactive control, while more beneficial compared to reactive control for most trials, would actually be detrimental to performance on the 10% of trials that have a non-target probe following an ‘A’ cue (AY trials). The other 20% of trials are split evenly between BX and BY trial types, both of which require a non-target response. Thus, when a ‘B’ cue is presented, participants can prepare a non-target response for the upcoming probe, because a non-target response will be the correct response regardless of the probe letter identity. Using proactive control in the AX-CPT allows for preparation of the specific (target vs. non-target) response. In the Stroop or anti-saccade task, in contrast, only the goal of say the color of the word or look away from where the stimulus appears can be maintained as preparation for a response, but in these tasks the participant does not have enough information to prepare an accurate, specific response such as red or look left. The participant only has enough information to accurately select a response once the stimulus has appeared. The ability to selectively prepare a response during the cue-probe interval in the AX-CPT facilitates the evaluation of the use of proactive and reactive cognitive control.

In the AX-CPT, the typical pattern of results, as it relates to proactive and reactive control, is that proactive control improves performance in particular on BX (and AX) trials. However, proactive control hurts performance on AY trials, given that the prepared target response during the cue-probe interval would need to be stopped and the alternative non-target response executed within the time limit for responding. Although initial AX-CPT research focused on cognitive control in individuals with schizophrenia (e.g., Servan-Schreiber, Cohen, & Steingard, 1996) and elderly adults (e.g., Braver et al., 2001), the role of individual differences in WMC have also been examined in the AX-CPT (Ball, 2015; Boudewyn et al., 2015; Redick, 2014; Redick & Engle, 2011; Richmond, Redick, & Braver, 2015; Stawarczyk, Majerus, Catale, & D’Argembeau, 2014). Across the various comparisons (individuals with schizophrenia vs. healthy controls; older vs. young adults; low- vs. high-WMC individuals), AX-CPT results have shown that the ‘intact’ group uses proactive control more frequently than the ‘impaired’ group. Interestingly, meta-analyses have shown that individuals with schizophrenia (Lee & Park, 2005) and elderly adults (Bopp & Verhaeghen, 2005) score lower on WMC measures compared to healthy, young adults, including the complex span tasks used to measure individual differences in WMC in the AX-CPT studies cited above.

Germaine to the current work, when examining individual differences in WMC in relation to AX-CPT performance, many authors have calculated a specific signal-detection-theory-derived index of proactive control, $d’$ (Boudewyn et al., 2015), $d’$ context (Redick & Engle, 2011; Richmond et al., 2015), or $d’$ proactive (Ball, 2015; Stawarczyk et al., 2014). The $d’$ variable is calculated by subtracting the BX non-target false alarm rates from the AX target hit rates. The probe letter X should be associated with a target response (AX trials), but sometimes the probe letter X is correctly responded to with a non-target response (BX trials). Thus, accurate responding to the probe depends upon the cue, in contrast to AY and BY trials (probe letters on AY and BY trials should always be associated with non-target responses). WMC is positively related to $d’$, indicating greater use of proactive control (Ball, 2015; Boudewyn et al., 2015; Redick & Engle, 2011; Richmond et al., 2015; Stawarczyk et al., 2014). In addition, Redick and Engle (2011) and Richmond et al. (2015) observed that individual differences in WMC were related to mean latency on AX, BX, and BY trial types, such that low-WMC individuals were slower than high-WMC individuals (but see Redick, 2014). However, WMC was either unrelated to AY RTs (Redick & Engle, 2011) or negatively related to AY RTs after controlling for BY RTs (Richmond et al., 2015). Thus, on those trials within the AX-CPT where one could use the cue to prepare the correct probe response (AX, BX, and BY trials), individuals with higher WMC were more likely to respond quicker than individuals lower in WMC.

As discussed thus far, the use of proactive versus reactive cognitive control in WMC research has typically been determined via descriptive statistics summarizing performance across the entire task. That is, cognitive control (or lack thereof) is typically examined via difference scores across the entire experiment (e.g., RTs of incongruent trials minus congruent trials in the Stroop task; AX hit rates versus BX false alarms in the AX-CPT). However, we propose that in addition to global

![Fig. 1. Example trial of each trial type with corresponding serial response box mapping.](Image)
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