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Working Memory Capacity and the Antisaccade Task: A Microanalytic-Macroanalytic Investigation of Individual Differences in Goal Activation and Maintenance

Matt E. Meier,

Department of Psychology, Western Carolina University

Bridget A. Smeekens,

Department of Psychology, University of North Carolina at Greensboro

Paul J. Silvia,

Department of Psychology, University of North Carolina at Greensboro

Thomas R. Kwapil, and

Department of Psychology, University of North Carolina at Greensboro

Michael J. Kane

Department of Psychology, University of North Carolina at Greensboro

Abstract

The association between working memory capacity (WMC) and the antisaccade task, which requires subjects to move their eyes and attention away from a strong visual cue, supports the claim that WMC is partially an attentional construct (Kane, Bleckley, Conway, & Engle, 2001; Unsworth, Schrock, & Engle, 2004). Specifically, the WMC-antisaccade relation suggests that WMC helps maintain and execute task goals despite interference from habitual actions. Related work has recently shown that mind wandering (McVay & Kane, 2009, 2012a, 2012b) and reaction time (RT) variability (Unsworth, 2015) are also related to WMC and they partially explain WMC's prediction of cognitive abilities. Here, we tested whether mind-wandering propensity and intraindividual RT variation account for WMC's associations with two antisaccade-cued choice RT tasks. In addition, we asked whether any influences of WMC, mind wandering, or intraindividual RT variation on antisaccade are moderated by (a) the temporal gap between fixation and the flashing location cue, and (b) whether targets switch sides on consecutive trials. Our quasi-experimental study re-examined a published dataset (Kane et al., 2016) comprising 472 subjects who completed 6 WMC tasks, 5 attentional tasks with mind-wandering probes, 5 tasks from which we measured intraindividual RT variation, and 2 antisaccade tasks with varying fixation-cue gap durations. The WMC-antisaccade association was not accounted for by mind wandering or intraindividual RT variation. WMC's effects on antisaccade performance were greater with longer fixation-to-cue intervals, suggesting that goal activation processes — beyond

the ability to control mind wandering and RT variability — are partially responsible for the WMC-antisaccade relation.

Keywords

working memory capacity; antisaccade; attention control; mind wandering; individual differences

The antisaccade task presents a salient cue to one side of a visual display followed by a target stimulus to the *other* side, which often must be identified before being quickly masked; despite knowing the rule and seeing many such trials, people have difficulty performing accurately. Results from the antisaccade task form a cornerstone of a prominent account of individual differences in working memory capacity (WMC; Kane, Conway, Hambrick, & Engle, 2007). The “executive attention” view proposes that WMC-related differences in higher-order abilities, ranging from following instructions (Engle, Carullo, & Collins, 1991) to learning a computer language (Shute, 1991), are caused in part by differences in lower-order attentional control processes. Task analyses of the antisaccade have indicated that successful performance is produced by suppressing or overcoming a prepotent responses (e.g., orienting to the cue) to execute a novel, goal-directed one (e.g., shifting attention away from the cue; Hutton, 2008; Munoz & Everling, 2004). Thus, WMC’s relation to antisaccade performance (and to related tasks requiring habit override) suggests that higher-WMC subjects are better able than lower-WMC subjects to maintain mental access to task goals in the face of the interference from contextually inappropriate, over-learned responses (Engle & Kane, 2004).

The executive-attention account grew, in part, from studies of the antisaccade task reported in the early 2000’s (Kane, Bleckley, Conway, & Engle, 2001; Unsworth, Schrock, & Engle, 2004; for other seminal findings, see Conway, Cowan, & Bunting, 2001; Conway & Engle, 1994; Conway, Tuholski, Shisler, & Engle, 1999; Engle, Tuholski, Laughlin, & Conway, 1999; Kane & Engle, 2003; Rosen & Engle, 1997, 1998). Later research provided evidence that WMC predicts other attention-related individual differences beyond interference control, namely, the propensity to mind wander (e.g., Kane et al., 2007; McVay & Kane, 2009) and to sustain attentional focus, as indicated by RT variability (e.g., Unsworth, 2015; Unsworth, Redick, Lakey, & Young, 2010). In light of these findings and the critical role that the WMC-antisaccade association plays in WMC theory, here we revisit the antisaccade task, examining the contributions of unexplored intra-task variables of fixation-to-cue (gap) intervals and target-side switches to the antisaccade’s association with WMC. Moreover, we assess the individual-differences constructs of mind-wandering propensity and RT variability — measured outside the antisaccade context — on antisaccade performance.

Two complementary individual-differences methods have contributed to attentional theories of WMC. The microanalytic approach typically explores relations between single criterion tasks and measures of WMC, particularly by examining *individual-by-treatment interactions* (Cronbach, 1957; Snow, 1989) between WMC and theoretically derived experimental manipulations within the criterion task. The macroanalytic approach, in contrast, examines cognitive processes at the construct level by using the shared variance across multiple tasks

to represent constructs (e.g., WMC, attention control) and assessing correlations (and sometimes statistical mediation or dissociations) among them. The antisaccade task has been featured in both approaches.

Microanalytic work with the antisaccade task indicates that WMC is related to performance in tasks that make minimum memory demands but substantial demands on executive control, thus crystallizing WMC as an attentional construct. For example, Kane, Bleckley, Conway, and Engle (2001) used complex span WMC measures to distinguish high WMC from low WMC subjects in an extreme-group design. Their antisaccade task required subjects to focus on a central fixation symbol that was removed for a variable interval (i.e., as a “gap” condition; Munoz & Everling, 2004) before an abrupt-onset cue (a flashing “=” symbol) indicated the left-versus-right location of a backward-masked target (*B*, *P*, or *R*). In one block of prosaccade trials, the target appeared at the location of the cue; in the other block, of antisaccade trials, the target appeared on the opposite side of the computer screen from the cue. WMC did not predict performance in the prosaccade condition, but it did in the antisaccade condition. The prosaccade condition allows for successful task completion by following the exogenously-driven, habitual response of orienting towards in the flashing cue. But in the antisaccade condition, subjects must either prevent orienting to the flashing cue (via inhibitory or other mechanisms; see Cutsuridis, Smyrnis, Evdokimidis, & Perantonis, 2007) or quickly disengage attention from the cue and redirect it in opposition. Indeed, in the antisaccade condition, lower-WMC subjects made more initial saccades toward the cue than did higher-WMC subjects, and they were also slower to initiate antisaccades. These findings suggested that measures of WMC index subjects’ ability to control their attention in the face of interference to execute goal-driven behaviors, even in tasks without substantial memory demands.

Unsworth, Schrock, and Engle (2004) further characterized the attentional account of WMC-related differences in a micro-analytic study that mixed prosaccade and antisaccade trials, rather than blocking them (both trials types featured a fixation-cue gap); the fixation preceding each trial (e.g., in Experiment 2, a small circle or diamond centrally presented) indicated the trial type. Subjects thus had to establish their action plan on each trial in accordance with the cue (making prosaccade trials less automatic than they are in blocked procedures). Here, lower-WMC subjects were slower and more error prone than were higher-WMC subjects on *both* anti- and prosaccade trials, suggesting that WMC differentially impacts task performance whenever goal activation is at a premium and voluntary control of attention is needed¹.

Subsequent macroanalytic work using latent variable models (i.e., confirmatory factor analysis and structural equation modeling) has quantified the contributions of attentional control abilities to WMC-related performance differences. Latent variable models allow researchers to represent the constructs of interest as the common variance among tasks thought to measure that construct. An important point to consider here is the validity of the labels used for the constructs: Simply because a researcher labels a construct “attentional

¹Kane et al., 2001, had similarly found that lower-WMC subjects’ prosaccade performance was particularly disrupted when they had previously completed blocks of antisaccade trials, as if they had difficulty disengaging from the antisaccade task demands.

control” is no guarantee that the common variance among the tasks — and the latent factor derived from it — actually represents attentional control. It is necessary to look across the indicator tasks from which the variable is derived and consider common task requirements.

As evidence of the importance of antisaccade tasks to theorizing about WMC’s attentional characteristics, we examined the factor loadings of 13 independent confirmatory factor analyses from the WMC literature with a latent attentional control factor and the antisaccade as an indicator variable (typically using manual choice responses and not eye-tracking; Chuderski, 2014; Chuderski, Taraday, N cka, & Smole , 2012; Kane et al., 2016; McVay & Kane, 2012b; Redick et al., 2016; Robinson, Gath, & Unsworth, 2016; Shipstead, Harrison, & Engle, 2015; Shipstead, Lindsay, Marshall, & Engle, 2015; Unsworth, Fukuda, Awh, & Vogel, 2014; Unsworth & Spillers, 2010; Unsworth, Spillers, & Brewer, 2009). Factor loadings can be interpreted similarly to standardized regression coefficients, indicating the amount of shared variance between an indicator and a factor (i.e., construct). The antisaccade loadings were large in every model, with a mean of .70 and range of .43 to .83. In eleven of the thirteen models, antisaccade had the highest loading. What most researchers are calling WMC-related attentional control, then, consists substantially of antisaccade-related variation. One reason for this is that antisaccade tasks have superior reliability compared to other common measures of attentional control, which tend to use difference scores as dependent variables (DVs; e.g., Stroop and flanker tasks). For example, in Kane et al. (2016), DVs from eight flanker tasks had an average internal reliability (coefficient alpha) of .53, whereas DVs from two antisaccade tasks had an average reliability of .91. Because the antisaccade task has become central to theorizing about WMC and the nature of the individual differences in attentional control, it is critical that we better understand it.

As discussed above, successful antisaccade task performance is achieved by executing the task goal of looking away from the flashing cue in the face of interference from the habitual response of looking towards it. Models of antisaccade performance suggest that this process may be analogous to a horse-race between simultaneous programming of the correct antisaccade and the erroneous prosaccade, with the winner (either in terms of speed or strength) dictating action (Curtsuridis et al., 2007; Godijin & Theeuwes, 2002; Hunt, Olk, von Muhlenen, & Kingstone, 2004; Trappenberg et al., 2001). For the correct action to be programmed, the task goal needs to be activated in working memory.

WMC-related differences may reflect either the initial degree of goal activation or the ability to maintain the goal of the task after initial activation. This follows from Oberauer’s (2009) suggestion that performance on tasks that require a subject to overcome competition, like the antisaccade task, can be broken into two factors: the ability to establish goal representations (or stimulus-response rule bindings) and the ability to maintain them over delays. If WMC-related differences are due to differences in goal activation, then we should expect to see higher-WMC subjects achieve a higher asymptote of performance than lower-WMC subjects; if, however, WMC-related performance differences are due to lapses of goal maintenance, then we should see that WMC does not predict the asymptote of performance, but at longer delays lower-WMC subjects’ performance should drop off more than should higher WMC-subjects’. We contend that the degree of goal activation and the maintenance

of once-activated goals are potentially separable mechanisms by which WMC may influence antisaccade performance.

Recent work (both micro- and macroanalytic) has elucidated characteristics of WMC-related attentional control that would seem to affect one's ability to maintain a goal, once instantiated (e.g., Poole & Kane, 2009). Lower-WMC subjects are somewhat more prone to mind wandering than are higher-WMC subjects in situations that put a premium on maintaining task goals (Kane et al., 2007; McVay & Kane, 2012a; 2012b). For example, McVay and Kane (2012a) found that mind wandering partially mediated the relationship between WMC and go/no-go task performance. By analogy, WMC-related differences in antisaccade performance may also have been partially caused by lower-WMC subjects mind wandering during the task and therefore momentarily losing access to the novel goal. Mind wandering within a task is most often measured by embedding thought probes that ask subjects to indicate what they were just thinking about (Smallwood & Schooler, 2005; 2014). Thus, mind-wandering reports reflect the subjective experience of being consciously off-task. This may only result if the attentional failure is sufficiently sustained or of a certain depth. It is possible, however, that more subtle attentional variability, which does not break through to conscious awareness (see Cheyne, Solman, Carriere, & Smilek, 2009), can also account for WMC-related performance differences.

In a macroanalytic study, Unsworth (2015) re-analyzed data from several studies where subjects completed WMC tasks, mind-wandering probes, attentional-control tasks, and lexical-decision tasks. Intraindividual RT variability during attentional-control tasks (but not lexical decision tasks) correlated significantly with WMC ($r = -.41$) and mind wandering constructs ($r = .40$). Similarly, Kane et al. (2016; using the present dataset) found that a latent variable constructed from RT variability measures from attention and memory tasks correlated with latent variables for WMC ($r = -.32$) and mind wandering ($r = .54$). Although mind wandering and RT variability were separable constructs in these studies, they correlated strongly and may thus result from similar underlying neural processes that vary quantitatively, with deeper or longer sustained attention failures marked by the subjective experience of mind wandering, but with shallower or shorter failures not necessarily experienced as off-task thinking (e.g., Cheyne et al., 2009; Mittner, Hawkins, Boekel, & Forstmann, 2016). To be clear, we conceive of mind wandering as being a subset of attentional lapses where subjects are completely disengaged from the experimenter-stipulated main task. Attentional lapses encompass these episodes and episodes where subjects are partially disengaged from the main task (see Adam, Vance, Fukuda, & Vogel, 2015).

These patterns of relations from macroanalytic studies jibe well with findings from microanalytic studies that have examined the relationship between single measures of RT variability, WMC, and mind wandering (McVay & Kane, 2009, 2012a): In go/no-go tasks, within-subject RT variability on "go" trials correlated negatively with WMC and positively with mind wandering during the task. Additionally, formal evidence-accumulation modeling indicated that the parameter reflecting trial-to-trial variation in drift rate correlated with WMC, mind wandering rate, and RT variability (McVay & Kane, 2012a). What has not been previously assessed, however, is how much do mind wandering and intraindividual RT

variability account for WMC's relation with other indices of attentional control. Said another way, is WMC-related attentional control anything more than the ability to avoid mind wandering and attentional fluctuations (i.e., RT variability)?

In the current study, a large sample of subjects performed two similarly constructed antisaccade-cued RT tasks (which we primarily analyze separately). As in Kane et al. (2001) and Unsworth et al. (2004), both antisaccade tasks contained variable fixation-to-cue intervals (i.e., gap conditions). These different intervals allowed us to test, here, whether WMC-related individual differences are specific to short or long cue delays. If WMC-related performance differences are localized to only trials with longer delays, this would suggest that WMC is not related to the ability to establish the task goal but rather to maintain the goal over the longer duration. If the WMC-antisaccade relation is localized to only trials following short delays, it would suggest that higher-WMC subjects are more quickly able to prepare themselves to execute the goal than are lower-WMC subjects.

We used measures from outside the antisaccade tasks to assess whether propensities for mind wandering or sustained-attention fluctuations may account for WMC-antisaccade associations. We expected that subjects who generally mind-wander (indicated by probed thought reports) or who exhibit frequent attentional fluctuations (indicated by RT variability) may have particular difficulty on trials with longer fixation-cue delay intervals because they may more frequently lose the task goal. If mind wandering or attentional fluctuations have relatively independent effects on performance from WMC, we are interested in the extent to which these variables moderate the WMC-antisaccade relation. A reasonable expectation is that subjects who mind wander a lot or show greater attentional fluctuation *and* have a lower-WMC will exhibit especially poor task performance relative to our other subjects.

We also examined the intra-task variable of target-side switches across consecutive trials. Eye-tracking studies with antisaccade trials have provided evidence that the action plan used on the previous trial can affect performance on the current trial. That is, subjects tend to make more errors on trials where the target switches sides because the previous action plan (e.g., *look left*) interferes with the selection of the current action plan (e.g., *look right*; Reuter, Philipp, Koch, & Kathmann, 2006). Kane et al. (2001) observed that lower-WMC subjects made more erroneous antisaccades in a prosaccade block when it was preceded by substantial antisaccade practice, suggesting that lower-WMC subjects had difficulty establishing a new action plan (or conversely inhibiting an old action plan). Theories of WMC that emphasize inhibition (Hasher, Lustig, Zacks, 2007) or competition resolution (Engle & Kane, 2004) would seem to predict that higher-WMC subjects would suffer less from these carryover effects than lower-WMC subjects. Here, we tested whether this WMC-related difference would be evident at the trial level. Indeed, two groups that tend to have lower WMC than healthy young adults — older adults and schizophrenic patients (Salthouse, 1990; Goldman-Rakic, 1994) — have shown increased target-side switch effects relative to controls (Franke et al., 2006; 2009; Olk & Jin, 2011). If having a higher WMC confers subjects with more flexible action plans, we may expect higher-WMC subjects to show a marked advantage over lower-WMC subjects when the target-side switches from one trial to the next. This difference may be particularly large on trials with short cue delays because the action plan from the previous trial will not have had time to attenuate.

The current study took a hybrid macro- and microanalytic approach. Although we did not use formal latent variable models for most analyses, we did form z-score composites for our cognitive constructs of WMC, attentional fluctuation, and mind wandering from multiple tasks, and we tested whether these composites' associations with antisaccade performance depended on either fixation-cue delay intervals or target-location repetitions versus switches.

Method

Kane et al. (2016) reported how we determined our sample size and all data exclusions, manipulations, and measures in the study (Simmons, Nelson, & Simonsohn, 2012). That macroanalytic study used overall accuracy rates from the antisaccade tasks reported here (as two of six markers of an “attentional restraint” latent variable), but did not examine main effects or interactions involving fixation-cue intervals or target-location sequences. The WMC, mind-wandering, and RT variability measures used here correspond to (but are not identical to, because of dropped subjects reported below) those reported by Kane et al. (Again, that study used latent variables rather than the z-score composite variables we use for our primary analyses here). This research was approved by the University of North Carolina at Greensboro institutional review board.

Subjects

The three-session study was conducted over five academic semesters. Five hundred forty-five undergraduates, aged 18–35, participated as partial fulfillment of an introductory course requirement. Of the 545 subjects who completed the informed consent in the first session, 492 completed two sessions, and 472 completed all three.

General Procedure

Subjects volunteered to complete three, 120 min testing sessions, in groups of 1 – 4. Only the currently relevant tasks are briefly described here; the other tasks, and more complete descriptions of the relevant tasks (as well as the fixed task order), are presented in Kane et al. (2016). We note here that the antisaccade letters task was completed as the 5th of 8 tasks in session 2, and the antisaccade arrows task was completed as the 1st of 9 tasks in session 3; thus, all subjects completed the letter task before the arrows task.

Antisaccade Tasks

Kane et al. (2016) sought to derive latent variables from multiple tasks that all reflected the same underlying construct but differed in their surface characteristics (i.e., method variance). Because we used two antisaccade tasks (in addition to two Stroop-like tasks and a go/no-go task) to assess an “attention restraint” construct, we did not want the two antisaccade tasks to be identical to each other. Thus, we used letter stimuli in one task and arrow stimuli in the other, and we used slightly different fixation-to-cue intervals for each task, while still sampling from a comparable range of fixation-to-cue intervals.

Antisaccade letters—Subjects identified a target letter (*B*, *P*, or *R*) on one side of the screen that was cued by a flash on the opposite side (modified from Kane et al., 2001). Subjects first saw a central-fixation array of three asterisks over one of five fixation-cue

delay intervals (i.e., gaps) that unpredictably ranged from 200–1800 ms (200, 600, 1000, 1400, or 1800 ms) followed by a flashing cue (“=”) presented 8.6 cm to the left or right of fixation. The flashing cue was presented by having the cue displayed for 100 ms and then followed by a 50 ms blank screen, with the sequence happening twice on every trial (i.e., cue-blank-cue-blank). The target letter appeared in the opposite screen location from the cue (8.6 cm from fixation) and was pattern-masked after 100 ms with the letter *H* for 50 ms then the digit 8 until the subject responded. Subjects responded via keys on the number keypad labeled *B*, *P*, and *R* with stickers. Stimuli were presented in white (12 point Courier New font) on a black background. The dependent measure was errors on 90 test trials.

Antisaccade arrows—Subjects identified an arrow on one side of the screen that was cued by a flash on the opposite side (modified from McVay & Kane, 2012b). Each trial first presented a central-fixation asterisk array for 250–2250 ms (250, 750, 1250, 1750, or 2250 ms)² followed by a flashing cue (“=”) 11.4 cm to the left or right of fixation, followed by a to-be-identified arrow (pointing up, down, left, or right) in the opposite screen location from the cue (11.4 cm from fixation). This arrow was displayed for 80 ms and then pattern masked by a plus sign for 50 ms, followed by a “♦” symbol, until response or 10 s, whichever came sooner. Subjects responded with the 2, 4, 8, and 6 keys on the number keypad for down, left, up, and right arrows, respectively. Stimuli were presented in black on a white background. The dependent measure was errors on 72 test trials³.

Working Memory Capacity

Complex span tasks—We assessed WMC with six computerized tasks. Of these, four were complex span tasks, wherein subjects memorized short sequences of items each interleaved with a processing task. At the end of each trial sequence of unpredictable length (consisting of processing and memory components), subjects recalled the memory items in serial order from a pool of 12–16 possible items. Each task began with three blocks of practice. First, subjects practiced memorizing small sets, then they practiced the processing task alone, then they practiced both task components together. Processing-only practice trials recorded decision response times (RTs); during the real task, if any processing-task decision was not made within 2.5 standard deviations of the processing-only practice RT mean, the program skipped the subsequent memory stimulus and the trial was counted as a processing error. We instructed all subjects that we could not use their data if they did not achieve 85% accuracy on the processing portion of the task. We dropped individual tasks for subjects who did not meet this accuracy criterion. The 85% processing criterion was used because: (a) it limits the subject’s ability to trade-off between the storage and processing portions of tasks (i.e., subjects can sacrifice processing to maximize storage); (b) it screens out subjects who are generally being noncompliant and not putting forth effort, and; (c) it is conventional in individual differences research that uses complex span tasks. We used the partial-credit

²Following the first semester of data collection, we discovered that error scores were near floor and positively skewed, suggesting subjects were performing too well on this second antisaccade task. We therefore adjusted the task to present the cues and targets for a shorter duration, to those indicated above; the original timing parameters were longer. We do not include data from the first semester of data collection in this task in the analyses presented here.

³Because the total amount of trials is not evenly divisible by five, all subjects completed either 14 or 15 trials per fixation-to-cue interval, with fixation-to-cue intervals sampled randomly without replacement. The mean number of trials per interval ranged from 14.38 – 14.42.

scoring method to score all complex span tasks, operationalized here as the total number of items from the task recalled in their correct serial position (Conway et al., 2005).

Operation Span: Subjects memorized sequences of 3–7 letters, each presented in alternation with a compound arithmetic equation to verify [e.g., $(3 \times 2) - 1 = 4$; half were true], and randomly selected without replacement from a set of 12. At recall, all 12 letters appeared in a grid; subjects recalled each letter by mouse-clicking on it. Each set length of 3–7 occurred three times in a random order for each subject. The dependent measure was the total number of letters recalled in correct serial position (of 75).

Reading Span: Subjects memorized sequences of 2–6 four-letter words, each presented in alternation with a sentence to verify as either sensible or nonsensical (e.g., "*I like to run in the sky*"; half were sensible), and randomly selected without replacement from a set of 15. The recall phase was identical to operation span, but with 15 words presented in a grid. Each set length of 2–6 occurred three times in a random order for each subject. The dependent measure was the total number of words recalled in correct serial position (of 60).

Symmetry Span: Subjects memorized sequences of 2–5 red squares appearing within a 4×4 matrix. Each red square appeared in alternation with a black-and-white pattern made from an 8×8 grid to verify if it was vertically symmetrical (half were symmetrical), and was randomly selected without replacement from the 16 possible squares. At recall, subjects saw an empty 4×4 matrix and mouse-clicked the red square locations. Each set length of 2–5 occurred three times in a random order for each subject. The dependent measure was the total number of red-square locations recalled in correct serial position (of 42).

Rotation Span: Subjects memorized sequences of 2–5 large and small arrows, radiating from fixation in one of 8 directions. Each arrow appeared in alternation with a rotated capitalized letter (F, G, J, R). Subjects had to verify the capitalized letter as either normal or mirror-reversed (half were normal). Arrows were randomly selected without replacement from 16 possible size-orientation combinations. At recall, subjects saw an array of 8 small and 8 large arrows and clicked on the arrowheads. Each set length of 2–5 occurred three times in a random order for each subject. The dependent measure was the total number of arrows recalled in correct serial position (of 42).

Additional WMC Tasks—To bolster our measurement of WMC (and to reduce method-specific variance) we included two measures that were not complex spans.

Updating Counters: Modeled after Lewandowsky, Oberauer, Yang, and Ecker (2010), each trial consisted of 3 phases: learning, updating, and recall. In the learning phase, subjects saw a horizontal array of 3–5 boxes. A digit (1–9) then appeared serially in each box in random order (for 1250 ms each). During updating, 2–6 box values were updated by presenting a digit with a plus or minus sign (e.g., $+2$; -5). Some boxes might change multiple times while others not at all. Subjects maintained only the current value (1–9) for each box. At recall, each box outline turned red (in random order, with no time limit) to prompt the subject to enter its final value. Each set size of 3–5 boxes was crossed with number of updates (2–6) to

generate 15 trials, presented in random order for each subject. The dependent measure was the proportion of correct values entered in the boxes (out of 60).

Running Span: Following Broadway and Engle (2010), each trial presented a sequence of letters (drawn without replacement from a set of 12), with only the final 3–7 to be recalled (cued by a digit at the beginning of each trial). For each set size, the trial length was unpredictably 2, 1, or 0 items longer than set size. Set sizes were blocked (3 trials at each size), with block order randomized for each subject. At recall, all 12 letters appeared in a grid, along with the set size, and subjects mouse-clicked the letters. The dependent measure was the total number of letters recalled in their correct serial position (of 75).

Mind Wandering Propensity

During the five tasks that collected mind wandering data, subjects reported their immediately preceding thoughts by responding to unpredictably appearing probes. Each probe asked “*What are you thinking about?*” and had subjects “*Please press a number on the keyboard*” that most closely matched their thought content in the instant before the probe appeared (see McVay & Kane, 2009, 2012a, 2012b). The on-screen choices (italicized below) were re-explained for each probed task: 1. *The task*, on-task thoughts about the stimuli or response; 2. *Task experience/performance*, evaluative thoughts about one’s performance; 3. *Everyday things*, thoughts about routine things that have happened or may happen; 4. *Current state of being*, thoughts about one’s current physical or emotional state, such as being sleepy, hungry, or cheerful; 5. *Personal worries*, thoughts about concerns or worries; 6. *Daydreams*, fantastic thoughts disconnected from reality; 7. *External environment*, thoughts about something task-unrelated in the immediate environment; 8. *Other*, only those thoughts that do not fit the other categories. The mind wandering dependent measure for each task was the proportion of probe responses 3–8. That is, thinking about the task (option 1) or one’s performance (option 2) were regarded as a task-related thought, and all other responses were interpreted as mind wandering.

Forty-five thought probes appeared during the Sustained Attention to Response Task (SART), a go/no-go task requiring subjects to press a key for animal names (89% of 675 trials) while withholding responses to vegetable names (11% of trials). Twenty probes appeared during the second block (150 trials) of a numerical Stroop task, which required subjects to respond via key-press to the tally of a row of 2–4 digits while ignoring the identity of the digits (e.g., 22; 444). Four probes appeared in the first trial block (4.2% of 96 block-1 trials) and 16 appeared in the second block (16.6% of 96 block-2 trials) of an arrow flanker task that presented a left- or right-facing target arrow amid a row of arrow distractors. Twelve probes were presented during a letter flanker task (following 8.3% of 144 trials) that presented a normal or mirror-reversed “F” amid a row of letter distractors. Finally, 15 probes appeared during a 2-back task (6.3% of 240 trials), in which subjects decided whether each word matched the one presented two trials ago; 25% of trials were 2-back matching targets, and 21% were 1- or 3-back lures.

Intraindividual RT Variability (RT CoV)—We assessed propensity for attentional fluctuations by examining intraindividual RT variability from non-conflict trials (i.e.,

congruent, neutral, or “go” trials) in five tasks (SART, number Stroop, arrow flanker, letter flanker, spatial Stroop). These were all of the tasks that measured RTs as a dependent variable and had neutral or congruent trials. We excluded incongruent trials from this calculation because we did not want to confound the experimental effect of incongruence with the general sustained-attention variation we sought to capture (see Kane et al., [2016] for more details regarding this decision). Specifically, we calculated the coefficient of variation (CoV) in RT for each subject by dividing their RT standard deviation by their RT mean, using only correct trials (but dropping correct trials immediately following error trials or thought probes). We calculated RT CoV from the 600 “go” trials of SART, from the 120 congruent trials (digit-tally matching) from the first block of number Stroop, from the 24 congruent trials (flankers facing the same direction as the target) of arrow flanker, from the 25 neutral trials (dots appearing in flanker locations) of arrow flanker, from the 48 congruent trials (flankers facing the target direction) of letter flanker, from the 24 neutral trials (dot flankers) of letter flanker, from the 40 congruent trials from spatial Stroop (where target directional words appeared in a compatible screen locations in a compatible relative position to an asterisk on-screen; e.g., the word “LEFT” to the left of an asterisk with both to the left of the screen).

Data Preparation and Loss

Kane et al. (2016) provided details regarding data elimination and loss from error, outliers, and minimal performance criteria. Here, in addition, we dropped data from 60 subjects who had three or more missing values for the WMC, mind wandering, or CoV indicator tasks. Thus, we created z-score composites for all subjects with at least three WMC, three mind wandering, and four CoV measures. The final sample included 472 subjects (462 subjects completed the letter antisaccade and 401 completed the arrow antisaccade task).

Data Analysis

Our primary analytic approach used Generalized Linear Mixed Models (GLMM) in the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) in the R system for statistical analysis (R Core Team, 2016). We used GLMMs to examine the predictors’ influence on the likelihood of antisaccade errors while accounting for the binomial distribution of trial-level accuracy (Dixon, 2008). In the raw data, correct trials were scored a 0 and errors a 1. Betas for the GLMMs are reported as log odds ratios with a positive log odds ratio meaning that an error is more likely to be committed and a negative odds ratio meaning that an error is less likely (relative to the overall baseline probability of an error). These models are fit by Laplace approximation. We interpret parameter estimates with Wald z-values greater than or equal to 2 as statistically significant (with our large sample size and number of trials per task corresponding to p values $< .05$). In all models reported, we entered subjects as random effects (random intercept only) to account for the non-independence of the data. We did not model random slopes because the relations between the slopes and our other predictors of antisaccade errors are central to our questions of interest. By not modeling the random slopes, we allowed the variation between slopes to be represented in the fixed-effect portion of the GLMM equation.

We formed composite variables for WMC, mind wandering, and intraindividual RT variability by converting scores from the individual indicator tasks to z scores and then averaging them together for a given construct. We treated WMC, mind wandering rates, and RT variability as continuous variables in all analyses, each centered on the grand mean of the sample. Our initial models also coded the antisaccade cue delay (fixation-to-cue delay interval) as a continuous predictor to make the models more likely to converge and to keep model output concise, representing cue delay as a single model parameter. If cue delay moderated the effects of one of our other predictor variables, we followed up with a model that had cue delay represented as a factor with five levels. This allowed us to explicitly determine at what delay the slopes diverged. Target-side switching was included in the models as an effect-coded variable (i.e., -0.5 represented a trial where the target side repeated and $+0.5$ represented a trial where the target side changed), so the parameter represents the experimental effect of target-side switching.

To decompose interactions between continuous variables, we changed the centering for one of them. For example, if we were interested in an interaction between attentional fluctuations and WMC, we ran three models: one centered at the WMC mean, one centered at one standard deviation above the WMC mean, and another centered one standard deviation below the WMC mean. Then we examined the RT CoV parameter for these different models. In the model centered one standard deviation below the mean, the RT CoV parameter shows how it predicts errors for subjects with lower WMC. By comparing the RT variability parameter with WMC centered in different locations, we learn how the rate of attentional fluctuations differentially predicts errors along the WMC continuum.

Because mind-wandering and RT CoV composites were moderately correlated, $r = .31$, as one would expect if both imperfectly indicate sustained attention capabilities (Cohen, 1988), we first entered mind-wandering propensity into the model and then, in a subsequent model, added RT CoV (note that WMC was correlated with both mind-wandering and RT CoV composites, but not as strongly; $r_s = .13$ and $.21$, respectively). If parameter values for mind wandering changed substantially when intraindividual RT variation was added, we concluded that their influence on the dependent measure was due to their shared variance (i.e., a shared construct or set of mechanisms). We implemented the same models for each antisaccade task. To protect against false positives, we adopted the conservative approach of focusing our interpretation on effects that replicated across both antisaccade tasks.

Results

Data and analysis scripts for the GLMM analyses below are available via the Open Science Framework (<https://osf.io/yrphw/>). Table 1 presents descriptive statistics for all tasks, Figure 1 displays violin and box plots for accuracy in each antisaccade task by fixation-to-cue delay, and Table 2 presents correlations among the measures (with internal consistency scores as indicators of reliability). In line with expectations, indicator variables for each construct correlated more strongly with those of the same construct than those of different constructs (e.g., WMC indicators correlated more strongly with each other indicators than with indicators of mind wandering or attentional fluctuations).

Letter Antisaccade

Models without RT CoV—The model included fixation-to-cue delay, target-side switches, mind wandering rate, WMC, and their interactions as predictors of antisaccade errors ($N = 462$); see Table 3 for the fixed effects estimates and z values. Subjects were less likely to commit errors at longer cue delays (and if they scored higher on WMC measures [see Figure 2]). Subjects were more likely to commit errors if they had a higher propensity to mind wander in other laboratory tasks and when the target switched sides. Cue-delay moderated both WMC's and target-side switching's effects on errors. The effect of mind wandering rate was not moderated by WMC or by cue delay, the latter indicating that propensity for mind wandering was not particularly problematic at longer delays, which might be hypothesized to induce sustained-attention failures. Target-side switch was not moderated by either of the individual-difference variables in the model, and none of the higher-order interactions were statistically significant.

In decomposing the $WMC \times Delay$ interaction, we found that, at the shortest cue delay (200 ms), higher-WMC subjects were less likely to commit errors than were lower-WMC subjects, $b = -0.18$, $SE = 0.03$, $Z = -5.0$, and at the two longest delays this negative slope accelerated. More specifically, the negative WMC slopes at the 1400 ms delay, $b = -0.09$, $SE = 0.03$, $Z = -2.6$, and at 1800 ms, $b = -0.13$, $SE = 0.03$, $Z = -3.8$, were more negative than the slope at 200 ms delay. Thus, the difference between higher and lower-WMC subjects was larger at the two longest delays. (Note that the WMC effects at the intermediate delays were statistically indistinguishable from that at 200 ms; 600 ms: $b = -.01$, $SE = .03$, $Z = -0.3$; 1000 ms: $b = -.05$, $SE = .03$, $Z = -1.6$).

Regarding the moderation of target-side switching by the cue delay, the effect of target-side switching was greatest at the 200 ms delay, with subjects more likely to make an error when the target switches sides from one trial to the next compared to when the target side repeats, $b = .36$, $SE = .05$, $Z = 7.8$. The difference in the likelihood to make errors on target-side switch trials than on target-side repeat trials was significantly reduced (indicated by negative parameter estimates) at the three longest delays (1000 ms: $b = -.14$, $SE = .07$, $Z = -2.1$; 1400 ms: $b = -.25$, $SE = .07$, $Z = -3.7$; 1800 ms: $b = -.26$, $SE = .07$, $Z = -3.9$). The effects of target-side switching and delay did not significantly differ between the 200 ms and 600 ms delay intervals (600 ms: $b = -.11$, $SE = .07$, $Z = -1.7$). Table 4 provides mean (of subject means) error rates for target-side repeat and switch trials as a function of delay.

Models including RT CoV—We next added attentional fluctuation propensity (i.e., CoV measures from outside the antisaccade context) to the model, along with cue delay, target-side repetition, WMC, and mind wandering as predictors of errors in letter antisaccade (see Table 5 for all fixed effect estimates and z values). Cue delay, target-side switching, and WMC remained significant predictors. And, whereas RT CoV predicted antisaccade errors, mind wandering propensity no longer did, suggesting that these measures of sustained attention failures accounted for some shared variance in errors.

As in our initial model that did not include RT CoV (and decomposed above), the difference in errors committed between higher and lower-WMC subjects was greater at longer cue delays, and the effect of target-side switching was reduced at longer delays. The effect of RT

CoV moderated the main effects of mind wandering and cue delay, but no other two-way or higher-order interactions were significant.

We examined the interaction between mind wandering and intraindividual RT variability by running a series of simple models with mind wandering and RT CoV as the only predictors. In a model centered one standard deviation above the mind wandering mean, the parameter value for RT CoV was .22, SE = 0.04, Z = 5.2; when centered at the mind wandering mean, this parameter was .17, SE = 0.03, Z = 5.9, and when centered one standard deviation below the mind wandering mean, the parameter was .13, SE = 0.04, Z = 3.4. Attentional fluctuations were thus a stronger predictor of errors for subjects who more often endorsed having task unrelated thoughts: People who struggled according to two indices of sustained attention performed worse than did those who struggled according to only one measure.

To better understand the interplay between cue delay and attentional fluctuation, we ran a simplified model with cue delay as a factor with five levels (200 ms was the reference level) and RT CoV as the only predictors (the full model would not converge). In parallel to our WMC findings, RT CoV significantly predicted antisaccade errors at 200 ms, $b = 0.14$, SE = 0.04, Z = 3.9, and became a significantly stronger predictor (compared to the 200 ms reference level) at the two longest delays (1400 ms: $b = 0.13$, SE = 0.03, Z = 3.9; 1800 ms: $b = 0.08$, SE = 0.03, Z = 2.5; at 600 ms: $b = .03$, SE = .03, Z = 0.8; at 1000 ms: $b = .04$, SE = .03, Z = 1.2).

Arrow Antisaccade

Model without RT CoV—We constructed the same models as used in our analysis of the letter antisaccade task on the arrow antisaccade. In the model with target-side switch, cue delay, mind wandering propensity, WMC, and their interactions (N = 401; see Table 6 for all fixed effects and z values), cue delay and WMC were again negative predictors of antisaccade errors, whereas target-side switch and mind wandering rate again showed a positive relation to errors. Here, the moderation of delay by WMC approached, but did not meet, our significance criterion. The effects of target-side switching were again moderated by cue-to-fixation delay, and no other two-way or higher-order interactions were statistically significant.

To decompose the target-side switch and fixation-to-cue delay interaction, we examined a model that had cue-to-delay interval dummy coded with the 250 ms delay as the reference level. Here, as in letter antisaccade, subjects were more likely to commit errors when the target side switched at the shortest delay, $b = 0.44$, SE = 0.06, Z = 7.5, and this switch cost on errors was significantly reduced at the 1250 ms, $b = -0.26$, SE = 0.09, Z = -3.0, 1750 ms, $b = -0.28$, SE = 0.09, Z = -3.3, and 2250 ms $b = -0.30$, SE = 0.09, Z = -3.5, delays relative to the 250 ms delay (the effect of target-side switching was not significantly different between the 250 ms and 750 ms delays; 750 ms: $b = -.15$, SE = .08, Z = -1.8).

Model with RT CoV—In the model adding RT CoV (see Table 7 for fixed effect parameter estimates and z values), just as in the letter antisaccade task, the parameter value for mind wandering was no longer significant, whereas the RT CoV parameter was; moreover, WMC once again interacted with fixation-cue delay. This model differed from the letter task model,

however, because here, RT CoV did not significantly moderate any other effects (it had moderated cue delay and mind wandering effects in letter antisaccade). The only other significant effect was the five-way interaction, which we judged to be uninterpretable.

Because the full model with fixation-to-cue delay coded as a factor with five levels would not converge, we ran a simplified model with only cue delay, WMC, and their interaction as predictors. In this model, the shortest delay of 250 ms was the reference level. Higher-WMC subjects committed fewer errors than lower-WMC subjects at the 250 ms delay, $b = -0.33$, $SE = 0.05$, $Z = -6.7$. The only statistically significant difference from this slope was at the 1750 ms delay, where the slope was steeper in favor of higher-WMC subjects, $b = -.09$, $SE = .04$, $Z = -2.1$. The slopes did not significantly differ at the other delays (750 ms: $b = -.05$, $SE = .04$, $Z = -1.3$; 1250 ms: $b = -.04$, $SE = .04$, $Z = -1.0$; 2250 ms: $b = -.06$, $SE = .04$, $Z = -1.5$).

Although attentional fluctuation propensity did not moderate the effects of cue delay in this task, in a simplified model with RT CoV and delay as the only predictors, we examined whether the effect of RT CoV on antisaccade was present at 250 ms delay, as it was with the letter antisaccade. Indeed, it was, $b = 0.23$, $SE = 0.05$, $Z = 4.4$. As suggested by the lack of interaction, however, this effect did not differ at longer fixation-to-cue intervals (750 ms: $b = .04$, $SE = .04$, $Z = 0.9$; 1250 ms: $b = .01$, $SE = .04$, $Z = 0.1$; 1750 ms: $b = .01$, $SE = .04$, $Z = 0.7$; 2250 ms: $b = .03$, $SE = .04$, $Z = 0.8$).

Disambiguation of the effects of fixation-to-cue delay on the WMC-antisaccade relation

Across both tasks, the slope depicting the relation between WMC and antisaccade performance changed as a function of delay (in the arrow antisaccade model without RT CoV, however, this interaction did not meet our criterion for statistical significance). A $WMC \times$ cue delay interaction may have resulted from a change in performance from people either at the bottom or top of the WMC distribution (or both). For example, higher-WMC subjects' advantage over lower-WMC subjects at longer delays may have occurred because their error rates decreased more across delays (implicating stronger goal-activation processes). Alternatively, lower-WMC subjects' errors may have increased with delay, suggesting more severe failures of goal maintenance.

To supplement our quantitative models and differentiate between these accounts, we created Figure 2 by splitting subjects into three bins by their WMC scores (i.e., low, mid, and high WMC) and visually inspected how delay impacted mean error rates for the different groups. In both antisaccade tasks, subjects at the higher end of the WMC distribution showed a decline in errors before leveling off towards the two longest delays, whereas subjects at the lower end of the WMC distribution also generally decreased their errors across delays, but never reached the same asymptote that higher-WMC subjects did.

Structural equation modeling analysis

Our GLMM analyses indicated that both WMC and RT CoV predicted antisaccade errors above and beyond the influences of other variables, including each other. What such analyses do not indicate clearly is the extent to which the *shared* variance among our abilities of interest (WMC, RT CoV, mind wandering) also predict variance in antisaccade

errors. We therefore conducted a structural equation modeling (SEM) analysis that excluded the within-subject variables of fixation-cue delay and target-side switches, but did take advantage of the complete dataset from Kane et al. (2016) and included more subjects than did our focused LMMs above; we used full-information maximum likelihood estimation for missing observations.

We modeled a “*general executive/sustained attention*” factor as the shared variance among all of our WMC, mind wandering, and RT CoV measures, and modeled antisaccade performance as the shared variance between letter and arrow antisaccade error rates (see Figure 3). Moreover, we modeled the variance that was unique to WMC, to mind wandering, and to RT CoV, by creating “residual” factors reflecting the variance shared among each of these sets of measures that was not shared by the other predictors (e.g., the “*WMC-Res*” factor represented variance shared among the six WMC tasks that was not shared with the mind wandering or RT CoV measures; this was the only factor for which higher scores reflected better performance); these “residual” factors were modeled as orthogonal to the general factor and to each other. To be consistent with the analyses in Kane et al. (2016), we also modeled residual pairwise correlations between a few of the individual predictor-task variables (see Kane et al. for specifics and rationale).

By several well established indicators of model fit (Schermelleh-Engel, Moosbrugger, & Müller, 2003), our model provided an adequate fit to the data, $\chi^2(142) = 275.81$, $\chi^2/df = 1.94$, CFI = .94, TLI = .91, SRMR = .046, RMSEA [90% CI] = .042 [.034, .049] (although several factor loadings .17 were non-significant with $\alpha = .05$). Of most importance, the antisaccade path estimates (analogous to standardized beta weights in regression) were significant only from the general executive/sustained attention factor and the WMC-Res factor, indicating that antisaccade performance was predicted by attentional processes shared by WMC, mind wandering (MW), and RT CoV, but also from WMC-specific processes. Both the MW-Res and RT CoV-Res factors non-significantly predicted antisaccade errors in the wrong direction.⁴

Discussion

Our goal was to examine the association between WMC and antisaccade-task performance in greater depth than has been done before. Across two antisaccade-cued choice RT tasks, we replicated the robust influence of WMC on antisaccade performance: Higher-WMC subjects committed fewer errors than did lower-WMC subjects. Beyond replicating this effect, we found strong evidence that WMC predicts antisaccade performance with the potentially confounding variables of mind-wandering and attentional-fluctuation propensities statistically controlled (in both our microanalytic GLMM analyses and our macroanalytic SEM analysis). Prior investigations of WMC-antisaccade performance did not include any other individual-difference variables as predictors (Kane et al., 2001; Unsworth et al., 2004). By accounting for (or at least limiting the contributions from; Westfall & Yarkoni, 2016) normal variation in mind wandering and attentional fluctuations, and still

⁴A structural model analogous to our LMM analyses, with separate but correlated latent variables for WMC, mind wandering, and RT CoV — but with no general executive factor — yielded results consistent with the LMMs. WMC significantly predicted antisaccade errors, $\gamma = -.53$ [95% CI $-.66, -.40$], as did RT CoV, $\gamma = .27$ [.05, .49], but mind wandering did not, $\gamma = .04$ [-.12, .20].

finding that WMC predicts antisaccade performance, we constrain the interpretation of the attentional mechanisms responsible for the WMC-antisaccade task performance relation.

In GLMMs with attentional fluctuations (i.e., RT CoV), WMC, and fixation-to-cue delay included as predictors, all accounted for unique variance in antisaccade errors. Higher WMC and longer delays led to fewer errors, whereas a higher rate of attentional fluctuations (across independent tasks) led to more errors. Higher-WMC subjects' advantage over lower-WMC subjects increased at longer delays—despite longer delays generally facilitating subjects' performance—suggesting that goal activation processes contribute to the WMC-antisaccade performance relation. This suggestion is consistent with previous claims that antisaccade errors are the product of under-activation of task goals in working memory (Eenshuistra, Ridderinkhof, & van der Molen, 2004; Nieuwenhuis, Broerse, Nielen, & de Jong, 2004; Reuter, Rakusan, & Kathmanna, 2005). We interpret the pattern depicted in Figure 2 as evidence that, whereas subjects across the WMC distribution use the time between fixation and cue to activate and maintain the “look away” goal to allow efficient execution of the task (for brain imaging evidence of this see Brown, Vilis, & Everling, 2007), lower-WMC subjects' goal activation or accessibility never reaches the same asymptote (i.e., strength) as that for higher-WMC subjects (i.e., the lines in Figure 2 representing the error rates for the different WMC groups never converge). Said another way, higher-WMC subjects better (or more quickly) activate the goal, as evidenced by their advantage at the 200 ms delay. They are also then better able than lower-WMC subjects to increase the goal's strength (until asymptote) as the cue-to-interval delays lengthened. Here, in examining the potential of goal activation and maintenance for linking WMC to antisaccade performance, we find evidence that higher-WMC subjects are superior to lower-WMC subjects in goal activation. (Note that support for WMC-related differences in goal maintenance would have been suggested by finding performance decrements across increasing cue delays—as goal maintenance demands increased—as well as lower WMC subjects showing a greater decrement across delays than higher WMC subjects.)

The proposal here, that WMC-related performance is related to goal activation, fits with prior assertions that higher-WMC subjects form more robust stimulus-response bindings (Schmiedek, Oberauer, Wilhelm, Süß, & Whitman, 2007; Wilhelm & Oberauer, 2006) and better use proactive (anticipatory) control to resolve conflict (Redick, 2014; Redick & Engle, 2011; Richmond, Redick, & Braver, 2015) compared to lower WMC subjects. Schmiedek et al. used the diffusion model (Ratcliff, 1978) to examine WMC-related performance in speeded two-choice response tasks with arbitrary stimulus-response mappings. They found that WMC (in a latent variable model) correlated strongly with a model parameter presumed to represent stimulus-response bindings. Like the findings here, Schmiedek et al. produced evidence in a simulation study that attentional lapses did not account for WMC's relation to this model parameter. What we have referred to here as goal activation seems consistent with what Schmiedek et al.'s formation of stimulus-response bindings (but inconsistent with findings from McVay and Kane [2012a], who found that WMC and mind wandering during a long-duration go/no-go task were more closely related to a model parameter reflecting attentional lapses than stimulus-response bindings).

This notion of WMC-related performance differences being related to goal activation processes is also consistent with Braver and colleague's notion of proactive and reactive cognitive control. Braver et al. (2007) propose that there are dual modes of cognitive control: (a) a proactive mode where, in accordance with goals, attention is preemptively deployed in an anticipatory manner to resolve conflict and; (b) a reactive mode, where attention is recruited to resolve conflict only after it is encountered. In line with our findings here, three recent investigations have found that higher-WMC subjects are more likely to engage in proactive (preparatory) control than are lower-WMC subjects (Redick, 2014; Redick & Engle, 2011; Richmond et al., 2015; see also Kane & Engle, 2003). More specifically, in an AX version of a continuous performance task, where only X's that are preceded by A's are targets that require a response, they find that higher-WMC subjects are more accurate than lower-WMC subjects in deciding whether to respond to X's (Redick, 2014; Redick & Engle, 2011) and that higher-WMC subjects are slower than lower-WMC subjects to react to Y targets following A trials (Richmond et al., 2015). Using the A or B cue to prepare action is the hallmark of proactive control, and both results suggest that higher-WMC subjects better activate the task goal in accordance with the cue than do lower-WMC subjects. This pattern of WMC-related differences in goal activation corresponds to the one we are describing here in the antisaccade task.

Recent evidence has also tied WMC to the memory for goals (MfG) model of goal-directed cognition (Foroughi, Werner, McKendrick, Cades, & Boehm-Davis, 2016). Foroughi et al. (2016) found that higher-WMC subjects were faster to resume a primary financial management task after being interrupted by having to do arithmetic problems. In the MfG model, the goal of the primary task is activated and then decays once task-related operations begin. Within this cognitive landscape there is a background of interference composed of non-primary task goals. When a person is performing a cognitive task, they are continually retrieving task goals. The relative positioning of primary-task goal activation to the interference level gives the probability that the primary-task goal will be sampled. That is, when primary-task goal activation is high relative to the interference level (which could reflect stronger initial goal activation or less decay with time), there is a high probability that the primary-task goal will be sampled. As the primary-task goal weakens and the ratio between this goal and interference lessens, people will sample task-irrelevant goals at a higher rate and therefore suffer from impaired performance on the primary task. Predictions from the MfG model have matched empirical results and simulation results from complex cognitive tasks (e.g., financial planning task [Foroughi et al., 2016] and the Tower of Hanoi task [Altman & Trafton, 2002]). Here, the antisaccade is the primary task and habitual prosaccades and goals external to the task are the interference level. Relative to tasks like financial planning, Tower of Hanoi, or reading passages, the antisaccade task is simple (i.e., it contains fewer subgoals) and it has discrete trials that happen over a shorter time span (e.g., Foroughi et al. had interruptions of 5, 10, and 15 seconds). That is, different tasks tap different aspects of ability. Relatively simple tasks with discrete trials over a short time span reduce the reliance on goal maintenance abilities and support the reactivation of the goal for each new trial and therefore highlight goal instantiation abilities. Longer, more complex tasks with trials happening over a longer time span emphasize goal maintenance abilities to a greater degree. Because of this, we speculate that the antisaccade task emphasizes WMC-

related goal activation/instantiation abilities more than goal maintenance abilities and the pattern of results found here will hold for tasks with similar characteristics.

Both intra-task variables we examined affected performance, and one moderated the WMC effect. As previously discussed, errors were reduced for trials that had longer fixation-to-cue delays (see also Fischer & Weber, 1997). This suggests that as the time elapses between fixation and cue (beyond 200 ms), subjects engage in attentional preparation for the cue and target (i.e., goal activation) and the interaction of fixation-cue delay with WMC indicates that higher-WMC subjects are better at activating the goal than are lower-WMC subjects. On trials where the target side switched from the previous trial, subjects also committed more errors. The likelihood of post-switch errors was reduced at longer delays, suggesting that activation levels of the motor program from previous trials dissipate over time. Unlike the effect of fixation-to-cue delays, however, the target-side switch effect was not moderated by any individual difference variables. We interpret these asymmetric effects of fixation-to-cue delays and target-side switching as providing evidence that target-side switch effects reflect a passive non-executive decay of a motor program while the WMC-related effects of the fixation-to-cue delays showcase the execution of an active executive process.

In our GLMMs, but not the SEM analysis, individual differences in vulnerability to attentional fluctuations (as measured by RT CoV) accounted for unique variance in antisaccade errors (even at the shortest gaps). We interpret the unique influence of RT CoV on antisaccade errors based on the results of the GLMMs but note that the evidence for this effect is not as strong as the evidence supporting the role of WMC-related goal activation processes. We suggest that subjects who frequently experience attentional lapses and mind wandering have difficulty in consistently activating antisaccade task goals (see also McVay & Kane, 2009; 2012a). This interpretation fits within the MfG model (Foroughi et al., 2016). MfG uses ACT-R (Anderson & Lebiere, 1998) as a theoretical foundation (Trafton & Altman, 2002). In ACT-R, goal activation processes are subject to noise. That is, goals are not always activated to a fixed height but are activated to a variable height that is roughly centered about an expected value of goal activation. A given subject may, on average, be able to activate a goal above the interference level—and perhaps even higher than most other subjects on most trials. However, if that subject also has greater variability in activation around this goal level than do other subjects, then on some trials their goal activation may be lower than the interference level, and even lower than that for subjects whose average goal activation level is lower than theirs. More simply put, holding average goal activation levels constant, subjects whose goal activation varies more than others will more often experience interference (in instantiating task goals) and make more errors.

Conclusion

In the current study, we clarified the nature of WMC-related attentional control that influences antisaccade performance. Here, we find evidence that WMC affects performance, in part, through goal activation mechanisms that are distinct from the abilities to avoid mind wandering, attentional fluctuations, and carryover effects from the previous trial (although some of WMC's predictive power is also shared with these sustained-attention constructs). Higher-WMC subjects perform better overall than lower-WMC subjects, and higher-WMC

subjects commit fewer errors on trials with short fixation-to-cue intervals than do lower-WMC subjects. This advantage for higher-WMC subjects became greater at longer fixation-to-cue intervals presumably because higher-WMC subjects used the additional time to better instantiate the goal (i.e., achieve higher goal activation). This finding allows future investigations using antisaccade tasks to more accurately theorize and define the attentional mechanisms related to WMC. The claim that WMC-related differences in antisaccade performance are partially attributable to goal activation processes may require researchers investigating determinants of WMC-performance relations to model goal instantiation and maintenance processes separately. That is, the evidence provided here suggests that the WMC-related attentional control construct may be able to be fractionated. Tying WMC-related goal instantiation and maintenance to neural functions may provide additional evidence for this fractionation and allow for a more mechanistic account of when (i.e., under what circumstances), why, and how WMC-related goal activation processes and maintenance mediate performance.

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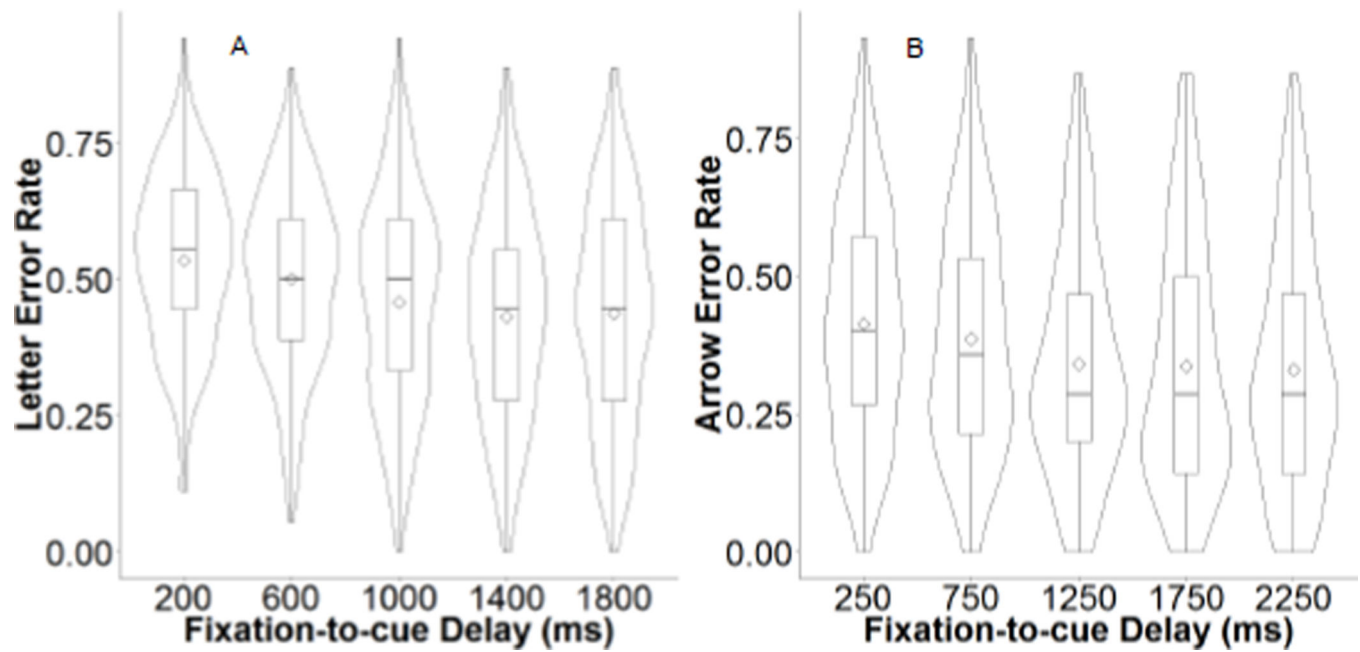


Figure 1.

Violin (density) and box plots of error rates for letter antisaccade (Panel A) and arrow antisaccade (Panel B) plotted as function of fixation-to-cue (i.e., gap) delay. Diamonds are the distribution mean. Horizontal lines in the middle of the box are the median. Lower Hinge represents the 25% of the distribution and the upper hinge represents the 75% of the distribution. The whiskers extend 1.5 times the interquartile range from the upper and lower hinges.

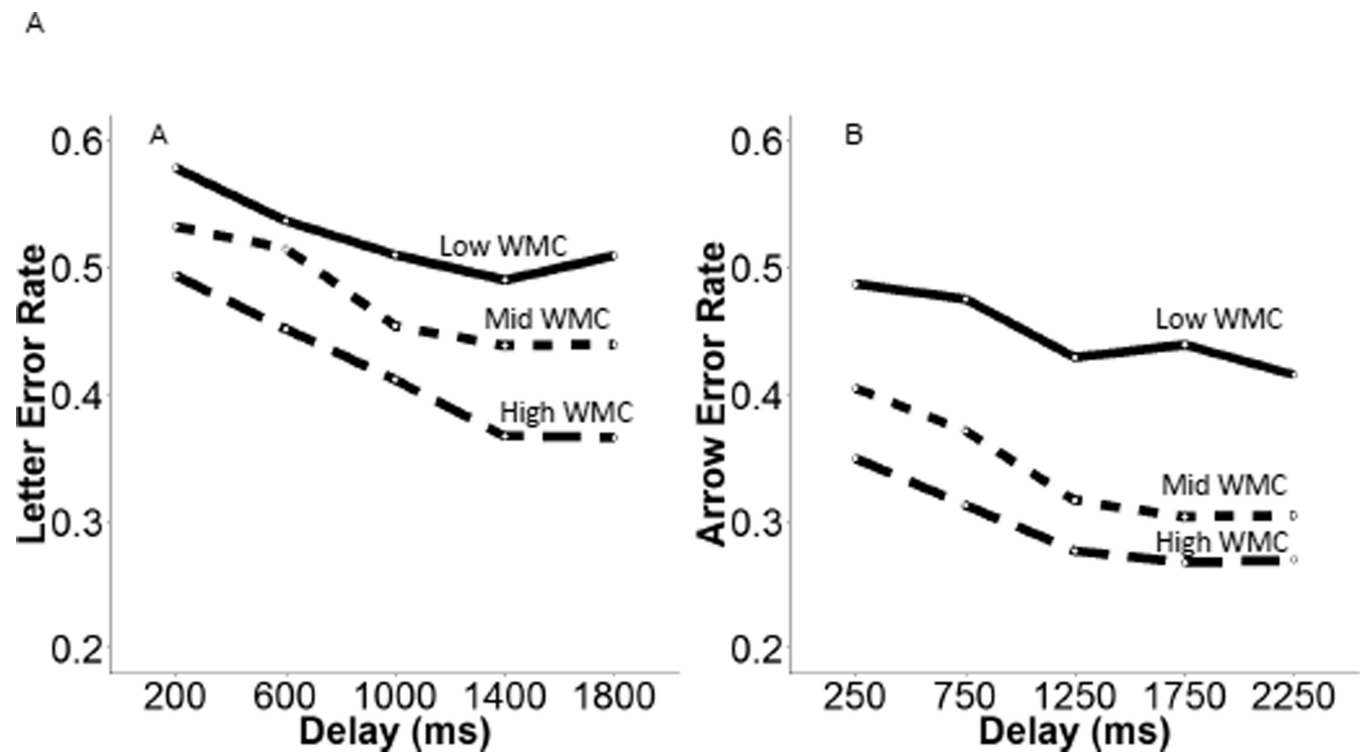


Figure 2.
Mean (of subject means) error rates for letter antisaccade (Panel A) and arrow antisaccade (Panel B) tasks plotted as a function of fixation-to-cue delay and WMC group.

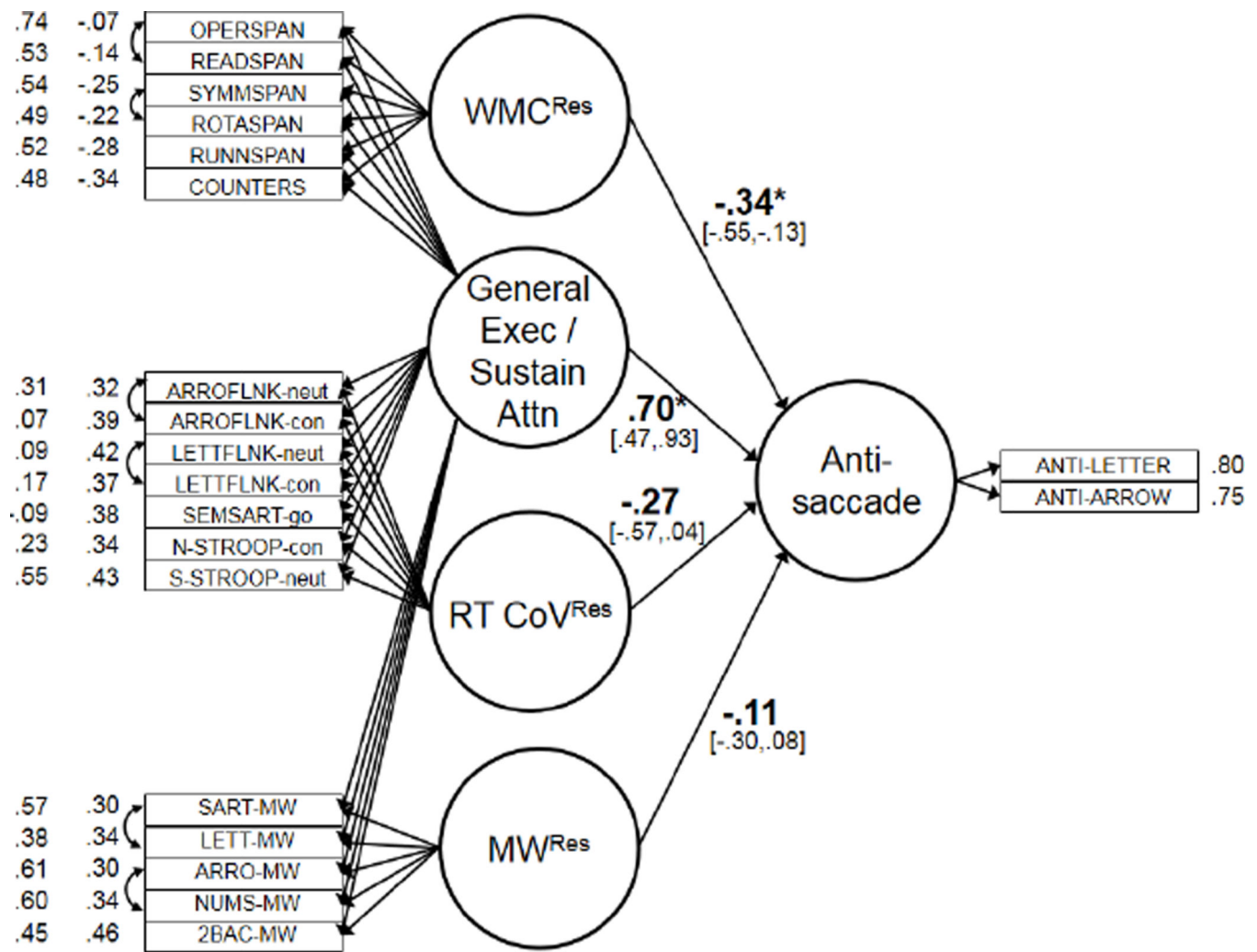


Figure 3.

Bifactor structural equation model depicting the prediction of antisaccade performance. The circles represent the latent variables for Antisaccade Performance (Anti-saccade), the variance common to all predictors (General Executive/Sustained Attention [General Exec/Sustained Attn]), the “residual” variance shared only among the WMC measures (WMC^{Res}), the “residual” variance for the RT CoV measures [RT CoV^{Res}], and the “residual” variance shared only among the mind wandering measures (MW^{Res}). The boxes represent the observed variables loaded onto each latent factor. The arrows represent the modeled direction of the pathway between variables. The rightmost column of numbers next to boxes indicates factor loadings onto the General Executive/Sustained Attention factor and the leftmost column of numbers next to the boxes indicates factor loadings on the WMC-specific, RT CoV-specific, or MW-specific factors. For the observed variables, ANTI-LETTER = letter antisaccade, ANTI-ARROW = arrow antisaccade, OPERSPAN = operation span, READSPAN = reading span, SYMMSPAN = symmetry span, ROTASPER = rotation span, RUNNSPAN = running span, COUNTERS = updating counters, ARROFLNK-neut = RT CoV for neutral trials in the arrow flanker, ARROFLNK-con = RT CoV for congruent trials in the arrow flanker, LETTFLNK-neut = RT CoV for neutral trials in the letter flanker, LETTFLNK-con = RT CoV for congruent trials in the letter flanker, SEMSART-go = SART for go trials, N-STROOP-con = N-STROOP for congruent trials, S-STROOP-neut = S-STROOP for neutral trials, SART-MW = SART for mind wandering trials, LETT-MW = LETT for mind wandering trials, ARRO-MW = ARRO for mind wandering trials, NUMS-MW = NUMS for mind wandering trials, 2BAC-MW = 2BAC for mind wandering trials.

LETTFLNK-con= RT CoV for congruent trials in the letter flanker, SEMSART-go= RT CoV for go trials in the semantic sart, N-STROOP-con=RT CoV for congruent trials from the number stroop, S-STROOP-neut=RT CoV for neutral trials in the spatial stroop, SART-MW= proportion of mind wandering reported in the semantic SART, LETT-MW = proportion of mind wandering reported in letter flanker, ARRO-MW = proportion of mind wandering reported in arrow flanker, NUMS-MW = proportion of mind wandering reported in number Stroop, 2BAC-MW = proportion of mind wandering reported in two-back task.

Table 1

Descriptive Statistics

Measure Type	Measure	M	SD	Min	Max	Skew	Kurtosis	N
Antisaccade	Letter Error Rate	0.47	0.15	0.08	0.80	-0.39	-0.54	462
	Arrow Error Rate	0.36	0.18	0.01	0.79	0.41	-0.70	401
Working Memory	Operation Span	50.95	14.02	6.00	75.00	-0.66	0.08	424
	Reading Span	33.87	11.08	3.00	59.00	-0.21	-0.50	419
	Symmetry Span	26.79	7.64	4.00	42.00	-0.34	-0.33	422
	Rotation Span	25.34	7.93	0.00	42.00	-0.52	-0.01	387
Updating Counters	Updating Counters	0.40	0.16	0.07	0.92	0.55	0.11	472
	Running Span	35.59	10.02	8.00	64.00	0.23	-0.10	456
	SART	0.50	0.24	0.00	1.00	-0.01	-0.79	468
	Number Stroop	0.45	0.31	0.00	1.00	0.30	-1.05	467
Mind Wandering	Arrow Flanker	0.49	0.31	0.00	1.00	0.10	-1.08	471
	Letter Flanker	0.58	0.26	0.00	1.00	-0.50	-0.55	414
	N-back	0.42	0.31	0.00	1.00	0.29	-1.12	456
	SART	0.78	0.32	0.22	2.08	1.18	1.21	466
RT CoV	Number Stroop	0.23	0.15	0.10	2.11	7.18	73.56	459
	Arrow Flanker Congruent	0.21	0.07	0.07	0.81	1.80	8.78	471
	Arrow Flanker Neutral	0.19	0.07	0.07	0.51	0.91	0.59	471
	Spatial Stroop	0.30	0.20	0.09	1.75	3.47	16.70	451
	Letter Flanker Congruent	0.23	0.10	0.09	0.72	1.48	3.00	414
	Letter Flanker Neutral	0.23	0.11	0.07	0.73	1.77	3.70	414

Note. M = Mean of subject means; SD = Standard deviation of subject means; Min = Minimum; Max = Maximum; RT = Response Time; CoV = Coefficient of Variation.

Table 2

Correlations among individual dependent measures, with reliabilities (coefficient alphas) presented on the diagonal.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1. Antisaccade-Letter Error Rate	0.89																			
2. Antisaccade-Arrow Error Rate	0.59	0.92																		
3. Operation Span	-0.20	-0.23	0.81																	
4. Reading Span	-0.17	-0.18	0.57	0.76																
5. Symmetry Span	-0.33	-0.30	0.43	0.38	0.68															
6. Rotation Span	-0.21	-0.36	0.44	0.32	0.54	0.76														
7. Updating Counters	-0.33	-0.32	0.36	0.22	0.37	0.29	0.85													
8. Running Span	-0.24	-0.26	0.44	0.36	0.28	0.20	0.38	0.55												
9. SART MW	0.12	0.04	0.00	-0.13	-0.09	0.00	-0.05	-0.04	0.92											
10. Number Stroop MW	0.13	0.12	-0.04	-0.12	-0.03	-0.03	-0.02	-0.13	0.46	0.90										
11. Arrow Flanker MW	0.16	0.07	0.01	-0.08	-0.03	0.02	-0.04	-0.11	0.43	0.67	0.91									
12. Letter Flanker MW	0.11	0.07	0.09	0.00	-0.09	-0.01	-0.02	0.04	0.51	0.33	0.37	0.78								
13. N-back MW	0.19	0.21	-0.06	-0.10	-0.06	-0.14	-0.13	-0.21	0.39	0.44	0.41	0.33	0.90							
14. SART CoV	0.30	0.20	-0.16	-0.17	-0.16	-0.11	-0.11	-0.15	0.18	0.18	0.16	0.17	0.21	0.97						
15. Number Stroop CoV	0.09	0.05	-0.01	0.05	-0.10	-0.01	-0.09	-0.05	0.12	0.16	0.13	0.19	0.14	0.11	0.79					
16. Arrow Flanker Congruent CoV	0.22	0.18	-0.06	-0.14	-0.14	-0.15	-0.20	-0.19	0.01	0.10	0.08	0.02	0.10	0.10	0.16	0.54				
17. Arrow Flanker Neutral CoV	0.12	0.14	-0.06	0.00	0.02	-0.05	-0.16	-0.12	-0.01	0.15	0.10	0.01	0.09	0.10	0.16	0.50	0.56			
18. Spatial Stroop CoV	0.04	0.08	-0.01	-0.02	0.04	-0.05	-0.08	-0.05	0.13	0.12	0.06	0.12	0.28	0.09	0.21	0.14	0.26	0.73		
19. Letter Flanker Congruent CoV	0.17	0.15	0.01	-0.04	-0.06	-0.04	-0.07	-0.06	0.18	0.09	0.05	0.27	0.16	0.05	0.17	0.22	0.20	0.21	0.50	
20. Letter Flanker Neutral CoV	0.21	0.17	0.02	-0.08	-0.11	-0.06	-0.10	-0.06	0.18	0.12	0.06	0.23	0.16	0.13	0.12	0.20	0.10	0.20	0.52	0.47

Note. MW = Mind wandering; CoV = Coefficient of variation

Table 3

Fixed Effect Estimates, Standard Errors, and z-values for a Model with Target-side switch, Cue-to-fixation delay, WMC, Mind Wandering and their Interactions as Predictors of Letter Antisaccade Errors

	Estimate	Std. Error	z value
(Intercept)	-0.13	0.03	-4.6
Target-side switch	0.21	0.02	10.2
Cue delay	-0.16	0.01	-15.5
WMC	-0.23	0.03	-8.3
Mind wandering	0.09	0.03	3.3
Target-side switch \times cue delay	-0.09	0.02	-4.4
Target-side switch \times WMC	-0.01	0.02	-0.3
Cue delay \times WMC	-0.05	0.01	-4.5
Target-side switch \times mind wandering	-0.01	0.02	-0.3
Cue delay \times mind wandering	0.01	0.01	0.7
Mind wandering \times WMC	-0.01	0.03	-0.5
Target-side switch \times cue delay \times WMC	0.01	0.02	0.5
Target-side switch \times cue delay \times mind wandering	0.01	0.02	0.4
Target-side switch \times WMC \times mind wandering	0.01	0.02	0.3
Cue delay \times WMC \times mind wandering	-0.01	0.01	-0.7
Target-side switch \times cue delay \times WMC \times mind wandering	0.00	0.02	0.2

Table 4

Mean (of subject means) target-side repeat and switch error rates (standard errors in parentheses) by antisaccade task and delay

Antisaccade Task	Delay(ms)	Target-side repeat	Target-side switch	Repeat - switch difference
Letter	200	0.49 (.01)	0.58 (.01)	0.08 (.01)
	600	0.48 (.01)	0.54 (.01)	0.06 (.01)
	1000	0.43 (.01)	0.49 (.01)	0.05 (.01)
	1400	0.42 (.01)	0.45 (.01)	0.02 (.01)
	1800	0.43 (.01)	0.45 (.01)	0.02 (.01)
Arrow	250	0.37 (.01)	0.46 (.01)	0.09 (.01)
	750	0.35 (.01)	0.41 (.01)	0.06 (.01)
	1250	0.32(.01)	0.36 (.01)	0.04 (.01)
	1750	0.32 (.01)	0.35 (.01)	0.03 (.01)
	2250	0.32 (.01)	0.34 (.01)	0.03 (.01)

Table 5

Fixed Effect Estimates, Standard Errors, and z-values for a Model with Target-side switch, Cue-to-fixation delay, WMC, RT CoV, Mind Wandering and their Interactions as Predictors of Letter Antisaccade Errors

	Estimate	Std. Error	z value
(Intercept)	−0.11	0.03	−3.7
Target-side switch	0.21	0.02	9.4
Cue delay	−0.16	0.01	−14.7
WMC	−0.20	0.03	−7.1
RT CoV	0.15	0.03	5.1
Mind wandering	0.04	0.03	1.3
Target-side switch × cue delay	−0.09	0.02	−4.2
Target-side switch × WMC	−0.01	0.02	−0.6
Cue delay × WMC	−0.04	0.01	−3.9
Target-side switch × RT CoV	−0.02	0.02	−1.0
Cue delay × RT CoV	0.03	0.01	2.6
WMC × RT CoV	0.01	0.03	0.4
Target-side switch × mind wandering	0.00	0.02	0.2
Cue delay × mind wandering	0.00	0.01	−0.3
Mind wandering × WMC	−0.04	0.03	−1.3
RT CoV × mind wandering	−0.07	0.03	−2.4
Target-side switch × cue delay × WMC	0.01	0.02	0.4
Target-side switch × cue delay × RT CoV	0.00	0.02	0.2
Target-side switch × WMC × RT CoV	−0.01	0.02	−0.3
Cue delay × WMC × RT CoV	0.00	0.01	0.2
Target-side switch × cue delay × mind wandering	0.01	0.02	0.4
Target-side switch × WMC × mind wandering	0.01	0.02	0.3
Cue delay × WMC × mind wandering	−0.01	0.01	−0.8
Target-side switch × RT CoV × mind wandering	0.01	0.02	0.7
Cue delay × RT CoV × mind wandering	0.00	0.01	−0.2
WMC × RT CoV × mind wandering	−0.04	0.02	−1.7
Target-side switch × cue delay × WMC × RT CoV	0.01	0.02	0.6
Target-side switch × cue delay × WMC × mind wandering	0.00	0.02	−0.1
Target-side switch × cue delay × RT CoV × mind wandering	0.01	0.02	0.5
Target-side switch × WMC × RT CoV × mind wandering	0.02	0.02	1.3
Cue delay × WMC × RT CoV × mind wandering	−0.01	0.01	−0.7
Target-side switch × cue delay × WMC × RT CoV × mind wandering	0.02	0.02	1.1

Table 6

Fixed effect estimates, standard errors, and z-values for model with Target-side switch, Cue delay, WMC, mind wandering and their interactions as predictors of arrow antisaccade errors

	Estimate	Std. Error	z value
(Intercept)	-0.68	0.04	-16.1
Target-side switch	0.25	0.03	9.1
Cue delay	-0.15	0.01	-11.4
WMC	-0.37	0.04	-8.7
Mind wandering	0.10	0.04	2.3
Target-side switch \times cue delay	-0.11	0.03	-3.9
Target-side switch \times WMC	-0.03	0.03	-0.9
Cue delay \times WMC	-0.02	0.01	-1.8
Target-side switch \times mind wandering	0.02	0.03	0.9
Cue delay \times mind wandering	0.01	0.01	0.4
Mind wandering \times WMC	0.03	0.04	0.7
Target-side switch \times cue delay \times WMC	0.02	0.03	0.7
Target-side switch \times cue delay \times mind wandering	-0.02	0.03	-0.7
Target-side switch \times WMC \times mind wandering	0.03	0.03	1.2
Cue delay \times WMC \times mind wandering	0.00	0.01	0.1
Target-side switch \times cue delay \times WMC \times mind wandering	0.00	0.03	-0.1

Table 7

Fixed Effect Estimates, Standard Errors, and z-values for a Model with Target-side switch, Cue-to-fixation delay, WMC, RT CoV, Mind Wandering and their Interactions as Predictors of Arrow Antisaccade Errors

	Estimate	Std. Error	z value
(Intercept)	-0.66	0.04	-15.08
Target-side switch	0.24	0.03	8.48
Cue delay	-0.16	0.01	-11.04
WMC	-0.34	0.04	-7.88
RT CoV	0.17	0.05	3.78
Mind wandering	0.05	0.04	1.04
Target-side switch \times cue delay	-0.11	0.03	-3.99
Target-side switch \times WMC	-0.03	0.03	-0.97
Cue delay \times WMC	-0.03	0.01	-2.01
Target-side switch \times RT CoV	0.00	0.03	-0.16
Cue delay \times RT CoV	0.00	0.02	-0.03
WMC \times RT CoV	0.00	0.04	0.09
Target-side switch \times mind wandering	0.03	0.03	0.99
Cue delay \times mind wandering	0.01	0.01	0.51
Mind wandering \times WMC	0.00	0.04	0.02
RT CoV \times mind wandering	-0.06	0.04	-1.38
Target-side switch \times cue delay \times WMC	0.01	0.03	0.41
Target-side switch \times cue delay \times RT CoV	-0.02	0.03	-0.7
Target-side switch \times WMC \times RT CoV	-0.03	0.03	-1.13
Cue delay \times WMC \times RT CoV	0.00	0.01	-0.11
Target-side switch \times cue delay \times mind wandering	0.00	0.03	-0.17
Target-side switch \times WMC \times mind wandering	0.03	0.03	1.07
Cue delay \times WMC \times mind wandering	0.00	0.01	0.28
Target-side switch \times RT CoV \times Mind wandering	-0.01	0.03	-0.36
Cue delay \times RT CoV \times mind wandering	0.02	0.01	1.13
WMC \times RT CoV \times mind wandering	0.00	0.04	-0.13
Target-side switch \times cue delay \times WMC \times RT CoV	-0.02	0.03	-0.8
Target-side switch \times cue delay \times WMC \times mind wandering	0.00	0.03	-0.16
Target-side switch \times cue delay \times RT CoV \times mind wandering	0.02	0.03	0.59
Target-side switch \times WMC \times RT CoV \times mind wandering	0.02	0.02	0.77
Cue delay \times WMC \times RT CoV \times mind wandering	0.01	0.01	1.18
Target-side switch \times cue delay \times WMC \times RT CoV \times mind wandering	0.05	0.02	2.02