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Working Memory Capacity and Sustained Attention: A Cognitive-Energetic Perspective

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A cognitive-energetic account of individual differences in working memory capacity (WMC) and sustained attention performance is proposed suggesting that variation in the voluntary control of the intensity of attention (intrinsic alertness) is critical for the relation between WMC and attention control. Four experiments examining individual differences were conducted to test this account. The results suggested that WMC was consistently related to the slowest reaction times in conditions where the interstimulus interval (ISI) was varied or was fixed at a long interval. Variation in WMC was not related to performance when the ISI was fixed at a short interval which is thought to decrease demands on intrinsic alertness. The current results are consistent with the hypothesis that normal variation in WMC and sustained attention performance are partially the result of individual differences in intrinsic alertness whereby low WMC individuals are less able to consistently control the intensity of attention than high WMC individuals. Other possible reasons for the relation between WMC and sustained attention performance such as differences in goal activation, speed of goal activation, goal maintenance during a trial, or sustaining goal maintenance across the duration of the task were associated with weaker and inconsistent evidence. Collectively we suggest that the current cognitive-energetic account can be used to understand individual differences in WMC and attention control and their relations with other cognitive abilities.

Keywords: working memory capacity, sustained attention, lapses of attention, individual differences

Working memory is a core cognitive construct that is needed to actively maintain, manipulate, and retrieve task relevant information in a wide variety of tasks. A great deal of research has demonstrated that individual differences in working memory capacity (WMC) are associated with performance in a number of cognitive domains. These include associations with performance on low-level attention and memory tasks as well as higher-level reasoning and comprehension tasks (see Engle & Kane, 2004; Unsworth & Engle, 2007 for reviews). A prominent theory of individual differences in WMC suggests that these individual differences are due to normal variation in attention control (or executive attention) abilities (Engle & Kane, 2004; Kane & Engle, 2002; Unsworth & Engle, 2007). By attention control we mean the set of attentional processes that aid in the ability to actively maintain information in the presence of interference and distraction. These attention control abilities are necessary when goal-relevant information (i.e., the current task goal) must be maintained in a highly active state in the presence of potent internal and external distraction (Engle & Kane, 2004). If the task goal is not sufficiently activated or if there is any lapse of attention (or goal neglect, Duncan, 1995) it is likely that the task goal will be lost from working memory resulting in attention being automatically captured by internal (e.g., mind-wandering; Kane et al., 2007; McVay & Kane, 2012a) or external distraction (e.g., Robison & Unsworth, 2015; Unsworth, Fukuda, Awh, & Vogel, 2014; Unsworth & McMillan, 2014). Thus, a key aspect of attention control is the ability to actively maintain the current goal in a highly active state and prevent attentional capture from internal and external sources. Evidence supporting these notions comes from a variety of studies which have examined relations between individual differences in WMC and performance on various attention control tasks (see Unsworth, 2016 for a review). Much of the prior research has focused on examining WMC and attention control in tasks thought to require the inhibition of strong external distractors such as found in the antisaccade, Stroop, and flanker paradigms. Kane et al. (2016) have suggested that these measures index somewhat distinct attention control abilities referred to as attention restraint (the ability to restrain from being captured by strong prepotent responses measured in tasks like antisaccade and Stroop) and attention constraint (the ability to constrain attention to task relevant stimuli measured in tasks like flankers). In the current study we examine the link between WMC and another important attention control ability: sustained attention.

Sustained Attention

Our ability to continuously pay attention to a task for some amount of time reflects a core aspect of attention control different from selective attention, divided attention, and spatial orienting of

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attention (Posner & Petersen, 1990; Sturm & Willmes, 2001; Stuss, Shallice, Alexander, & Picton, 1995; van Zomeren & Brouwer, 1994). This sustained attention ability refers to attention control processes that are needed to maintain attention and engagement on task over time on relatively monotonous tasks (also referred to as vigilant attention; Langner & Eickhoff, 2013; Lim & Dinges, 2008; Robertson & O'Connell, 2010). In particular, Robertson, Manly, Andrade, Baddeley, and Yiend (1997) suggest that sustained attention is "the ability to self-sustain mindful, conscious processing of stimuli whose repetitive, non-arousing qualities, would otherwise lead to habituation and distraction by other stimuli" (p. 747). Importantly, in this conceptualization, sustained attention is needed to maintain focus on task over both relatively short (seconds) and long (minutes to hours) intervals.

A key finding in sustained attention research is that performance tends to decrease as a function of time-on-task (the vigilance decrement). These time-on-task effects were initially found with long-duration tasks (e.g., Mackworth, 1950), but they have also been found with much shorter duration tasks (Lim & Dinges, 2008; Nuechterlein, Parasuraman, & Jiang, 1983). In general a large number of studies have found that detection accuracy decreases and reaction time (RT) increases as time-on-task increases in a number of different paradigms (Parasuraman, 1986; Parasuraman & Davies, 1977; See, Howe, Warm, & Dember, 1995; see also Hockey, 2013, for a review of early research on decrements in performance on continuous work tasks).

In addition to time-on-task effects, another key aspect of sustained attention is the notion that attention fluctuates from moment-to-moment leading to variability in task performance. These fluctuations in attention can lead to relatively minor changes in task engagement (and minor shifts in performance), or these fluctuations can lead to much larger changes in task engagement (and large shifts in performance). These more extreme fluctuations can be conceptualized as lapses of attention whereby an individual briefly disengages from the current task. Thus, these fluctuations and lapses in attention should result in more trial-to-trial variability in performance (such as very slow RTs; Bertelson & Joffe, 1963; Bills, 1931, 1935) and trial-to-trial variability in subjective reports of attentional state (e.g., Smallwood et al., 2004; Unsworth & McMillan, 2014).

Collectively, changes in sustained attention are likely due to changes in energetic factors such as motivation (e.g., intrinsic motivation to do well, extrinsic motivators such as incentives, etc.), arousal (e.g., circadian rhythm, sleep deprivation, etc.), and alertness. Alertness refers to the overall readiness to respond to external information. Recent theorizing suggests that alertness can be subdivided into phasic alertness (short-term readiness following a warning signal), tonic alertness (slow changing readiness linked to circadian rhythm and wakefulness), and intrinsic alertness (voluntary control of readiness over seconds to minutes in the absence of external cues: Langner et al., 2012; Sadaghiani & D'Esposito, 2015; Sturm & Willmes, 2001; van Zomeren & Brouwer, 1994). Thus, the intensity of attention that is allocated to a task is determined in part by current alertness levels with aspects of alertness being voluntarily controlled (intrinsic alertness). Accordingly, alertness levels are seen as being a prerequisite for other types of attention. That is, if alertness levels are too low, it will be difficult for other aspects of attention (selective attention and divided attention) to function properly.

A common means of examining fluctuations in sustained attention and alertness is to use simple RT tasks with variable interstimulus intervals (ISIs). In these tasks participants have to detect the occurrence of a target that typically occurs at an uncertain time point. Thus, participants must maintain focused attention on the stimulus and maintain a high level of preparation in order to rapidly detect the occurrence of the signal and press the corresponding key once the signal occurs. This preparatory maintenance process is thought to be effortful requiring a great deal of intrinsic alertness (Jennings & van der Molen, 2005; Langner & Eickhoff, 2013; Steinborn, Langner, & Huestegge, 2017; Woodrow, 1914). Indeed, Posner and Boies (1971) suggested that the "foreperiod of a reaction time task may be considered as a miniature vigilance situation where alertness must be developed rapidly and maintained over a relatively brief interval" (p. 391). Any lapse of attention, whereby attention is not adequately sustained and focused on the stimulus, should result in a longer than normal RT. Thus, a critical aspect of sustained attention is the ability to maintain a preparatory state of readiness over uncertain intervals. Fluctuations in intrinsic alertness then should translate into performance fluctuations.

Prior research suggests a relation between WMC and some aspects of attention control, yet less research has been done examining relations between WMC and sustained attention. For example, Unsworth, Redick, Heitz, Broadway, & Engle (2009) found that a sustained attention factor was correlated with WMC ($r = .27$) suggesting that high WMC individuals were better at sustaining their attention than low WMC individuals. Furthermore, in a number of studies we found that the slowest trials on the psychomotor vigilance task tend to correlate with WMC, this measure tends to load with other attention control measures (such as antisaccade, Stroop, and flankers), and this latent variable is strongly related to WMC (Robison & Unsworth, 2018; Unsworth, Brewer, & Spillers, 2012; Unsworth, Spillers, & Brewer, 2009; Unsworth & McMillan, 2014, 2017; Unsworth, Redick, Lakey, & Young, 2010; Unsworth & Robison, 2017a; Unsworth & Spillers, 2010). Research with other sustained attention tasks has also found relations with WMC (Buehner, Krumm, Ziegler, & Pluecken, 2006; McVay & Kane, 2009, 2012b; Schweizer & Moosbrugger, 2004), but this is not always the case (e.g., McVay & Kane, 2012b). One problem with these studies is that they relied on global indicators of performance and did not necessarily examine factors such as time-on-task relations with WMC. Thus, while there is evidence that WMC is related to sustained attention performance, it is not clear what this relation actually represents.

A Cognitive-Energetic Model of Individual Differences in Working Memory Capacity and Intrinsic Alertness

In order to understand individual differences in sustained attention and their relation with WMC and other cognitive constructs we propose a cognitive-energetic model highlighting the importance of the intensity of attention to goal maintenance. As noted by Hockey, Gaillard, and Coles (1986), energetics refers to "the processes involved in the initiation, maintenance, and regulation of behavior" (p. 6). Broadly energetics is concerned with the intensive aspect of processing and behavior and is associated with related concepts of arousal, activation, motivation, and effort. Thus, cognitive energetic models combine cognitive processing models with the notion that intensive aspects of processing vary both within and between participants (e.g., Broadbent, 1971; Hockey et al., 1986; Kahneman, 1973; Sanders, 1983). The current model is based heavily on prior theorizing on these issues (e.g., Aston-Jones & Cohen, 2005; Cohen, Aston-Jones, & Gilzenrat, 2004; Hockey, 1993, 1997, 2011, 2013; Kahneman, 1973; Kane & McVay, 2012; Kanfer & Ackerman, 1989; McVay & Kane, 2010; Sanders, 1983; Shallice, Stuss, Alexander, Picton, & Derkzen, 2008; Stuss et al., 1995; 2005).

Shown in Figure 1 is the current model. This model represents an extension of our recent locus coeruleus-norepinephrine account of individual differences in WMC and attention control (Unsworth & Robison, 2017a, 2017b). In this model the intensity of attention (associated with the locus coeruleus-norepinephrine system) modulates current control levels (associated with the frontal-parietal network). The intensity of attention is influenced by overall motivation levels (both intrinsic and extrinsic motivation such as incentives), overall arousal levels (influenced by factors such as circadian rhythm, sleep deprivation, drugs, etc.) and intrinsic alertness (voluntary control over intensity and task engagement). When the intensity of attention is high task engagement is high leading to optimal levels of control. However, when the intensity of attention is low, task engagement is low and current control levels are inadequate. Thus, the intensity of attention determines, in part, how well control is implemented on any given trial.

Key aspects of control are goal management processes (Hockey, 2013). As noted by Hockey (2013) "from a control theory perspective, goals are the starting point to all behavior" (p. 134). Thus, the control component can be further broken down into different goal management processes including goal selection, goal activation, and goal maintenance (Hockey, 1997, 2011, 2013). In line with prior theorizing, one of the first aspects of control is the selection of the current goal. In typical laboratory tasks this is the current task goal (perform well on the current task; labeled G in Figure 1 based on Hockey, 2011, 2013). The current task goal is contrasted with other personally relevant goals such as current personal concerns (Klinger, 1999; McVay & Kane, 2010) and biological goals such as the need for sleep, the need for food, and the need to use the restroom (see also Altmann & Trafton, 2002). Assuming the participant wants to perform the current task (in order to get payment or course credit) the task goal (G) is selected over the competing goals (labeled g1, g2 in Figure 1 based on Hockey, 2011, 2013). Goal selection is also likely influenced by a number of factors including the current instructions (be fast, be accurate), the availability of incentives (payment is contingent on performance), as well as overall self-efficacy. Furthermore, given that the task goal is likely less important to the participant than other goals, it is necessary that the task goal (G) be sufficiently activated above other competing goals (see also Altmann & Trafton, 2002). It is assumed that this goal activation process takes time (Unsworth, Spillers, Brewer, & McMillan, 2011; Woodrow, 1914). In some situations it is possible that the task goal is not sufficiently activated when the trial begins leading to the wrong response or a delayed response. Once the task goal is activated it needs to be actively maintained in working memory during the course of the trial to bias responding to the correct response. If the task goal is not properly maintained throughout the duration of the trial, the task goal might lose activation allowing for one of the competing goals to gain access to the focus of attention and hijack

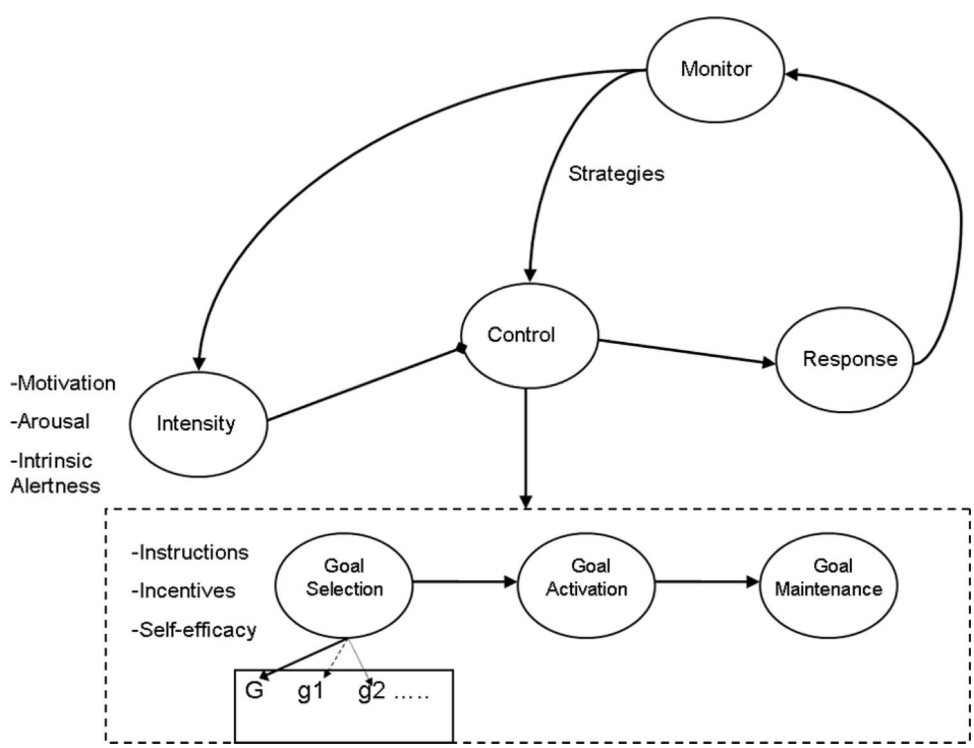

Figure 1. Cognitive-energetic model. See text for description.

attention away from the current task (due to external or internal distraction).

Depending on the effectiveness of the control component several possible responses can occur which are monitored by a monitoring component (associated with the salience network). These include a fast and accurate response, a very slow and accurate response, or an error (either fast or slow) response. With both a slow and accurate response and an error response it is assumed that the monitoring process is activated, sending feedback to the intensity of attention component which reorients attention to the task at hand and increases overall attention allocation to the task resulting in higher levels of task engagement. Of course as noted by Hockey (2011, 2013) and others (Kanfer & Ackerman, 1989) individuals might not always want to increase further attention to the task, but rather settle for the current performance levels. The monitoring component also likely sends feedback to the control component to allow for a change in strategies (e.g., changing speed–accuracy trade-off thresholds, changing how the task is performed).

As noted previously, simple RT tasks require a great deal of sustained attention and intrinsic alertness for optimal performance. Specifically, consider the psychomotor vigilance task. On each trial in this task participants are presented with a row of zeros in the center of the screen and after a variable interstimulus interval (ISI: 1–10 s) the zeros begin to count up. The participants' task is to press the spacebar as quickly as possible once the numbers start counting up. Theoretically it is assumed that intrinsic alertness and the intensity of attention fluctuate both within and between trials. This has an impact on preparatory processes in which you need to select the task goal among competitors, energize and activate the task goal, and maintain the task goal in a ready state while waiting for the stimulus to occur. When intrinsic alertness is high, preparatory processes are engaged such that the task goal is selected, activated and maintained during the ISI so that when the numbers begin counting up there is a fast RT. However, when intrinsic alertness is low, preparatory processes are not fully engaged leading to a weakened task goal activation and/or an inability to maintain the task goal over the interval. This should result in a longer than normal RT. Following these longer than normal RTs, we would expect that the monitoring process would signal the intensity component to ramp up intensity levels so that performance is restored on the next trial resulting in a fast RT.

In terms of individual differences we suggest that intrinsic alertness abilities are critical for determining variation in performance and for the relation between WMC and sustained attention (and perhaps attention control more broadly). Specifically, we suggest that low WMC individuals are less able to voluntarily control and adapt their intensity of attention in a goal directed manner compared with high WMC individuals. These deficits in intrinsic alertness should result in lowered behavioral performance on a wide variety of attention control tasks where the need for preparatory attention is high such as sustained attention tasks.

Of course differences in intrinsic alertness (intensity of attention) can manifest in different ways. For example, it is possible that high and low WMC individuals differ in the ability to energize or activate the task goal over competing goals. As shown in Figure 2a, high WMC individuals may be better able to activate the task goal to a higher level than low WMC individuals (see also Meier, Smeekens, Silvia, Kwapil, & Kane, 2018 for a similar account of individual differences in WMC on the antisaccade task). This would result in overall better performance (faster RTs) on the psychomotor vigilance task across all ISIs for high WMC individuals compared with low WMC individuals given that high WMC individuals are in a heightened state of readiness on every trial compared with low WMC individuals (see Table 1 for predictions for each possibility). Additionally, assuming that the task goal is activated only slightly higher than the competing goals for low WMC individuals, we might expect that low WMC individuals experience more mind-wandering as potent internal goals are more likely to break into the focus of attention for these individuals compared with high WMC individuals. Thus, this suggests that high WMC individuals should be faster than low WMC individuals (a shift in the entire RT distribution) and when examining RTs for each ISI there should be a main effect of WMC but no interaction.

Another possible way that differences in intensity could manifest is as differences in how quickly the task goal can be energized/activated. As shown in Figure 2b, high WMC individuals may be able to more quickly activate the task goal than low WMC individuals. This would suggest that when the ISI is short that low WMC individuals might not yet have the task goal fully activated resulting in worse performance compared with high WMC individuals (see also Meier et al., 2018 for a similar account of individual differences in WMC on the antisaccade task). However, with a sufficiently long ISI low WMC individuals should have plenty of time to activate the task goal to the same level as high WMC individuals. This scenario predicts that high WMC individuals should be faster than low WMC individuals overall, but critically when examining RTs as a function of ISI these differences should be localized to the shortest ISIs (see Table 1). Thus, there should be an interaction between WMC and ISI.

Conversely, it is possible that differences in intensity manifest as differences in the ability to actively maintain the task goal for the duration of the trial. As shown in Figure 2c, high WMC individuals may be better able to actively maintain the task goal throughout the entire trial, whereas low WMC individuals cannot maintain this high level of activation and as the trial proceeds the task goal loses activation until it eventually drops below the competing goals. This would suggest that when the ISI is long, low WMC individuals are not able to keep the task goal fully activated resulting in worse performance compared with high WMC individuals. This possibility predicts that high WMC individuals should be faster than low WMC individuals overall and there should be an interaction between WMC and ISI with differences localized to the longest ISIs (see Table 1).

Yet another possibility is that high and low WMC individuals differ in their ability to sustain the task goal over runs or blocks of trials. That is, perhaps early on in the task low WMC individuals can allocate as much attention to the task as high WMC individuals, but as time on task increases, low WMC individuals are unable to sustain this high level of intensity resulting in worse and worse performance (longer RTs and more mind-wandering) compared with high WMC individuals. This possibility essentially suggests that differences in WMC should occur as a function of time-on-task with low WMC individuals demonstrating a steeper time-on-task effect (i.e., a greater vigilance decrement) than high WMC individuals (see Table 1).

Finally, it is possible that WMC differences in intensity result from differences in the consistency of intrinsic alertness across

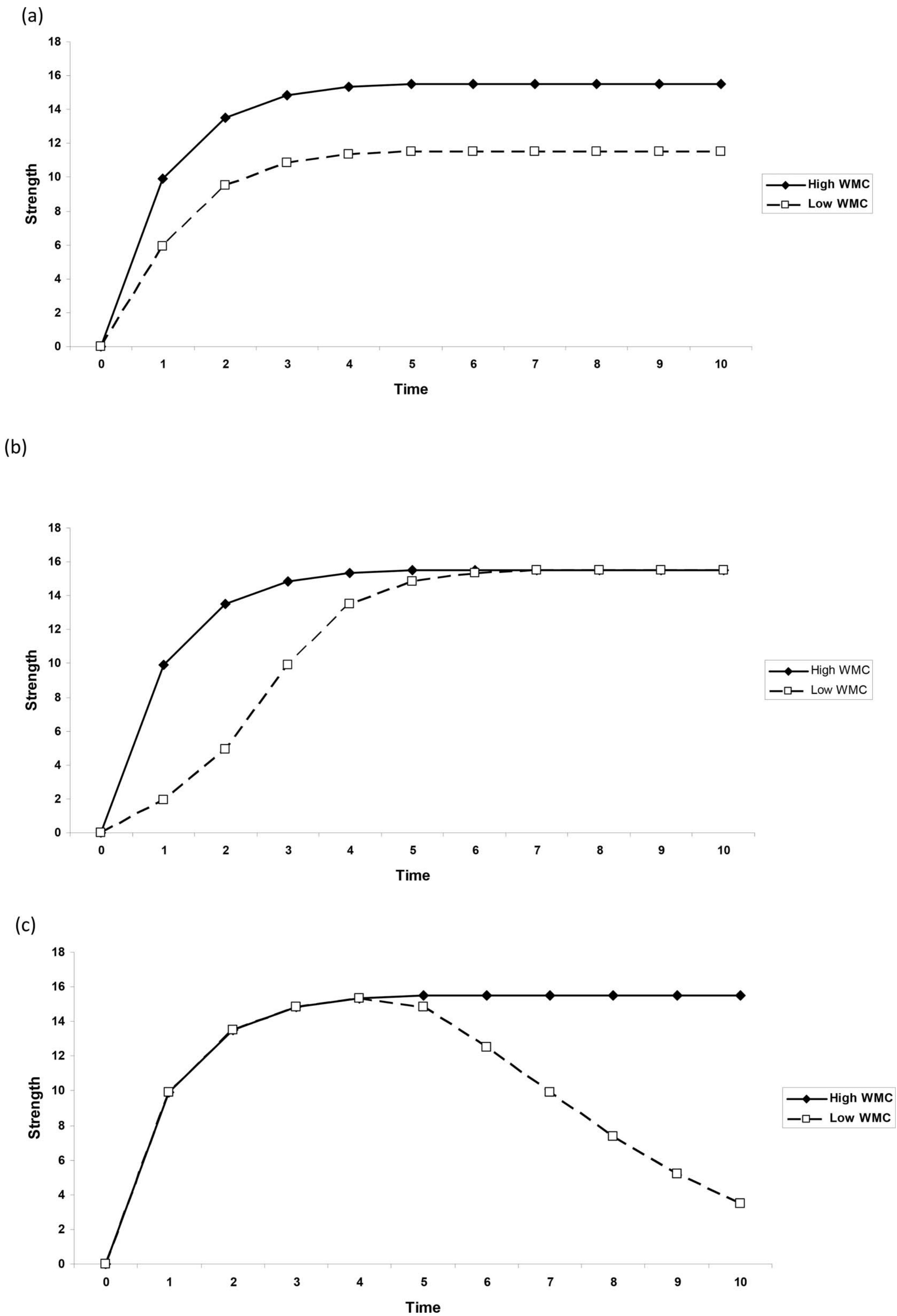

Figure 2. (a) Differences between high and low working memory capacity (WMC) individuals in terms of overall goal activation strength (arbitrary units). (b) Differences between high and low working memory capacity (WMC) individuals in terms of how quickly the goal can be activated. (c) Differences between high and low working memory capacity (WMC) individuals in terms of goal maintenance abilities.

Table 1
Possible Working Memory Capacity Differences in Sustained Attention and Predicted Effects

Possibility	Predicted WMC effect
Goal Activation Strength	WMC Main Effect on RTs
Speed of Activation	WMC × ISI Interaction Localized to Shortest ISIs
Goal Maintenance	WMC × ISI Interaction Localized to Longest ISIs
Sustain Attention	WMC × Block Interaction Localized to Later Blocks
Lapses of Attention	WMC × RT Quintile Interaction Localized to Slowest RTs

Note. WMC = working memory capacity; RT = reaction time; ISI = interstimulus interval.

trials. This possibility suggests that WMC differences on sustained attention tasks result from differences in trial-to-trial fluctuations of the intensity of attention. Specifically, it is possible that high and low WMC individuals perform fairly equivalently on most trials, but that low WMC individuals experience more lapses of attention than high WMC individuals in which on a subset of trials the intensity of attention is lower for low WMC individuals resulting in potentially poor goal selection, weakened goal activation, or inabilities in goal maintenance. This account predicts that not only should high WMC individuals be faster than low WMC individuals overall, but specifically suggests that these RT differences should be localized to the slow tail of the distribution (see Table 1). That is, most of the time low WMC individuals can perform just as well as high WMC individuals, but they experience more lapses of attention than high WMC individuals resulting in a larger subset of trials with especially slow RTs.

To examine these issues we conducted four individual differences experiments in which participants performed various versions of the psychomotor vigilance task along with multiple measures of WMC.

Experiment 1

In our first experiment we examined the relation between WMC and sustained attention by having participants perform a fairly standard version of the psychomotor vigilance task along with three complex span measures of WMC. To examine the issues discussed above we specifically examined WMC differences as a function of ISI, time-on-task, and overall RT distributions.

Method

Participants. A total of 165 participants were recruited from the subject-pool at the University of Georgia. Data was collected over one full academic semester. One participant did not complete the psychomotor vigilance task and three participants were excluded due to excessively long RTs on the psychomotor vigilance task leaving a final sample of 161 participants with full data. Participants were between the ages of 18 and 35 and received course credit for their participation. Each participant was tested individually. None of the participants participated in any of the other experiments.

Materials and procedure. After signing informed consent, all participants completed operation span task, symmetry span task, reading span task, and the psychomotor vigilance task. The four tasks were completed in a 2-hr session, during which participants completed other cognitive ability tasks including three episodic memory tasks (free recall, paired associates, and picture source recognition), two additional attention control tasks (antisaccade, flankers), and two prospective memory tasks as part of a larger project which is reported in Unsworth, Brewer, et al. (2012).

Tasks.

Working memory capacity (WMC) tasks.

Operation span (Ospan). Participants solved a series of math operations while trying to remember a set of unrelated letters (F, H, J, K, L, N, P, Q, R, S, T, Y). Participants were required to solve a math operation and after solving the operation they were presented with a letter for 1 s. Immediately after the letter was presented the next operation was presented. Three trials of each list-length (three to seven) were presented, with the order of list-length varying randomly. At recall, letters from the current set were recalled in the correct order by clicking on the appropriate letters (see Unsworth, Heitz, Schrock, & Engle, 2005; Redick et al., 2012 for more details). Participants received three sets (of list-length two) of practice. For all of the span measures, items were scored if the item was correct and in the correct position. The score was the total number of correct items in the correct position.

Symmetry span (Symspan). In this task participants were required to recall sequences of red squares within a matrix while performing a symmetry-judgment task. In the symmetry-judgment task participants were shown an 8 × 8 matrix with some squares filled in black. Participants decided whether the design was symmetrical about its vertical axis. The pattern was symmetrical half of the time. Immediately after determining whether the pattern was symmetrical, participants were presented with a 4 × 4 matrix with one of the cells filled in red for 650 ms. At recall, participants recalled the sequence of red-square locations in the preceding displays, in the order they appeared by clicking on the cells of an empty matrix. There were three trials of each list-length with list-length ranging from two to five. The same scoring procedure as Ospan was used (see Redick et al., 2012; Unsworth et al., 2009 for more task details).

Reading span (Rspan). Participants were required to read sentences while trying to remember the same set of unrelated letters as Ospan. For this task, participants read a sentence and determined whether the sentence made sense or not (e.g., "The prosecutor's dish was lost because it was not based on fact. ?"). Half of the sentences made sense while the other half did not. Nonsense sentences were made by simply changing one word (e.g., "dish" from "case") from an otherwise normal sentence. Participants were required to read the sentence and to indicate whether it made sense or not. After participants gave their response they were presented with a letter for 1 s. At recall, letters from the current set were recalled in the correct order by clicking on the appropriate letters. There were three trials of each list-length with list-length ranging from three to seven. The same scoring procedure as Ospan was used (see Redick et al., 2012; Unsworth et al., 2009 for more task details).

WMC composite. As the three complex span tasks showed acceptable internal consistency (α's ranging from .77–.82), we computed a composite WMC score for each participant using principal axis factoring and allowing the three tasks to load onto a single factor. The resulting factor loadings for operation span, symmetry span, and reading span were .72, .65, and .90, respectively. This factor score is used in all subsequent analyses involving WMC.

Psychomotor vigilance task. The psychomotor vigilance task (Dinges & Powell, 1985) was used as the primary measure of sustained attention. Participants were presented with a row of zeros on screen and after a variable amount of time the zeros began to count up. The participants' task was to press the spacebar as quickly as possible once the numbers started counting up. After pressing the spacebar the RT was left on screen for 1 s to provide feedback to the participants. Interstimulus intervals were randomly distributed and ranged from 1 s to 10 s in increments of 500 ms. The entire task lasted for 10 min for each individual (roughly 75 total trials).

Results

For all the RT results reported, false alarms (i.e., hitting the spacebar before the numbers started counting) were excluded. On average there were 3.24 (SD = 4.23) false alarms.[1] In addition, RTs that fell below 150 ms were excluded from all RT analyses.

Time-on-task analyses. First time-on-task effects were examined. RTs were grouped into five blocks with each block representing 2 min of task time. Consistent with previous work (Kribbs & Dinges, 1994; Parasuraman, 1986), RTs increased as a function of time-on-task indicating a vigilance decrement, $F(4, 640) = 30.94$, $MSE = 9485.18$, $p < .001$, partial $\eta^2 = .16$. Specifically, RTs increased on average by 98 *ms* from Block 1 to Block 5 and this increase was significantly different from zero, $t(160) = 12.87$, $p < .001$. Entering WMC as a covariate in an ANCOVA suggested a main effect of WMC, $F(1, 159) = 19.40$, $MSE = 43{,}673.04$, $p < .001$, partial $\eta^2 = .11$, in which high WMC individuals were faster overall than low WMC individuals ($r = -.33$). Importantly, there was also a significant WMC × Block interaction, $F(4, 636) = 4.64$, $MSE = 9274.44$, $p = .001$, partial $\eta^2 = .03$. As shown in Figure 3a, high and low WMC individuals demonstrated similar performance on Block 1, but low WMC individuals demonstrated a much steeper increase in RTs over blocks than high WMC individuals. Indeed, there was a correlation between the magnitude of the vigilance decrement (Block 5 minus Block 1) and WMC, $r = -.37$, $p < .001$, suggesting that low WMC individuals demonstrate larger vigilance decrements than high WMC individuals. Note, in order to illustrate the effects of interest with WMC, we present high (top 25% of WMC scorers) and low WMC (bottom 25% of WMC scorers) groups. For all analyses WMC was treated as continuous, rather than as arbitrary, discrete groups.

Interstimulus interval analyses. Next, we examined RTs as a function of ISI. Here we examined mean RT for 10 different ISIs ranging from 1–10 s with ISIs in an interval being averaged together. For example, ISIs of 1 s and 1.5 s were averaged together and ISIs of 2 s and 2.5 s were averaged together. Any missing values were replaced with the grand mean. Consistent with prior research (Niemi & Näätänen, 1981; Woodrow, 1914) there was an effect of ISI, $F(9, 1440) = 29.42$, $MSE = 9492.20$, $p < .001$, partial $\eta^2 = .16$, with the shortest ISIs being associated with the slowest RTs and longer ISIs being associated with the faster RTs. Entering WMC as a covariate in an ANCOVA suggested a main effect of WMC, $F(1, 159) = 21.05$, $MSE = 91{,}554.64$, $p < .001$, partial $\eta^2 = .12$. There was also a significant WMC × ISI interaction, $F(9, 1431) = 1.98$, $MSE = 9434.49$, $p = .038$, partial $\eta^2 = .01$. As shown in Figure 3b, the difference in RT between high and low WMC individuals was greatest at the shortest ISIs, with the smallest difference occurring at the longest ISI.

Quintile analyses. In our final analysis we more fully examined WMC differences in RT by examining the full distribution of RTs. Specifically, each individual's RTs were ranked ordered from fastest to slowest. Next, these rank ordered responses were placed into five bins such that 20% of each individual's responses were placed into each bin. These quintiles were then averaged across participants in order to examine potential WMC differences in the distributions. Consistent with the other results there was a main effect of WMC, $F(1, 159) = 19.19$, $MSE = 47{,}215.06$, $p < .001$, partial $\eta^2 = .11$. There was also a significant WMC × Quintile interaction, $F(4, 636) = 11.30$, $MSE = 20{,}761.85$, $p < .001$ partial $\eta^2 = .07$. As shown in Figure 3c, high and low WMC individuals demonstrated smaller differences for the fastest RTs (Quintiles 1 and 2), however there were large differences for the slowest quintiles. Specifically, RT differences in the first quintile were slight, $r = -.17$, $p = .035$, but increased for the last quintile, $r = -.28$, $p < .001$ Thus, RT differences on the psychomotor vigilance task between high and low WMC individuals were primarily localized to the slow tail of the distribution consistent with prior research (Unsworth et al., 2010; Unsworth, Redick, Spillers, & Brewer, 2012; Wiemers & Redick, 2018).[2]

We also examined the number of lapses (i.e., RTs > 500 ms). On average there were 9.89 (SD = 9.65) lapses per participant and the number of lapses correlated with WMC, $r = -.37$, $p < .001$ with low WMC individuals experiencing more lapses of attention than high WMC individuals. Additionally, it should be noted that the number of lapses significantly correlated with the Quintile 5, $r = .76$, $p < .001$, suggesting that these two variables largely measure the same thing.

Discussion

The results from Experiment 1 suggested a number of interesting findings. Specifically, low WMC individuals demonstrated larger time-on-task (vigilance decrement) effects than high WMC individuals. Although high and low WMC individuals demon-

[1] Note in Experiment 1 false alarms were correlated with WMC ($r = -.21$, $p = .009$). In Experiment 2 WMC was not related to false alarms in either the varied condition ($r = -.14$, $p = .14$) or the fixed condition ($r = -.08$, $p = .38$). In Experiment 3 WMC was not related to false alarms in either the Fixed 2 condition ($r = .08$, $p = .36$) or the Fixed 8 condition ($r = .06$, $p = .51$). In Experiment 4 false alarms were not correlated with WMC ($r = -.02$, $p = .72$).

[2] Note we also examined variability in RTs with the coefficient of variation and found overall similar results with WMC related to the coefficient of variation ($r = -.20$, $p = .01$). This is not surprising given that the slowest 20% of trials is highly correlated with the coefficient of variation ($r = .90$, $p < .001$).

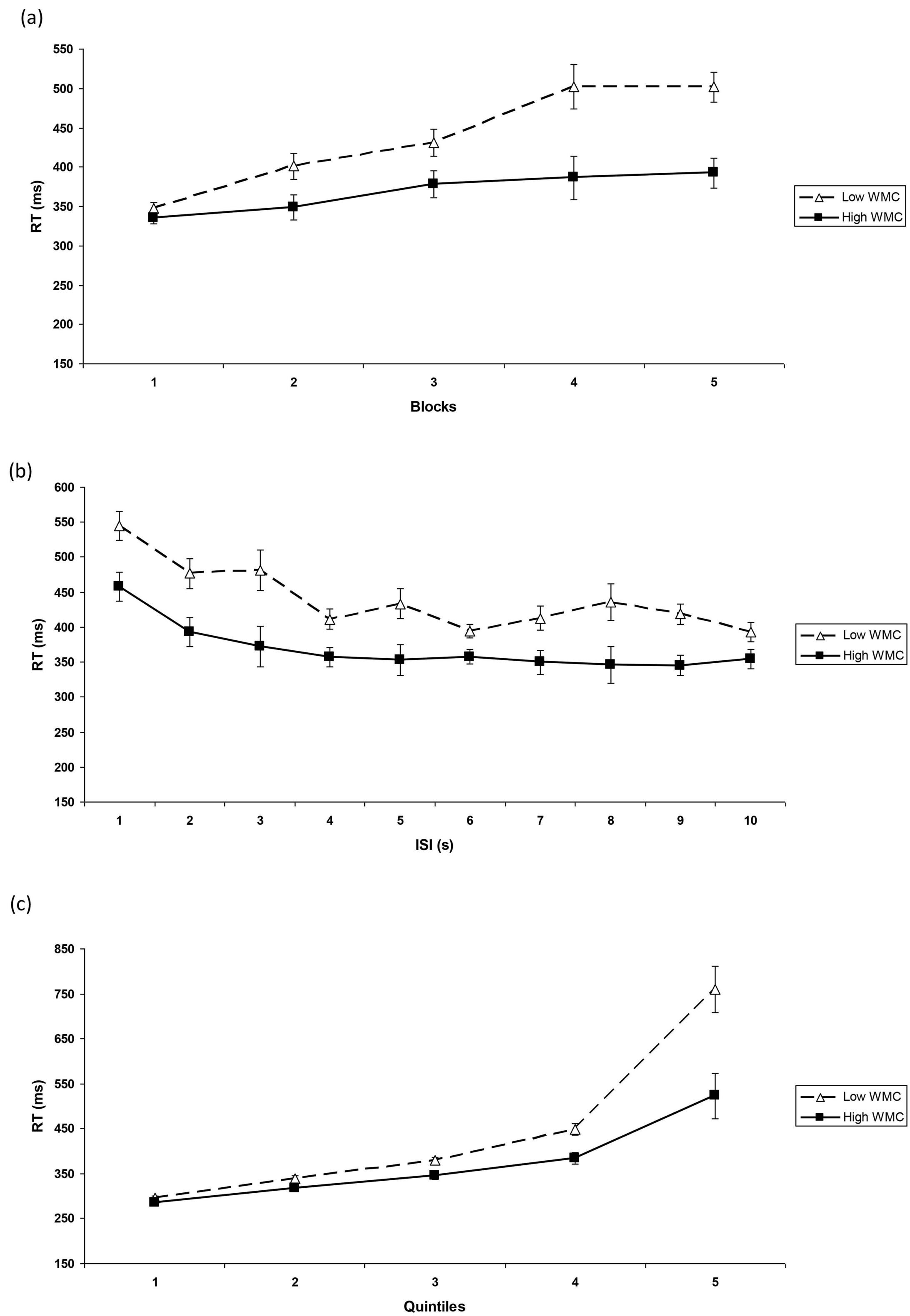

Figure 3. (a) Time-on-task effects as a function of working memory capacity (WMC) in Experiment 1. (b) Interstimulus interval effects as a function of working memory capacity (WMC) in Experiment 1. (c) Quintile plots as a function of working memory capacity (WMC) in Experiment 1. RT = reaction time. Error bars reflect one standard error of the mean.

strated similar performance early in the task, low WMC individuals demonstrated larger decrements in performance as time-on-task increased than high WMC individuals. These results support the hypothesis that part of the reason that low WMC individuals perform more poorly on measures of sustained attention is because they are less able to sustain the same high level of intensity as high WMC individuals across blocks of trials. Examining ISI effects similarly suggested an interaction with WMC. Specifically, although there were clear RT differences, with high WMC individuals being faster than low WMC individuals, this effect seemed largest for the shortest ISIs. These results seem consistent with the notion that low WMC individuals are slower to activate the task goal than high WMC individuals and that at a relatively short ISI, low WMC individuals are not yet in a heightened state of readiness resulting in worse performance. As ISI increases, however, low WMC individuals have sufficient time to activate the task goal to a similar extent as high WMC individuals, thereby reducing performance differences. Although the results are consistent with this hypothesis, it should be noted that the overall interaction effect was quite small accounting for only 1% of the variance. Thus, the evidence supporting differences in how quickly a task goal can be activated was fairly weak. Finally, examining the full distribution of RTs suggested that WMC differences were not across the board, but rather were primarily localized to the slowest trials. These results seem to go against possibilities suggesting that differences between high and low WMC individuals should result in a shift in the entire distribution (such as predicted by differences in the strength of goal activation or any basic speed of processing account). Rather, these results are more in line with a lapses of attention hypothesis suggesting that high and low WMC individuals perform equivalently on most trials, but that low WMC individuals experience more lapses of attention on a subset of trials than high WMC individuals. Indeed, there was a robust correlation between WMC and a putative measure of lapses of attention on the psychomotor vigilance task. Overall the results from Experiment 1 are consistent with several hypotheses of WMC differences in sustained attention.

Experiment 2

The results from Experiment 1 suggested a number of differences between high and low WMC individuals in sustained attention performance. Experiment 2 was conducted to better tease apart these differences. In this experiment participants again performed the three complex span measures of WMC along with two versions of the psychomotor vigilance task. Specifically, participants performed the standard psychomotor vigilance task with variable ISIs along with a version of the psychomotor vigilance task in which the ISI was always fixed at 2 s (i.e., the numbers always counted up after 2 s). A key aspect of sustained attention tasks is the uncertainty of when the signal will occur (Jennings & van der Molen, 2005; Woodrow, 1914). With a variable ISI the demands on intrinsic alertness (and the intensity of attention) are high because participants must activate and maintain the task goal at a high level (i.e., maintain readiness) in order to rapidly press the spacebar once the numbers begin counting. A fixed temporal structure in which the stimulus always occurs at the same time, however, requires less focused attention and typically results in better overall performance on sustained attention tasks (Langner & Eickhoff, 2013; Shaw, Finomore, Warm, & Matthews, 2012; Unsworth, Robison, & Miller, 2018). Rather than needing to maintain intrinsic alertness throughout the entire interval, participants can ramp up attention and preparation in line with the occurrence of the stimulus (based on their time estimation abilities). Thus, the psychomotor vigilance task with a fixed ISI should be less attention demanding resulting in weaker correlations with WMC than the more standard psychomotor vigilance task.

Furthermore, with a relatively short ISI not only can participants anticipate when the stimulus will occur, but fast pacing of the task should also promote more task engagement and fewer lapses of attention between trials. This notion is consistent with prior research on goal-neglect which suggests that task pacing influences goal maintenance abilities (De Jong, Berendsen, & Cools, 1999). That is, in a fast paced task attention should be tightly focused on the task goal resulting in better performance and fewer lapses of attention. Thus, if the relation between WMC and sustained attention is partially due to differences in lapses of attention, we should see not only a reduction in the number of lapses in the fixed ISI condition, but we should also see a reduced (and perhaps nonsignificant) relation with WMC. Additionally, if differences arise due to high WMC individuals ability to maintain the task goal over a lengthy interval compared with low WMC individuals, then when the ISI is fixed at 2 s WMC differences should disappear. If, however, WMC differences are due to differences in how quickly participants can activate the task goal, then we should still see a correlation with WMC and of a similar magnitude as is seen in the varied condition given that in Experiment 1 the largest differences seemed to occur for the shortest ISIs (1–2 s). Finally, if differences are due to differences in goal activation strength, then regardless of the particular ISI we should still see WMC differences (and of a similar magnitude as those found in the varied ISI condition) if low WMC individuals cannot activate the task goal to the same level as high WMC individuals. Thus, Experiment 2 provides a means of not only replicating the basic findings from Experiment 1, but also adjudicating between the various possible reasons for the relation with WMC.

Method

Participants. A total of 126 participants were recruited from the subject-pool at the University of Oregon. Data was collected over one full academic quarter. Ten participants were excluded for having missing WMC data and six participants were excluded because they only completed one version of the psychomotor vigilance task leaving a final sample of 110 participants with full data. Participants were between the ages of 18 and 35 and received course credit for their participation. Each participant was tested individually. None of the participants participated in any of the other experiments.

Materials and procedure. After signing informed consent, all participants completed operation span (Ospan) task, symmetry span (Symspan) task, reading span (Rspan) task, and two versions of the psychomotor vigilance task. Order of the two psychomotor vigilance tasks was counterbalanced across participants. The five tasks were completed in a 2-hr session, during which participants completed other cognitive ability tasks including delayed free recall and antisaccade which were irrelevant to the present investigation.

Tasks.

WMC tasks. Same as Experiment 1

WMC composite. The resulting factor loadings for operation span, symmetry span, and reading span were .76, .61, and .81, respectively.

Psychomotor vigilance task. In the varied ISI condition the psychomotor vigilance task was the same as Experiment 1. In the fixed ISI condition the ISI was always fixed to 2 s.

Results

For all the RT results reported false alarms were excluded. In the varied condition there were on average 2.44 ($SD = 3.40$) false alarms. However, in the fixed condition participants averaged 10.14 ($SD = 10.95$) false alarms. The difference across conditions was significant, $t(109) = 8.30$, $p < .001$ In addition, RTs that fell below 150 ms were excluded from all RT analyses.

Time-on-task analyses. First time-on-task effects were examined. The data were submitted to a 2 (ISI Condition: Varied vs. Fixed) × 5 (Block) ANOVA. There was a main effect of ISI condition, $F(1, 109) = 208.95$, $MSE = 5795.88$, $p < .001$, partial $\eta^2 = .66$, in which RTs were faster in the fixed condition ($M = 324$ *ms*, $SE = 4.5$) than in the varied condition ($M = 390$ ms, $SE = 5.1$). There was also a main effect of block, $F(4, 436) = 26.80$, $MSE = 1096.94$, $p < .001$, partial $\eta^2 = .20$, with RTs generally increasing over blocks. Critically, there was a ISI Condition × Block interaction, $F(4, 436) = 30.11$, $MSE = 907.04$, $p < .001$, partial $\eta^2 = .22$. Examining each ISI condition separately suggested that there was a significant time-on-task effect in the varied condition, $F(4, 436) = 40.12$, $MSE = 1403.72$, $p < .001$, partial $\eta^2 = .27$, in which RT increased by roughly 57 ms from Block 1 to Block5. However, in the fixed condition there was not a significant time-on-task effect, $F(4, 436) = .64$, $MSE = 600.26$, $p = .631$, partial $\eta^2 = .006$, with the RT difference between Block 1 and Block 5 being less than 1 ms.

Adding WMC as a covariate in an ANCOVA suggested that the main effect of WMC was not quite significant, $F(1, 108) = 3.18$, $MSE = 19{,}304.16$, $p = .08$, partial $\eta^2 = .03$. Furthermore, WMC did not interact with ISI condition, $F(1, 108) = .04$, $MSE = 5847.37$, $p = .842$, partial $\eta^2 = .000$, or block, $F(4, 432) = .74$, $MSE = 808.68$, $p = .57$, partial $\eta^2 = .007$. The WMC × ISI Condition × Block interaction was also not significant, $F(4, 432) = 1.57$, $MSE = 902.35$, $p = .18$, partial $\eta^2 = .01$. Thus, unlike Experiment 1 there was not strong evidence for a relation between WMC and time-on-task effects. Shown in Figure 4 are the time-on-task effects as a function of WMC and ISI condition. Examining the vigilance decrement (Block 5 minus Block 1) for each condition suggested a not quite significant relation with WMC in the varied condition, $r = -.17$, $p = .08$ and a nonsignificant relation for the fixed condition, $r = .04$, $p = .66$.

Interstimulus interval analyses. Next, we examined RTs as a function of ISI in the varied condition to see if the results would replicate Experiment 1. There was an effect of ISI, $F(9, 981) = 76.15$, $MSE = 1850.63$, $p < .001$, partial $\eta^2 = .41$, with the shortest ISIs being associated with the slowest RTs and the longest ISIs being associated with the fastest RTs. Entering WMC as a covariate in an ANCOVA suggested no main effect of WMC, $F(1, 108) = 2.60$, $MSE = 26{,}438.71$, $p = .11$, partial $\eta^2 = .02$. Consistent with Experiment 1 there was a significant WMC × ISI interaction, $F(9, 972) = 1.96$, $MSE = 1834.42$, $p = .040$, partial $\eta^2 = .02$, in which WMC differences were largely localized to the shortest ISIs.

Quintile analyses. Next the full RT distributions were analyzed for each condition in a 2 (ISI Condition: Varied vs. Fixed) × 5 (Quintile) ANOVA. There was a main effect of ISI condition, $F(1, 109) = 205.25$, $MSE = 5875.36$, $p < .001$, partial $\eta^2 = .65$, with faster RTs in the fixed than in the varied condition. There was a main effect of quintile as would be expected, $F(4, 436) = 527.60$, $MSE = 2253.43$, $p < .001$, partial $\eta^2 = .83$. There was also a ISI Condition × Quintile interaction, $F(4, 436) = 60.51$, $MSE = 1009.28$, $p < .001$, partial $\eta^2 = .36$, suggesting that the overall distribution for the fixed condition was faster and there was reduction in the slow tail of the distribution compared with the varied condition.

Entering WMC in as a continuous covariate in an ANCOVA suggested that the main effect of WMC was not quite significant, $F(1, 108) = 3.09$, $MSE = 19{,}213.1$, $p = .08$, partial $\eta^2 = .03$. The WMC × ISI Condition was not significant, $F(1, 108) = .04$, $MSE = 5927.79$, $p = .85$, partial $\eta^2 = .000$. However, there was a significant WMC × Quintile interaction, $F(4, 432) = 4.97$, $MSE = 2174.15$, $p = .001$, partial $\eta^2 = .04$. Critically, there was also a significant WMC × ISI Condition × Quintile interaction, $F(4, 432) = 2.78$, $MSE = 993.11$, $p = .027$, partial $\eta^2 = .03$. Examining each ISI condition separately suggested that there was a significant WMC × Quintile interaction in the varied condition, $F(4, 432) = 5.06$, $MSE = 2384.36$, $p = .001$, partial $\eta^2 = .05$. As shown in Figure 5a, WMC differences were primarily localized to the slowest quintile replicating Experiment 1. However, in the fixed ISI condition the WMC × Quintile interaction was not significant, $F(4, 432) = 1.91$, $MSE = 782.9$, $p = .108$, partial $\eta^2 = .02$. As shown in Figure 5b, WMC differences even at the slowest quintile were not significant.

We also examined the number of lapses (i.e., RTs > 500 ms). On average there were 7.93 ($SD = 8.02$) lapses in the varied condition and 4.89 ($SD = 8.85$) lapses in the fixed condition, which was significantly different $t(109) = 3.43$, $p = .001$, suggesting that the number of lapses were significantly reduced with a fixed ISI. The number of lapses in the varied condition correlated with WMC, $r = -.19$, $p = .04$, but the correlation was not significant in the fixed condition, $r = -.07$, $p = .44$. These results are broadly consistent with the overall results from the full RT distribution analyses suggesting that WMC differences arose in the slowest trials in the varied condition, but these differences were reduced and eliminated in the fixed condition.

Discussion

The results from Experiment 2 were largely consistent with Experiment 1 when considering the varied condition. WMC interacted with ISI suggesting that WMC differences were largest at the shortest ISIs. Additionally, WMC interacted with quintile suggesting that WMC differences were largely localized to the slowest trials. Likewise, WMC correlated with number of lapses. The only real difference occurred when examining time-on-task effects. Whereas there was a strong time-on-task relation with WMC in Experiment 1, the relation was not quite significant (and much weaker) in Experiment 2. Exam-

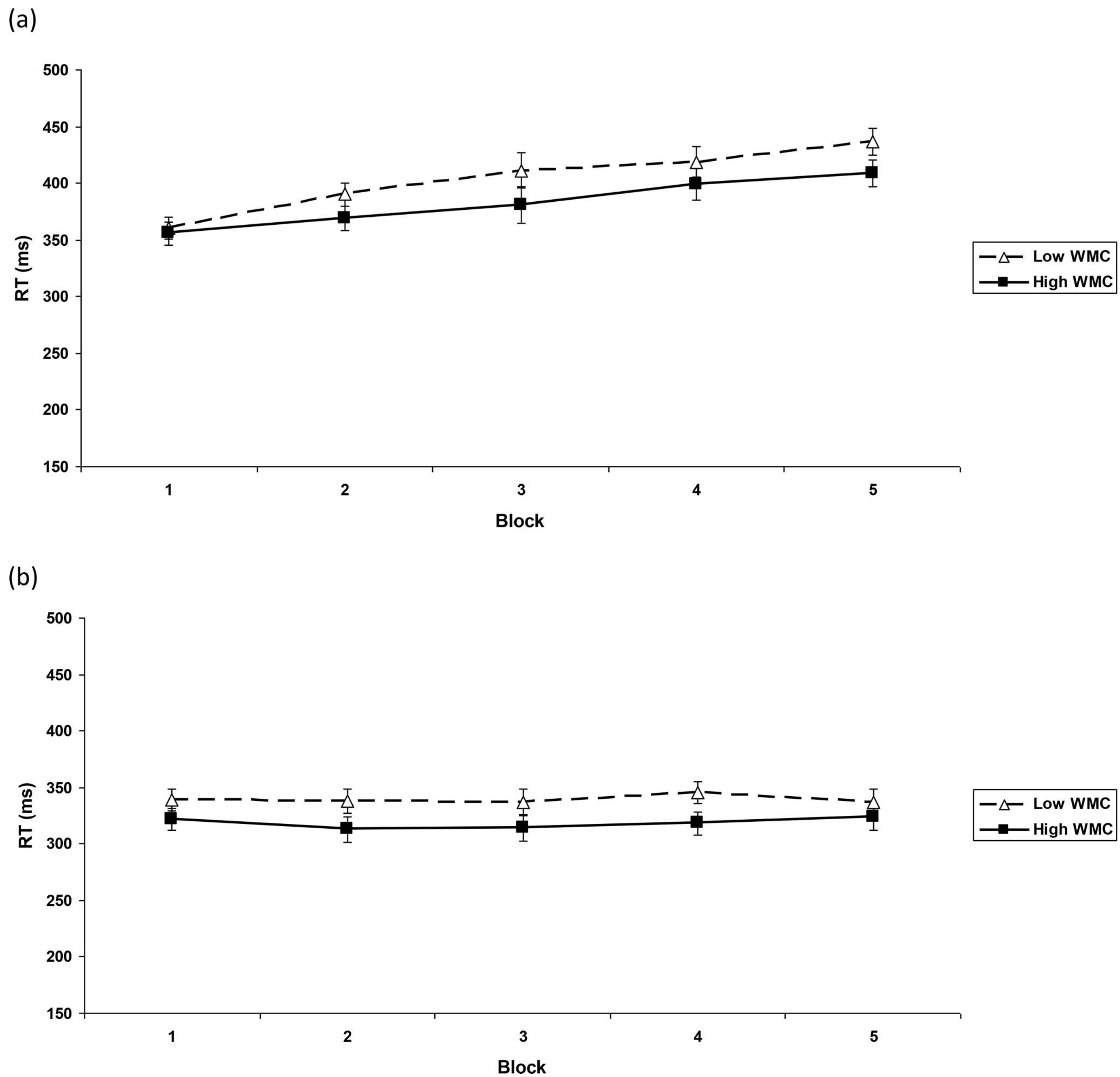

Figure 4. (a) Time-on-task effects as a function of working memory capacity (WMC) in the varied condition in Experiment 2. (b) Time-on-task effects as a function of working memory capacity (WMC) in the fixed at 2 s condition in Experiment 2. RT = reaction time. Error bars reflect one standard error of the mean.

ining the fixed condition, however, suggested that WMC was no longer related to performance. Specifically, WMC was not related to time-on-task effects, did not interact with quintile, and was not related to the number of lapses. Thus, by fixing the ISI at 2 s we were able to eliminate WMC differences in the psychomotor vigilance task. As noted above, by fixing the ISI at 2 s we theoretically reduced the need for intrinsic alertness as participants always knew when the stimulus would occur, and thus eliminated WMC differences. Furthermore, and consistent with prior research (De Jong et al., 1999) by fixing the ISI at 2 s we also likely reduced goal maintenance requirements across trials leading to a reduction in the number of lapses of attention. These results are consistent with the notion that WMC differences in sustained attention are largely due to differences in the consistency of the intensity of attention with low WMC individuals experiencing more lapses than high WMC individuals when the demands on intrinsic alertness are high. Reducing situations where lapses of attention occur reduced the relation with WMC to near zero. Although the results are consistent with the lapses of attention hypothesis, they are generally not consistent with the other hypotheses. For example, if WMC differences are due to differences in the ability to activate the

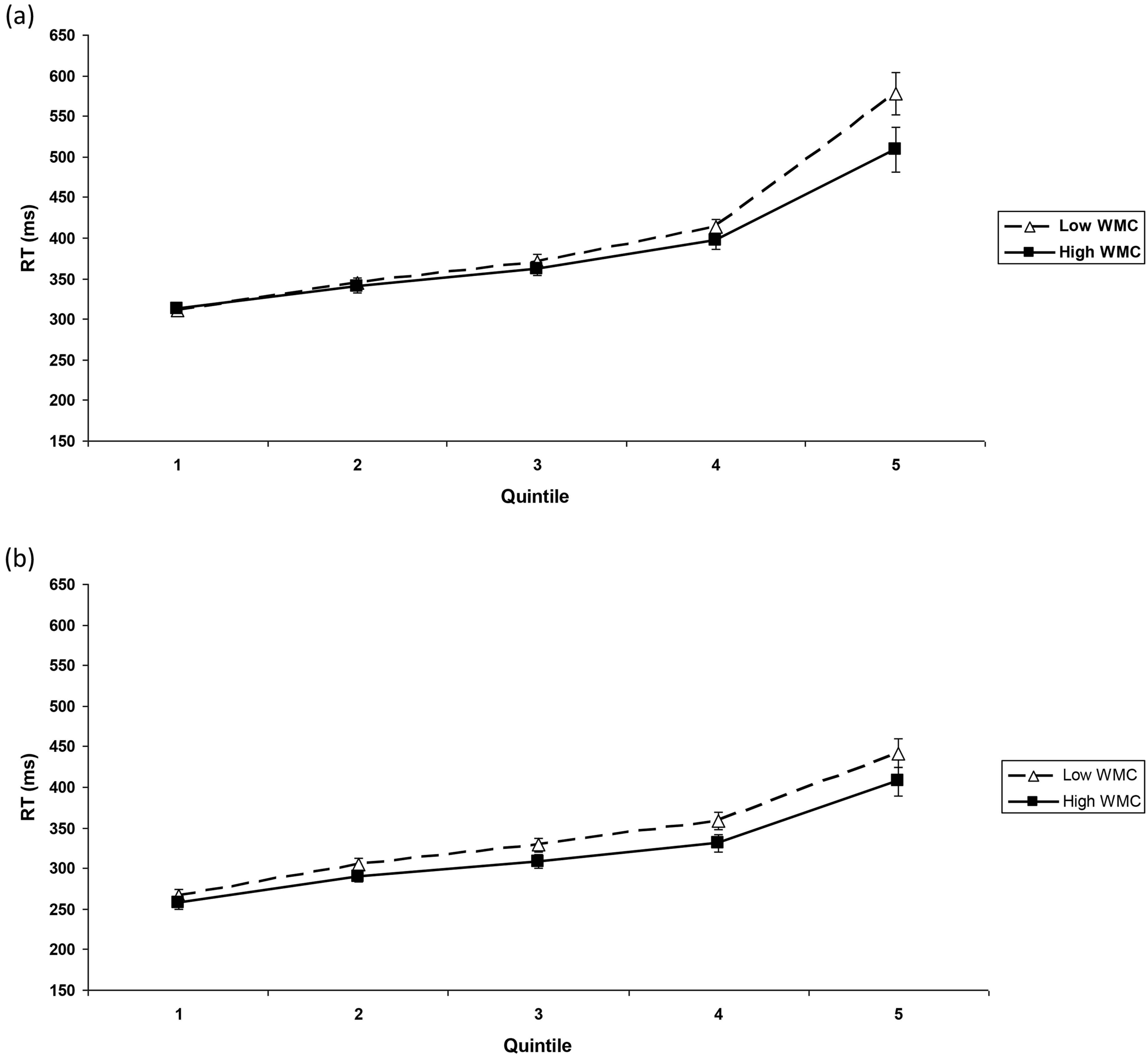

Figure 5. (a) Quintile plots as a function of working memory capacity (WMC) in the varied condition in Experiment 2. (b) Quintile plots as a function of working memory capacity (WMC) in the fixed at 2 s condition in Experiment 2. RT = reaction time. Error bars reflect one standard error of the mean.

task goal to the same level, then we should have seen WMC differences in both conditions and these differences should have been reflected in all quintiles. This was clearly not the case. If WMC differences were due to differences in how quickly the task goal could be activated, then we should have still seen differences when the ISI was fixed at 2 s given that Experiment 1 suggested that ISIs around 1–2 s resulted in the largest WMC differences. However, rather than maintaining or increasing the relation with WMC, the fixed ISI condition reduced the correlation with WMC. Similarly, if WMC differences were due to differences in the ability to sustain attention across the entire duration of the task we should have seen WMC relations with time-on-task effects consistent with Experiment 1. However, although there were clear time-on-task effects in the varied condition, this did not interact with WMC and the correlation between WMC and the vigilance decrement was not quite significant. Overall, these results seem most consistent with the notion that WMC differences in sustained attention are largely the result of differences in the consistency of the intensity of attention.

Experiment 3

The results from Experiment 2 suggested that having a fixed ISI reduced WMC differences. In Experiment 3 we examine whether any fixed interval will work or whether only a short ISI will lead to reduced WMC differences. In this experiment participants again performed the same three complex span WMC measures and two versions of the psychomotor vigilance task. One version was the fixed at 2 s ISI version from Experiment 2 and the other version was a fixed at 8 s ISI task. If fixing the ISI at any specific interval is enough to reduce intrinsic alertness we should see that there are no differences between the two conditions in terms of time-on-task effects, RT distributions, or the number of lapses. Furthermore, both conditions should lead to reduced and nonsignificant relations with WMC. However, if the fixed at 2 s ISI reduces the need for intrinsic alertness because participants can accurately estimate when the stimulus will occur within a trial and because goal-neglect is reduced trial-to-trial then only here should WMC differences be eliminated. For example, in reviewing simple RT results up to that point, Woodrow (1914) and others suggested that the maximum amount of time that attention could be maintained in a state of readiness was around 2 s and that longer durations resulted in worse performance because attention needed to be refreshed. In fact, Woodrow (1914) commented that "a longer period than 2 s allows more time than is needed and so affords a chance for wandering of the attention" (p. 50). Thus, in the fixed at 8 s ISI it should be much harder to maintain a high level of attention during the long ISI resulting in more task disengagement than the short ISI. Furthermore, and consistent with De Jong et al. (1999) the long ISI condition should result in more task disengagement across trials as participants can take task-contingent time-outs (Shaw et al., 2012). Indeed, prior research has suggested that task pacing has a strong influence on mind-wandering rates (Antrobus, 1968; Giambra, 1995; Grodsky & Giambra, 1990–1991), in which fast paced tasks should promote on-task behaviors, whereas slow paced tasks should promote mind-wandering and task disengagement. Thus, during both tasks we intermittently presented participants with thought probes to ascertain whether they were currently on-task or whether they were mind-wandering. If WMC differences are due to differences in lapses of attention (partially due to mind-wandering) we should see WMC differences in the condition that promotes more lapses and more mind-wandering compared with the condition where lapses and mind-wandering are reduced.

Furthermore, like the prior experiment, the current experiment provides us with an additional opportunity to disentangle the other hypotheses regarding the relation between WMC and performance. Specifically, if WMC differences are due to how quickly one can activate the task goal we should see large WMC differences in the fixed at 2 s condition because low WMC individuals presumably do not have sufficient time to activate the task goal. In the fixed at 8 s ISI condition, however, low WMC individuals should have plenty of time to activate the task goal leading to no WMC differences. However, if differences are due to the ability to maintain the task goal during the lengthy delay, then the opposite pattern of results should occur with WMC differences occurring in the 8 s ISI, but not at the 2 s ISI. If WMC differences are due to differences in the ability to fully activate the task goal then we should see differences in both ISI conditions given that low WMC individuals should be impaired overall regardless of the specific ISI. Furthermore, if WMC differences are due to differences in the ability to sustain attention across the task WMC differences should interact with time-on-task.

Method

Participants. A total of 149 participants were recruited from the subject-pool at the University of Oregon. Data was collected over one full academic quarter. Six participants were excluded for having excessive RTs on at least one version of the psychomotor vigilance task leaving a final sample of 143 participants with full data. Participants were between the ages of 18 and 35 and received course credit for their participation. Each participant was tested individually. None of the participants participated in any of the other experiments.

Materials and procedure. After signing informed consent, all participants completed operation span (Ospan) task, symmetry span (Symspan) task, reading span (Rspan) task, and two versions of the psychomotor vigilance task. Order of the two psychomotor vigilance tasks was counterbalanced across participants. The five tasks were completed in a 2-hr session, during which participants completed other cognitive ability tasks including a choice RT task and digit RT task which were irrelevant to the present investigation.

Tasks.

WMC tasks. Same as Experiment 1

WMC composite. The resulting factor loadings for operation span, symmetry span, and reading span were .89, .49, and .76, respectively.

Psychomotor vigilance task. In the Fixed 2 ISI condition the ISI was always fixed to 2 s. In the Fixed 8 ISI condition the ISI was always fixed to 8 s. Participants performed 80 trials in each version of the psychomotor vigilance task.

Thought probes. During the psychomotor vigilance task participants were periodically presented with thought probes asking them to classify their immediately preceding thoughts. Participants received 12 probes periodically during the task. We used the same thought probes as McVay and Kane (2012a) and Unsworth and McMillan (2013) which asked participants to press one of six keys to indicate what they were thinking just prior to the appearance of the probe. Specifically, participants saw:

What were you just thinking about?

1. The current task.
2. My performance on the task or how long it is taking.
3. A memory from the past.
4. Something in the future.
5. Current state of being.
6. Other.

During the instructions participants were given specific instructions regarding the different categories. Responses 3–6 were classified as mind wandering.

Results

For all the RT results reported, false alarms were excluded. In the Fixed 2 condition participants averaged 4.25 (SD = 3.95) false alarms and in the Fixed 8 condition participants averaged 3.06 (SD = 3.08) false alarms, and this difference was significant,

$t(142) = 4.23$, $p < .001$. In addition, RTs that fell below 150 ms were excluded from all RT analyses.

Time-on-task analyses. First time-on-task effects were examined. RTs were grouped into five blocks with 16 trials per block. The data were submitted to a 2 (ISI Condition: Fixed 2 vs. Fixed 8) × 5 (Block) ANOVA. There was a main effect of ISI condition, $F(1, 142) = 115.90$, $MSE = 5410.36$, $p < .001$, partial $\eta^2 = .45$, in which RTs were faster in the Fixed 2 condition ($M = 326$ *ms*, $SE = 4.2$) than in the Fixed 8 condition ($M = 369$ *ms*, $SE = 4.8$). There was also a main effect of block, $F(4, 568) = 12.93$, $MSE = 959.55$, $p < .001$, partial $\eta^2 = .08$, with RTs generally increasing over blocks. Critically, there was a ISI Condition × Block interaction, $F(4, 568) = 23.74$, $MSE = 901.72$, $p < .001$, partial $\eta^2 = .14$. Examining each ISI condition separately suggested that there was a significant time-on-task effect in the Fixed 8 condition, $F(4, 568) = 29.27$, $MSE = 1014.85$, $p < .001$, partial $\eta^2 = .17$, in which RT increased by roughly 37 ms from Block 1 to Block 5. There was also an effect in the Fixed 2 condition, $F(4, 568) = 4.05$, $MSE = 819.42$, $p = .003$, partial $\eta^2 = .03$. However, here RT demonstrated a quadratic trend ($p < .001$) in which RTs initially went down across blocks and then came back up at Block 5. The difference between Block 1 and Block 5 was roughly 6 ms. Whereas the Fixed 8 condition demonstrated a standard time-on-task effect, RTs did not increase in the Fixed 2 condition consistent with Experiment 2.

Adding WMC in as a covariate in an ANCOVA suggested that there was a main effect of WMC, $F(1, 141) = 4.79$, $MSE = 23{,}070.11$, $p = .03$, partial $\eta^2 = .03$. The WMC × ISI Condition interaction was not quite significant, $F(1, 141) = 3.32$, $MSE = 5323.58$, $p = .071$, partial $\eta^2 = .02$. Neither the WMC × Block, $F(4, 564) = 1.69$, $MSE = 954.89$, $p = .15$, partial $\eta^2 = .01$, nor the WMC × ISI Condition × Block interaction were significant, $F(4, 564) = .47$, $MSE = 905.081$, $p = .76$, partial $\eta^2 = .003$. Consistent with Experiment 2 there was not strong evidence for a relation between WMC and time-on-task effects. Shown in Figure 6 are the time-on-task effects as a function of WMC and ISI condition. Examining the vigilance decrement (Block 5 minus Block 1) for each condition suggested no significant relation with WMC in either condition (Fixed 2: $r = -.04$, $p = .66$; Fixed 8: $r = -.11$, $p = .18$).

Quintile analyses. Next the full RT distributions were analyzed for each condition in a 2 (ISI Condition: Fixed 2 vs. Fixed 8) × 5 (Quintile) ANOVA. There was a main effect of ISI condition, $F(1, 142) = 173.83$, $MSE = 6318.39$, $p < .001$, partial $\eta^2 = .55$, with faster RTs in the Fixed 2 condition than in the Fixed 8 condition. There was a main effect of quintile as would be expected, $F(4, 568) = 435.35$, $MSE = 2906.93$, $p < .001$, partial $\eta^2 = .79$. There was also an ISI Condition × Quintile interaction, $F(4, 568) = 19.01$, $MSE = 1151.28$, $p < .001$, partial $\eta^2 = .12$, suggesting that the overall distribution for the Fixed 2 condition was faster and there was reduction in the slow tail of the distribution compared with the Fixed 8 condition.

Entering WMC in as a continuous covariate in an ANCOVA suggested there was a main effect of WMC, $F(1, 141) = 5.61$, $MSE = 26{,}449.19$, $p = .02$, partial $\eta^2 = .04$. The WMC × ISI condition was not significant, $F(1, 141) = 1.19$, $MSE = 6310.01$, $p = .28$, partial $\eta^2 = .008$. The WMC × Quintile interaction was also not significant, $F(4, 564) = 1.23$, $MSE = 2902.28$, $p = .29$, partial $\eta^2 = .009$. Critically, there was a significant WMC × ISI Condition × Quintile interaction, $F(4, 564) = 3.54$, $MSE = 1131.05$, $p = .007$, partial $\eta^2 = .02$. Examining each ISI condition separately suggested that there was a significant WMC × Quintile interaction in the Fixed 8 condition, $F(4, 564) = 2.63$, $MSE = 2049.43$, $p = .033$, partial $\eta^2 = .02$. As shown in Figure 7b, WMC differences were largest in the slowest quintiles replicating the prior experiments. However, in the Fixed 2 ISI condition the WMC × Quintile interaction was not significant, $F(4, 564) = 1.10$, $MSE = 1983.89$, $p = .36$, partial $\eta^2 = .008$, replicating the same condition from Experiment 2. As shown in Figure 7a, WMC differences at the slowest quintile were not significant.

We also examined the number of lapses (i.e., RTs > 500 ms). On average there were 6.00 ($SD = 7.38$) lapses in the Fixed 8 condition and 2.90 ($SD = 5.13$) lapses in the Fixed 2 condition, which was significantly different $t(142) = 6.53$, $p < .001$, suggesting that the number of lapses were significantly reduced in the Fixed 2 condition compared with the Fixed 8 condition. Unlike the prior experiments, the number of lapses did not significantly correlate with WMC in either condition (Fixed 2: $r = -.11$, $p = .19$; Fixed 8: $r = -.15$, $p = .07$).

Thought probes. Our final set of analyses examined self-reports of mind-wandering from the thought probes. The data were submitted to a 2 (ISI Condition: Fixed 2 vs. Fixed 8) × 5 (Block) ANOVA. There was a main effect of ISI condition, $F(1, 142) = 65.56$, $MSE = .941$, $p < .001$, partial $\eta^2 = .32$, in which mind-wandering rates were greater in the Fixed 8 ($M = .34$, $SD = .25$) than in the Fixed 2 condition ($M = .16$, $SD = .23$). There was a significant main effect of block, $F(4, 568) = 24.81$, $MSE = .61$, $p < .001$, partial $\eta^2 = .15$, suggesting that mind-wandering rates generally increased with block. Additionally, there was a significant ISI Condition × Block interaction, $F(4, 568) = 4.25$, $MSE = .60$, $p = .002$, partial $\eta^2 = .03$, suggesting that mind-wandering rates increased more across blocks in the Fixed 8 condition than in the Fixed 2 condition.

Adding WMC in as a covariate in an ANCOVA suggested that there was a main effect of WMC, $F(1, 141) = 5.076$, $MSE = 2.39$, $p = .03$, partial $\eta^2 = .04$, in which low WMC individuals experienced more mind-wandering than high WMC individuals, $r = -.19$, $p = .03$. Furthermore, the WMC × ISI Condition interaction was significant, $F(1, 141) = 4.33$, $MSE = .92$, $p = .04$, partial $\eta^2 = .03$, suggesting that mind-wandering rates were correlated with WMC in the Fixed 8 condition, $r = -.24$, $p = .004$, but not in the Fixed 2 condition, $r = -.07$, $p = .40$. Neither the WMC × Block, $F(4, 564) = 1.23$, $MSE = .60$, $p = .30$, partial $\eta^2 = .009$, nor the WMC × ISI Condition × Block interaction were significant, $F(4, 564) = .79$, $MSE = .60$, $p = .53$, partial $\eta^2 = .006$.

Discussion

Consistent with the results from Experiment 2, there was no time-on-task effect when the ISI was fixed to 2 s and performance in the fixed at 2 s ISI condition was not related to WMC. Examining the fixed at 8 s ISI condition also suggested no relation between time-on-task and WMC. Importantly, there was interaction between quintile and WMC with the largest WMC differences occurring at the slowest quintile consistent with the varied ISI task in Experiments 1 and 2. Furthermore, examining mind-wandering rates via thought probes embedded in the psychomotor vigilance

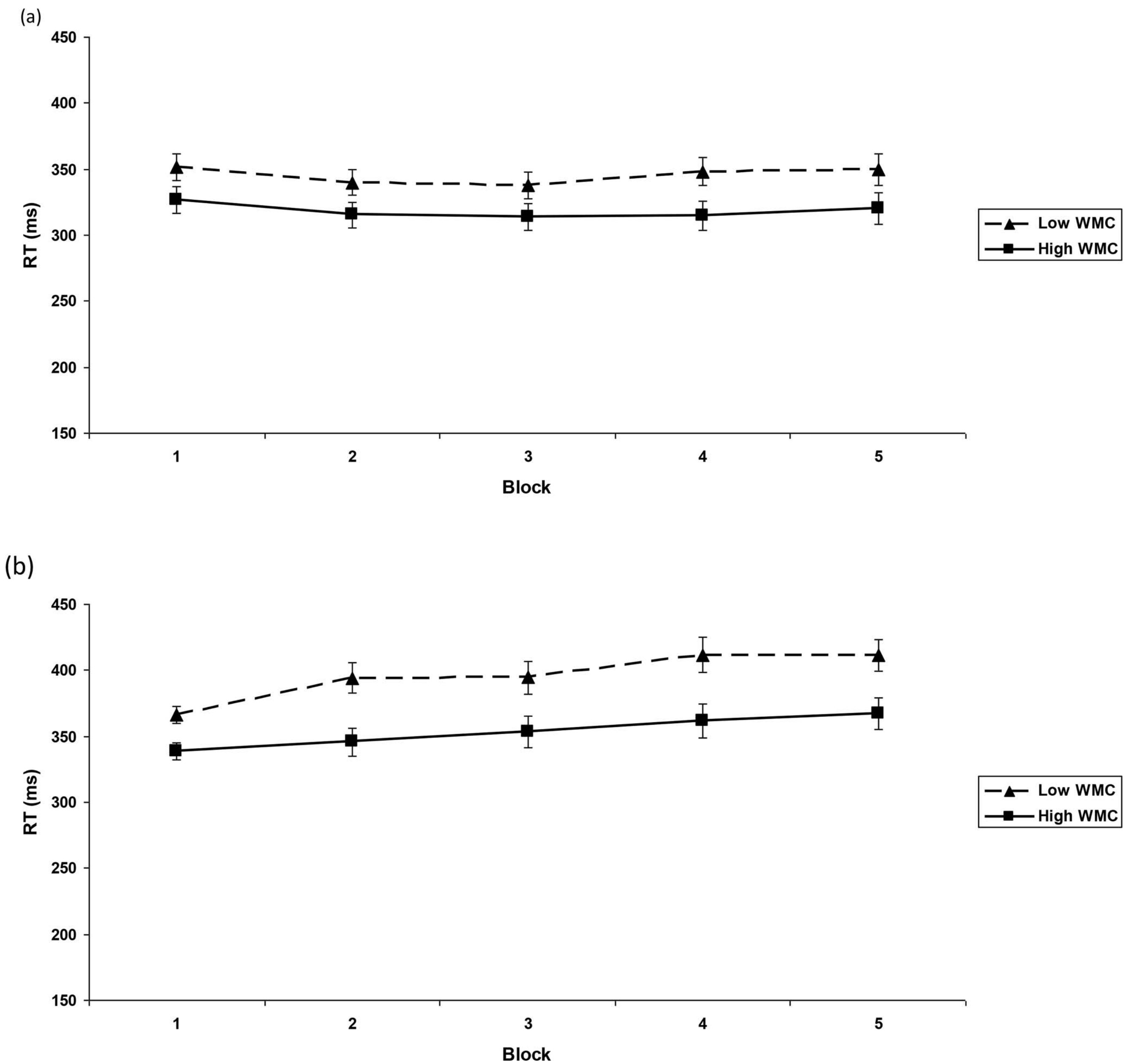

Figure 6. (a) Time-on-task effects as a function of working memory capacity (WMC) in the fixed at 2 s condition in Experiment 3. (b) Time-on-task effects as a function of working memory capacity (WMC) in the fixed at 8 s condition in Experiment 3. RT = reaction time. Error bars reflect one standard error of the mean.

task suggested that there was more mind-wandering in the fixed at 8 s ISI condition than in the fixed at 2 s ISI condition. Importantly, mind-wandering rates in the 8 s ISI condition correlated with WMC, but mind-wandering rates in the 2 s ISI condition did not. These results are consistent with the notion that a primary reason for the relation between WMC and sustained attention performance is due to differences in intrinsic alertness in which low WMC individuals experience more lapses of attention than high WMC individuals because they cannot consistently ramp up the intensity of attention on a trial-by-trial basis. In situations where the demands on intrinsic alertness are reduced both within a trial and across trials (i.e., the fixed at 2 s ISI) there are fewer lapses of attention, less reported mind-wandering, and reduced WMC differences. However, in situations where demands on intrinsic alertness are high both within and across trials (i.e., the fixed at 8 s ISI), there are more lapses of attention, greater reports of mind-wandering, and robust WMC differences. Furthermore, and consistent with Experiment 2, the results were less consistent with the other possibilities. As such the current results provide support for the hypothesis that the WMC to sustained attention relation is primarily due to differences in the consistency of the intensity of attention.

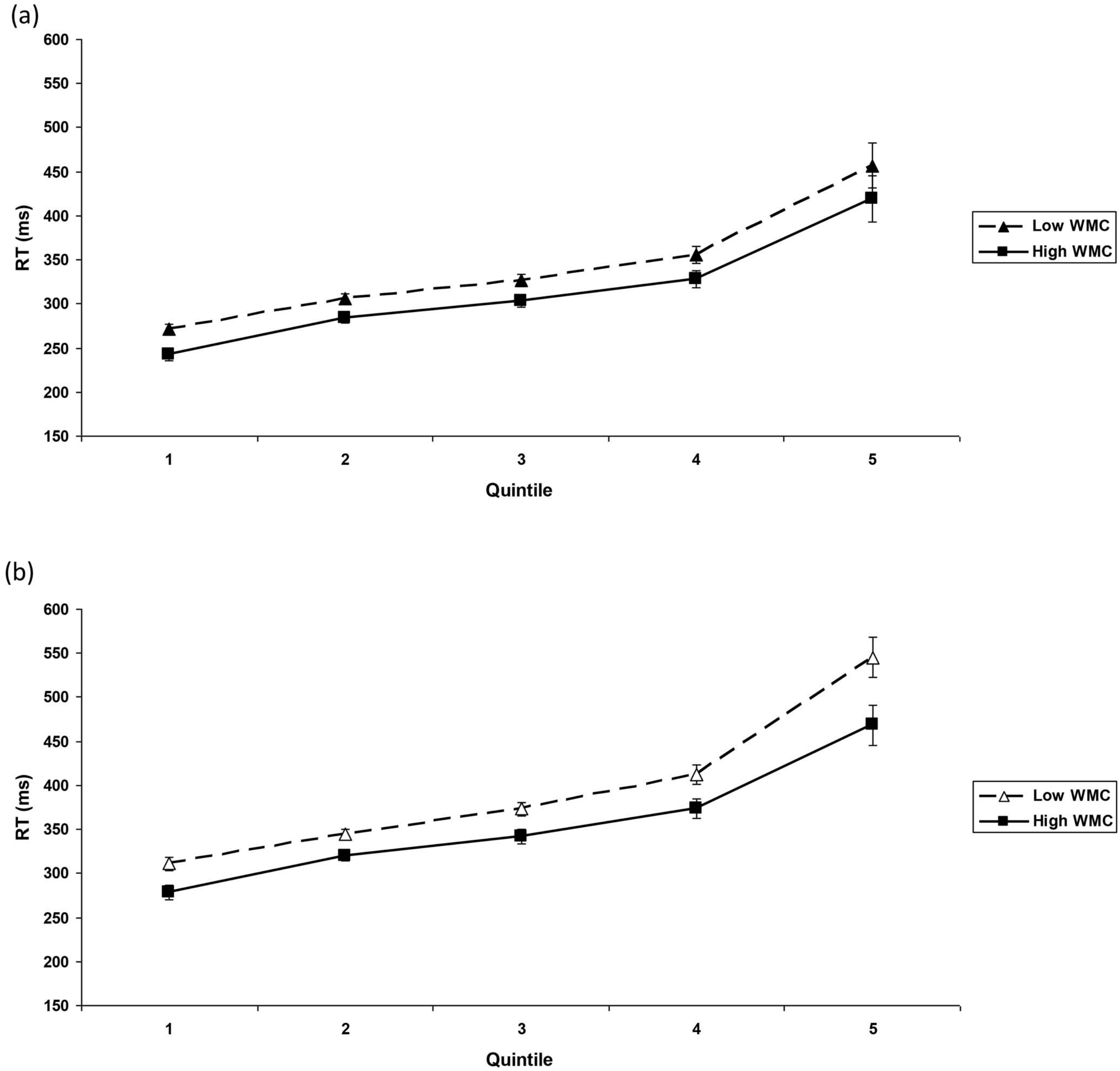

Figure 7. (a) Quintile plots as a function of working memory capacity (WMC) in the fixed at 2 s condition in Experiment 3. (b) Quintile plots as a function of working memory capacity (WMC) in the fixed at 8 s condition in Experiment 3. RT = reaction time. Error bars reflect one standard error of the mean.

Experiment 4

Experiment 4 was conducted in order to further examine relations between WMC and sustained attention. In particular, there were inconsistent results across the prior three experiments in terms of the relation between WMC and time-on-task. In order to better examine these relations and in order to ensure that we had enough power to detect small relations we examined data from a recent large scale study from our laboratory in which over 300 participants performed the three complex span WMC tasks and the standard psychomotor vigilance task from Experiment 1. Similarly, given generally small relations between WMC and ISI in Experiments 1 and 2 we examined those effects as well. Thus, with a much larger sample size we should be able to better detect and determine potentially small relations between WMC and aspects of sustained attention performance. Another potential reason for the current WMC to sustained attention relations found in the prior experiments is that perhaps low WMC individuals are simply not motivated to perform the tasks compared with high WMC individuals resulting in more mind-wandering and overall worse performance on the psychomotor vigilance task. Although prior research has found that WMC and motivation both account for performance on various tasks, WMC and motivation tend not to be correlated and account for separate variance in task performance (e.g., Heitz, Schrock, Payne, & Engle, 2008; Robison & Unsworth, 2018; Unsworth & McMillan, 2013). Thus, in order to better test any potential role of motivation, following the psychomotor vigilance task participants were asked about their motivation to perform the task. Finally, similar to Experiment 3 participants were periodically presented with thought probes during the psychomotor vigilance task to get an idea of how off-task thinking and mind-wandering are related to performance and to WMC.

Method

Participants. A total of 335 participants were recruited from the subject-pool at the University of Oregon. Data was collected over three full academic quarters. Thirteen participants were excluded for having missing data on several tasks, two were excluded for having excessive RTs on the psychomotor vigilance task, and one participants was excluded for having a large number of false alarms on the first two blocks of trials leaving a final sample of 319 participants with full data. Participants were between the ages of 18 and 35 and received course credit for their participation. Each participant was tested individually. The current data are from Robison, Miller, and Unsworth (2017) which is a large-scale individual differences study on mind-wandering. None of the current results are presented in that article.

Materials and procedure. After signing informed consent, all participants completed Ospan, Symspan, Rspan, and the same version of the psychomotor vigilance task from Experiments 1 and 2. The tasks were completed in a 2-hr session, during which participants completed other cognitive ability tasks including antisaccade, Stroop, visual search, N-back, breath counting, and digit RT.

Tasks.

WMC tasks.

Ospan. Participants completed a shortened version of the task from Experiment 1 in which there were two trials per set size for a total score of 50.

Symspan. Participants completed a shortened version of the task from Experiment 1 in which there were two trials per set size for a total score of 28.

Rspan. Participants completed a shortened version of the task from Experiment 1 in which there were two trials per set size for a total score of 50.

WMC composite. The resulting factor loadings for operation span, symmetry span, and reading span were .73, .60, and .72, respectively.

Psychomotor vigilance task. Same as Experiment 1 except that during the task participants were presented with thought probes periodically.

Thought probes. Response options for the thought probes were based on prior investigations of mind-wandering and other thought content (i.e., external distraction, task-related interference; mind-blanking; Robison et al., 2017; Robison & Unsworth, 2018; Stawarczyk, Majerus, Maj, Van der Linden, & D'Argembeau, 2011; Unsworth & Robison, 2016b; Ward & Wegner, 2013). After 20% of trials, probes appeared asking participants to report their current thoughts. Specifically, they saw a screen that said:

Please characterize your current conscious experience.

1. I am totally focused on the current task.
2. I am thinking about my performance on the task.
3. I am distracted by sights/sounds/physical sensations.
4. I am intentionally thinking about things unrelated to the task.
5. I am unintentionally thinking about things unrelated to the task.
6. My mind is blank.

Responses 3–6 were averaged into an off-task composite.

Motivation question. Following the psychomotor vigilance task, participants were asked how motivated they felt to perform well on the task along with questions about task difficulty, overall alertness, and interest in the task (Robison & Unsworth, 2018). Specifically, participants were asked "How motivated were you to perform well on the task?"; "How interested were you in the task?"; "How easy/difficulty did you find the task?"; and "How alert do you feel right now?"

Participants responded on a 1 to 6 scale. responses to the motivation question were used as our measure of motivation.

Results

For all the RT results reported false alarms were excluded. On average there were 3.45 ($SD = 5.01$) false alarms. In addition, RTs that fell below 150 ms were excluded from all RT analyses.

Time-on-task analyses. First time-on-task effects were examined. Similar to the prior experiments, RTs increased as a function of time-on-task, $F(4, 1272) = 96.79$, $MSE = 1792.21$, $p < .001$, partial $\eta^2 = .23$. Specifically, RTs increased on average by 55 ms from Block 1 to Block 5. Entering WMC as a covariate in an ANCOVA suggested a main effect of WMC, $F(1, 317) = 25.24$, $MSE = 11{,}475.39$, $p < .001$, partial $\eta^2 = .07$, in which high WMC individuals were faster overall than low WMC individuals ($r = -.26$). Importantly, there was also a significant WMC × Block interaction, $F(4, 1268) = 4.53$, $MSE = 1772.54$, $p = .001$, partial $\eta^2 = .01$. As shown in Figure 8a, high and low WMC individuals demonstrated largely similar performance on Block 1, but low WMC individuals demonstrated a much steeper increase in RTs over blocks than high WMC individuals. There was a correlation between the magnitude of the vigilance decrement (Block 5 minus Block 1) and WMC, $r = -.18$, $p = .001$, suggesting that low WMC individuals demonstrated larger vigilance decrements than high WMC individuals.

Interstimulus interval analyses. Next, we examined RTs as a function of ISI. Consistent with the prior experiments there was an effect of ISI, $F(9, 2862) = 102.56$, $MSE = 31{,}341.08$, $p < .001$, partial $\eta^2 = .24$, with the shortest ISIs being associated with the slowest RTs and the longest ISIs being associated with the fastest RTs. Entering WMC as a covariate in an ANCOVA suggested a main effect of WMC, $F(1, 317) = 22.86$, $MSE = 22{,}368.41$, $p < .001$, partial $\eta^2 = .07$. There was also a significant WMC × ISI

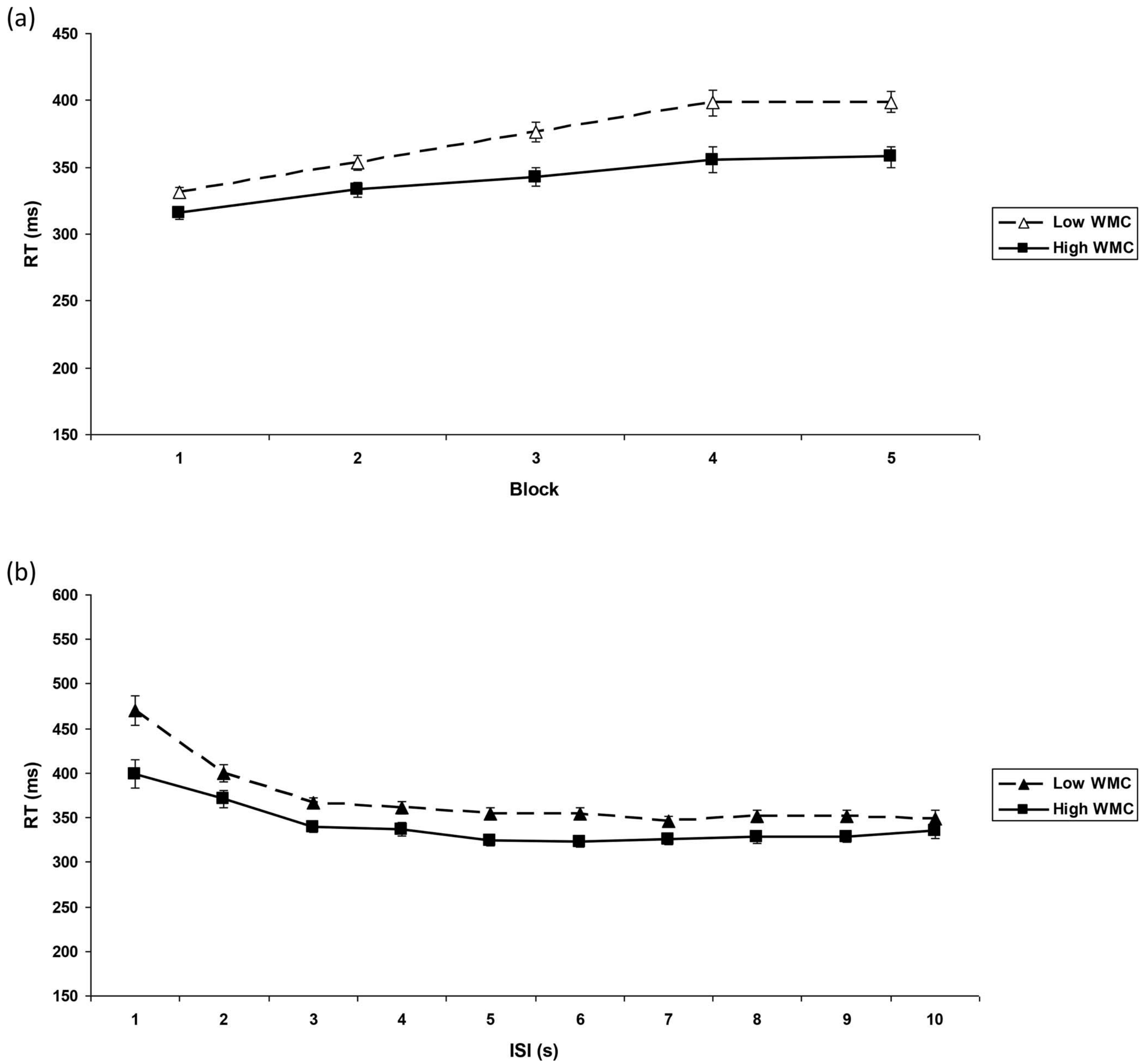

Figure 8. (a) Time-on-task effects as a function of working memory capacity (WMC) in Experiment 4. (b) Interstimulus interval effects as a function of working memory capacity (WMC) in Experiment 4. (c) Quintile plots as a function of working memory capacity (WMC) in Experiment 4. (d) Reaction times for trials before and after a lapse trial as a function of working memory capacity (WMC) in Experiment 4. RT = reaction time. Error bars reflect one standard error of the mean.

interaction, $F(9, 2853) = 2.75$, $MSE = 3123.85$, $p = .003$, partial $\eta^2 = .009$. As shown in Figure 8b, the difference in RT between high and low WMC individuals was greatest at the shortest ISIs, with the smallest difference occurring at the longest ISI. Although note that the effect size was very small accounting for approximately only 1% of the variance.

Quintile analyses. Next we examined WMC differences across the full RT distributions. There was a main effect of WMC, $F(1, 317) = 24.18$, $MSE = 10{,}317.57$, $p < .001$, partial $\eta^2 = .07$. There was also a significant WMC × Quintile interaction, $F(4, 1268) = 9.69$, MSE = 2462.99, $p < .001$ partial $\eta^2 = .03$. As shown in Figure 8c, RT differences in the slowest quintile were correlated with WMC, $r = -.22$, $p < .001$.

We also examined the number of lapses (i.e., RTs > 500 ms). On average there were 4.21 ($SD = 4.73$) lapses and the number of lapses correlated with WMC, $r = -.19$, $p = .001$.

Trials before and after a lapse. We also examined potential RT differences for trials before and after a lapse (RT greater than

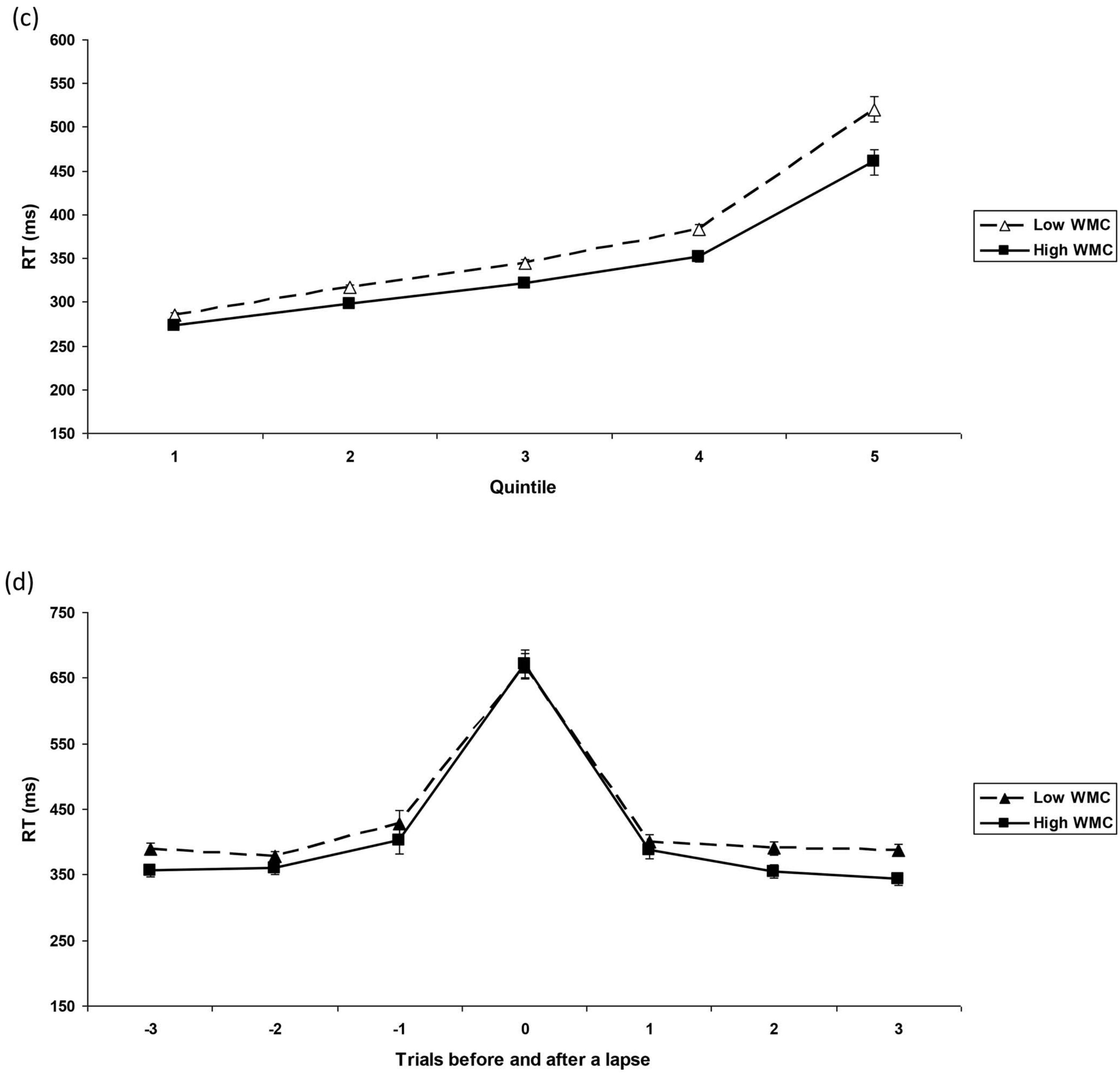

Figure. 8 (continued)

500 ms) trial. Bertelson and Joffe (1963) found that prior to lapse trials RTs tend to increase and that following a lapse trial RTs tended to quickly drop back down to average levels. To examine this we examined RTs on the three trials prior to a lapse trial, RTs on the lapse trial, and RTs on the three trials after a lapse trial. Note for these analyses there were only 255 participants available for analysis as some participants did not have any lapses. Consistent with Bertelson and Joffe (1963) there was a main effect of trial, $F(6, 524) = 468.52$, $MSE = 6945.67$, $p < .001$, partial $\eta^2 = .65$, in which RTs increased prior to a lapse and then quickly decreased following a lapse. Entering WMC in as a covariate suggested that the main effect of WMC was not quite significant, $F(1, 127) = 3.52$, $MSE = 37{,}040.29$, $p = .063$, partial $\eta^2 = .03$. Furthermore, WMC did not interact with trial, $F(6, 762) = 1.18$, $MSE = 7279.91$, $p = .32$, partial $\eta^2 = .009$. As shown in Figure 8d, high and low WMC individuals demonstrated largely similar patterns in RTs for trials before and after lapse trials and their lapse RT were similar. Thus, although high and low WMC individuals differed in the number of lapses, they did not differ in how they experienced lapses of attention.

Relations among the measures. Next we examined relations among WMC, self-reports of off-task thinking, self-reports of motivation, and aspects of sustained attention performance. Shown in Table 2 are the correlations. As can be seen, WMC was related

Table 2
Correlations Among All Measures in Experiment 4

Measure	1	2	3	4	5	6
1. WMC	—					
2. Off	−.04	—				
3. Motivation	.02	−.35*	—			
4. VigDec	−.18*	.17*	−.16*	—		
5. Slow	−.22*	.25*	−.21*	.68*	—	
6. Lapse	−.19*	.30*	−.24*	.58*	.87*	—

Note. WMC = working memory capacity; Off = off-task thinking reports in the psychomotor vigilance task; Motivation = motivation report in the psychomotor vigilance task; VigDec = vigilance decrement in the psychomotor vigilance task; Slow = slowest quintile in the psychomotor vigilance task; Lapse = number of lapses in the psychomotor vigilance task.
* Significant at the $p < .05$ level.

to the sustained attention measures, but not to self-reports of off-task thoughts or task motivation. These measures, however, were related to each other and with the sustained attention measures. Thus, although task motivation was related to performance on the sustained attention task, motivation did not mediate the relation between WMC and sustained attention. Indeed, partialling motivation out of the relations did not alter any of the WMC to sustained attention correlations.

Our final set of analyses examine whether the relation between WMC and time-on-task (vigilance decrement) was due to lapses of attention. The prior results suggest that WMC is more strongly related with indicators of lapses of attention (the slowest 20% of trials and the number of lapse trials) than measures of the vigilance decrement and both indicators of lapses are related to the vigilance decrement. Thus, it seems possible that the relation between WMC and the vigilance decrement is due to shared variance with lapses of attention. To examine this, we examined the partial correlation between WMC and the vigilance decrement controlling for the slowest 20% of trials or the number of lapses. Controlling for the slowest 20% of trials resulted in a reduction in the correlation ($pr = -.05$, $p = .37$) as did controlling for the number of lapses ($pr = -.10$, $p = .09$). These results suggest that although WMC was related to individual differences in the vigilance decrement, this relation was primarily due to shared variance with lapses of attention. Another way of examining this is to examine the WMC × Block interaction demonstrated previously, but now after excluding any lapse trials. That is, if the relation between WMC and the time-on-task effect is due to lapses of attention, then when lapse trials (RTs greater than 500 ms) are excluded, there should no longer be a significant WMC × Block interaction. This was indeed the case. When excluding lapse trials, there was still a main effect of block, $F(4, 1252) = 181.28$, $MSE = 334.55$, $p < .001$, partial $\eta^2 = .37$, with RTs increasing from Block 1 to Block 5 by roughly 35 ms. However, the WMC × Block interaction was no longer significant, $F(4, 1248) = .73$, $MSE = 334.83$, $p = .57$, partial $\eta^2 = .002$. Thus, the relation between WMC and the time-on-task effect seems to be due to individual differences in lapses of attention rather than differences in the ability to sustain attention across the entire task.

Discussion

The results from Experiment 4 largely replicated the results from the prior experiments (especially Experiment 1) using the same task. WMC interacted with time-on-task such that low WMC individuals demonstrated a steeper increase in RT across blocks than high WMC individuals. Additionally, there was a weak interaction between WMC and ISI with the largest WMC differences occurring at the shortest ISI. Furthermore, WMC interacted with quintile with the largest WMC differences occurring for the slowest RTs. Thus, utilizing a much larger sample size we were able to replicate the findings from Experiment 1. We extended these results by demonstrating that although WMC was negatively correlated with the overall number of lapses, high and low WMC individuals did not differ in how they experienced a lapse of attention and demonstrated that individual differences in motivation did not mediate the relation between WMC and each indicator of sustained attention performance. Finally, although WMC indicated weak (and somewhat inconsistent relations) with time-on-task effects, we found that the relation between WMC and the vigilance decrement was due to shared variance with lapses of attention. Once variance in lapses of attention was accounted for WMC no longer predicted the vigilance decrement.

General Discussion

In four experiments we examined the relation between WMC and sustained attention. In all four experiments participants performed multiple WMC measures along with the psychomotor vigilance task and multiple indicators of sustained attention were examined. Examining time-on-task effects suggested robust effects were found in the standard version of the psychomotor vigilance task with varied ISIs (Experiments 1, 2, and 4) along with a version where the ISI was fixed at 8 s (Experiment 3). Time-on-task effects were not found when the ISI was fixed at 2 s (Experiments 2 and 3) suggesting that when demands on preparatory processes and intrinsic alertness were low, time-on-task effects were eliminated (see also Lisper & Törnros, 1974). In terms of individual differences in WMC a number of findings emerged. Shown in Table 3 is a summary of the results across the four experiments in terms of the primary effects of interest and their relation with WMC. As seen in Table 3, WMC interacted with time-on-task in both Experiments 1 and 4, but not in Experiment

Table 3
Summary Across Experiments of Whether Working Memory Capacity Was Related to Each Indicator of Sustained Attention Performance

Experiment	Indicator: Time-on-task	ISI	Quintile	Lapse	Off-task thoughts
Exp. 1	Yes	Yes	Yes	Yes	—
Exp. 2 Varied	No	Yes	Yes	Yes	—
Exp. 2 Fixed 2	No	—	No	No	—
Exp. 3 Fixed 2	No	—	No	No	No
Exp. 3 Fixed 8	No	—	Yes	No	Yes
Exp. 4	Yes	Yes	Yes	Yes	No

Note. Dashes (—) indicates that the indicator was not examined.

2 using the same psychomotor vigilance task or in Experiment 3 when the ISI was fixed at 8 s. Thus, although there were robust time-on-task effects in each of these experiments and conditions, WMC was not always related to time-on-task effects.

In the varied ISI conditions of the psychomotor vigilance task we replicated prior research suggesting that RTs are longest with the shortest ISI (Jennings & van der Molen, 2005; Niemi & Näätänen, 1981; Woodrow, 1914). In terms of individual differences in WMC, ISI interacted with WMC in each experiment where the ISI was varied. Specifically, as shown in Table 3, in Experiments 1, 2, and 4 WMC interacted with ISI such that WMC differences where largest for the shortest ISI condition. In no case were WMC differences largest for the longest ISI condition. Furthermore, it should be noted that although ISI interacted with WMC in each experiment where ISI was varied, these effects tended to be small (E1 = approximately 1% of the variance; E2 = roughly 2% of the variance; E4 = slightly less than 1% of the variance). Thus, while consistent, these relations tended to be quite small.

Examining the full RT distribution suggested that in conditions where the ISI was fixed at 2 s the overall distributions were left-shifted indicating a change in the overall speed of responses and the slow tail of the distribution was reduced indicating that there was a reduction in the number of very slow responses. In terms of individual differences in WMC, quintile interacted with WMC in each experiment where the ISI was varied or when it was fixed at 8 s. In the fixed at 2 s ISI condition in Experiments 2 and 3, WMC no longer interacted with quintile suggesting no differences in the RT distributions for high and low WMC individuals in these conditions. Similarly, given strong relations between the number of lapses and the slowest 20% of trials, the number of lapses tended to correlate with WMC in most experiments.

Finally, when self-reports of mind-wandering and off-task thinking were assessed, these reports inconsistently correlated with WMC. Specifically, when the ISI was fixed at 2 s in Experiment 2 mind-wandering rates did not correlate with WMC. When the ISI was fixed at 8 s in the same experiment, mind-wandering rates did correlate with WMC. However, in Experiment 4 when ISI was varied, off-task thinking (a combination of mind-wandering, external distraction, and mind-blanking) did not correlate with WMC. Thus, there was inconsistent evidence for a relation between WMC and self-reports of off-task thinking.

A Cognitive-Energetic Account of Individual Differences in Working Memory Capacity and Sustained Attention

In the Introduction we proposed a cognitive-energetic model based on much prior theorizing (Cohen et al., 2004; Hockey, 1993, 1997, 2011, 2013; Kahneman, 1973; Sanders, 1983). In this model the amount of control is modulated by the current intensity of attention levels. When the intensity of attention is high, participants are fully engaged in the current experimental task leading to proper goal selection, goal activation, and goal maintenance. However, when the current intensity of attention levels are low, participants are not fully engaged in the current task leading to potential problems in goal selection (where other potent goals might be selected), weakened goal activation (where the current task goal might not be activated above other competing goals), and/or weakened goal maintenance (where the current task goal might not be maintained over a delay). Critically, we suggested that the relation between individual differences in WMC and sustained attention is due to normal variation in intrinsic alertness. That is, the relation between WMC and attention control (specifically sustained attention in the current study) likely results from individual differences in the ability to voluntarily control the intensity of attention on a moment-by-moment basis. Evidence in general support of this claim is the finding that when the ISI was varied (or fixed at a long interval) WMC correlated with performance. However, when the ISI was fixed at a short interval, WMC no longer correlated with performance. Theoretically, the varied ISI task places high demands on intrinsic alertness as the task goal will need to be selected and activated relatively quickly in case the stimulus appears early on in a short ISI trial. Furthermore, the task goal will need to be maintained at a high level (or quickly refreshed) for the duration of the trial on long ISI trials. Thus, one must be in a state of high readiness and must maintain that state for potentially several seconds. However, when the ISI is fixed at 2 s, demands on intrinsic alertness are much lower as attention needs to be ramped up at a predictable time. The current results suggest that the relation between WMC and sustained attention is partially the result of variation in intrinsic alertness.

Furthermore, we suggested that there are a number of potential ways that individual differences in intrinsic alertness can manifest in terms of goal-management processes. Specifically, it was noted that it is possible that low WMC individuals are unable to activate or energize the task goal to the same level as high WMC individuals leading to consistent impairments. By this account, high WMC individuals should respond more quickly than low WMC individuals on all trials as high WMC individuals are in a heightened state of readiness on each trial compared with low WMC individuals, resulting in overall faster RTs. However, as shown in Table 3 WMC interacted with quintile such that RT differences were localized to the slowest RTs rather than occurring for all RTs (even the fastest RTs). Thus, the current data seem inconsistent with the notion that high and low WMC individuals necessarily differ in the ability to activate the task goal to the same level. Recently, Meier et al. (2018) suggested a similar account of WMC differences in the antisacccade task. Specifically, examining the cue-delay interval (similar to ISI in the current study), Meier et al. (2018) found that high WMC individuals had higher accuracy rates than low WMC individuals at all cue-delay intervals. They suggested that these differences were partially due to differences the asymptote of goal activation processes whereby low WMC individuals could not activate the antisaccade goal to the same level as high WMC individuals. One problem with this conclusion, however, is that because they focused on accuracy it is not possible to really examine continuous and gradual differences when the outcome of each trial is binary (correct vs. incorrect). Examining RT, however, does provide a means of examining potential continuous differences in goal activation strength. It is possible that given clear differences between the psychomotor vigilance task and the antisaccade task that WMC differences in goal activation are present in the antisaccade, but not in the psychomotor vigilance task. Future research is needed to better examine the extent that WMC differences in the antisaccade are due to difference in goal activation processes.

Another potential way in which differences in the intensity of attention could manifest is as differences in how quickly the task goal can be activated/energized. By this account, low WMC individuals cannot activate the task goal as quickly as high WMC individuals resulting in slower RTs specifically on trials where the ISI is relatively short. As shown in Table 3, there was some support for this hypothesis as ISI interacted with WMC in each experiment where the ISI was varied and differences were largest at the shortest ISIs. However, there was also inconsistent evidence for this hypothesis, especially in Experiments 2 and 3 where ISI was fixed at 2 s. If WMC differences are due to how quickly the task goal can be activated we would expect that when the ISI is fixed at 2 s, WMC differences should be as large (if not larger) than when the ISI is varied. That is, with a constant short ISI, low WMC individuals should be slower on every trial to activate the task goal compared with high WMC individuals resulting in overall worse performance. However, as shown in Table 3, when the ISI was fixed at 2 s WMC no longer correlated with performance. Furthermore, if WMC differences are localized to the shortest ISIs, then when the ISI was fixed at 8 s there should be no WMC differences as 8 s should be plenty of time for low WMC individuals to activate the task goal to the same level as high WMC individuals. However, as shown in Table 3, when the ISI was fixed at 8 s WMC did correlate with performance. Thus, there is inconsistent evidence for the notion that WMC differences are due to differences in how quickly the task goal can be activated. Furthermore, when WMC did interact with ISI the effects were generally small. Thus, we acknowledge that it is possible that there may be small WMC differences in the speed of goal activation, or there may be differences only for a subset of WMC individuals (i.e., only some low WMC individuals have problems in how quickly the task goal can be activated). Furthermore, it is possible that WMC differences at the shortest ISIs in the standard version of the psychomotor vigilance task do not necessarily indicate that low WMC individuals cannot activate the task goal quickly, but rather that they typically do not activate the task goal early in the trial. That is, when the ISI varies from 1–10 s, on average the stimulus will occur around 5 s. Low WMC individuals may wait to begin ramping up the task goal based on when they expect the stimulus to occur, whereas high WMC individuals may activate the task goal early on and try to keep it maintained throughout the delay. Thus, the difference might be a result of strategic differences in when participants are willing to ramp up attention based on time-estimation abilities (i.e., Broadway & Engle, 2011a, 2011b).

Rather than differences being due to how quickly the task goal can be activated, another possibility that was suggested was that low WMC individuals can rapidly activate the task goal to the same extent as high WMC individuals, but they cannot maintain this activation over the course of the trial, resulting in worse performance on long ISI trials. However, as noted above, when ISI interacted with WMC the largest differences occurred for the shortest, but not longest ISIs. Thus, there was little evidence for this hypothesis. The only real evidence consistent with this hypothesis were the results from Experiment 3 when the ISI was fixed at 8 s. Here WMC did correlate with performance. Thus, it is possible that when the ISI was relatively long that low WMC individuals found it difficult to maintain attention on the task and were captured by potent internal thoughts. Indeed, in this condition mind-wandering rates were correlated with WMC, suggesting that low WMC individuals were more likely to have their attention hijacked by internal thoughts than high WMC individuals. This suggests that when the ISI is fixed at a relatively long interval; low WMC individuals find it more difficult to maintain attention on task than high WMC individuals.

Another potential reason for the relation between WMC and sustained attention that was suggested is that low WMC individuals are unable to maintain a high level of intrinsic alertness across the entire task than high WMC individuals. This predicts that there should be no WMC differences early in the task, but WMC differences should increase with time-on-task. As shown in Table 3, there was inconsistent evidence for this hypothesis. Specifically, WMC only interacted with time-on-task in Experiments 1 and 4. Furthermore, a detailed examination of the data from Experiment 4 suggested that the WMC to time-on-task relation was actually due to shared variance with the slowest RTs. When the slowest RTs were excluded, there were still robust time-on-task effects, but WMC no longer correlated with time-on-task. These results suggest that there may be small and inconsistent relations between WMC and time-on-task (which are largely due to the slowest RTs). As such, it does not seem like the relation between WMC and performance on sustained attention tasks is due to differences in the ability to sustain attention across blocks of trials.

The final account that was suggested for the relation between WMC and performance on sustained attention tasks is that WMC differences largely come down to lapses of attention whereby low WMC individuals experience more lapses of attention than high WMC individuals. Specifically, this account suggests that on most trials high and low WMC individuals have the same intensity of attention levels, but that low WMC individuals have more fluctuations in the intensity of attention (possibly due to differences in locus coeruleus-norepinephrine functioning; Unsworth & Robison, 2017b) than high WMC individuals. This account predicts that WMC differences should be localized to the slowest RTs and to other indicators of lapses. As shown in Table 3, the bulk of the evidence is consistent with this hypothesis. In each experiment WMC interacted with RT quintile with WMC differences largely being localized to the slowest RTs. Furthermore, when the ISI was fixed at 2, the number of lapses were drastically reduced and WMC was no longer related to the slowest RTs (Experiments 2 and 3). Thus, WMC was only related to performance in conditions where lapses of attention were frequent. Additionally, in Experiment 3 mind-wandering rates in the fixed at 8 s ISI condition (but not the fixed at 2 s ISI condition) were related to WMC. These results are broadly consistent with the notion that individual differences in WMC are partially due to fluctuations in the intensity of attention.

Although the bulk of the evidence is in support of this hypothesis, two pieces of evidence are inconsistent with the lapses/fluctuations hypothesis. One, in Experiment 3 the number of lapses did not quite correlate with WMC. However, it should be noted that the number of lapses and the slowest 20% of RTs were highly correlated, $r = .92$, $p < .001$, both were related to mind-wandering rates ($r = .37$, $p < .001$ in both cases), and both the slowest 20% of trials and mind-wandering rates were related to WMC. Second, in Experiment 4 self-reports of off-task thinking were not related to WMC. It is not clear why off-task reports were not related with WMC as we and others have seen this relation several times (Kane et al., 2016; McVay & Kane, 2012a; Unsworth & McMillan, 2014;

Unsworth & Robison, 2017a). Thus, on the whole the evidence is very much in line with the notion that the relation between WMC and sustained attention are largely due to differences in the consistency of the intensity of attention. These lapses can occur early on in a trial resulting in a delay in activating the task goal and thus, very slow RTs on short ISI trials. These lapses might also occur later in trial whereby the task goal is not sufficiently activated/maintained and other competing goals hijack attention away from the primary task.

These results suggest a key reason for the relation between WMC and sustained attention is due to individual differences in lapses of attention. Furthermore, this variation in lapses of attention should have an impact not only on performance on sustained attention (and other attention control) measures, but also on measures of WMC. That is, those individuals who experience frequent lapses of attention should experience lapses on a wide variety of tasks that require intrinsic alertness, and this should partially determine the relation among those measures. Indeed, prior research has demonstrated that lapses of attention and mind-wandering occur on WMC measures and partially account for individual differences in those measures (Adam, Mance, Fukuda, & Vogel, 2015; Mrazek et al., 2012; Robison & Unsworth, 2019; Unsworth & Robison, 2016a). At the same time, performance on WMC tasks is not solely due to variation in lapses of attention, and thus the relation between WMC and performance on various tasks is likely due to a number of factors (Unsworth, 2016). Importantly, the current model provides a means of investigating variation in intrinsic alertness and lapses and how this variation is related to WMC and attention control abilities more broadly.

Just Processing Speed?

A possible alternative explanation for the current results is that the relation between WMC and performance on the psychomotor vigilance task is simply due to differences in processing speed. High WMC individuals are faster at processing information than low WMC individuals and this occurs throughout the entire RT distribution. However, because there is a lower limit on RTs, it is possible that the absolute magnitude of differences are smaller for the fastest RT quintiles and increase for the slowest quintiles. This would predict small differences at the fastest quintiles, but larger differences at the slowest quintiles in line with the current results. Importantly, however, a speed of processing view predicts that even though the absolute magnitude of differences changes, the rank ordering of individuals does not. Thus, a processing speed account predicts that the correlation between WMC and each RT quintile should be roughly the same (Salthouse, 1993, 1998, 2000). Furthermore, a processing speed account predicts that the same information is present in the fastest and slowest RTs such that there should not be any unique variance in the slowest RTs once the fastest RTs are accounted for. Conversely, a lapses of attention account predicts that the correlation between WMC and each RT quintile should tend to increase and furthermore there should be unique variance associated with the slowest RTs once the fastest RTs are taken into account (Salthouse, 1993). That is, the slowest RTs should provide unique information that is not present in the fastest RTs. Salthouse (1993, 1998) examined these notions with aging samples and found that although the absolute magnitude of differences increased with each successive RT bin, the correlations with age were roughly equivalent across each RT bin (the correlations actually decreased in Salthouse, 1998). Furthermore, age was no longer related to the slowest RTs after accounting for the fastest RTs. As such, Salthouse (1993, 1998) suggested that there was little to no evidence in support for a lapses of attention account for aging differences, but rather that the evidence supported a speed of processing account.

To examine these issues in the current data we investigated the correlation between WMC and each RT quintile for the experiments where the standard psychomotor vigilance task was used. Shown in Table 4 are the correlations. As can be seen, the correlations tend to increase from Quintiles 1–4 and then there is a slight decrease for Quintile 5. The one exception to this trend was Experiment 4 of the current study where the correlations were roughly equivalent across quintiles. Combining data from Experiments 1, 2, and 4 suggest the same overall pattern. To further examine these issues, we reanalyzed data from five prior studies that used the same psychomotor vigilance task and measures of WMC. Again, the correlations tended to increase. Combining data from all of the experiments ($N = 1{,}551$) also suggested a general increase in the correlations. Furthermore, in each individual dataset and in the combined dataset there was a significant WMC ×

Table 4
Correlations Between Working Memory Capacity and Each Reaction Time Quintile in the Current Experiments and Prior Data

Dataset	Q1	Q2	Q3	Q4	Q5	prQ5.Q1
Experiment 1	−.17*	−.30*	−.32*	−.39*	−.28*	−.24*
Experiment 2 Varied	−.01	−.06	−.09	−.13	−.20*	−.24*
Experiment 4	−.25*	−.25*	−.26*	−.26*	−.22*	−.14*
Experiments 1–4	−.17*	−.22*	−.25*	−.29*	−.22*	−.17*
Unsworth and Spillers (2010)	−.09	−.13	−.14	−.15	−.26*	−.24*
Unsworth and McMillan (2014)	−.20*	−.25*	−.25*	−.26*	−.26*	−.21*
Unsworth and McMillan (2017)	−.06	−.09	−.12	−.14*	−.14*	−.12
Unsworth and Robison (2017a)	−.13	−.15	−.16*	−.19*	−.27*	−.25*
Robison and Unsworth (2018)	−.14*	−.17*	−.19*	−.20*	−.14*	−.08
Combined	−.13*	−.17*	−.20*	−.23*	−.20*	−.17*

Note. Q = reaction time quintile; prQ5.Q1 = correlation between working memory capacity and Quintile 5 after partialling out Quintile 1.
* Significant at the $p < .05$ level.

Quintile interaction. Thus, unlike aging results which have suggested similar relations across RT quintiles, the current data suggests that the correlations with WMC (in young adults) tend to increase.

We next examined whether the slowest RTs would share unique variance with WMC once the fastest RTs were taken into account. Shown in Table 4 are the partial correlations between WMC and Quintile 5, controlling for Quintile 1. As can be seen, in all but two data sets, Quintile 5 shared unique variance with WMC after controlling for Quintile 1. Furthermore, in the combined dataset WMC and Quintile 5 shared unique variance after accounting for Quintile 1. Unlike the relations seen in prior aging work (Salthouse, 1993, 1998), in the current analyses WMC demonstrated unique relations with the slowest RTs in line with a lapses of attention account and inconsistent with a speed of processing account. Thus, although some of the relation between WMC and RTs on the psychomotor vigilance task may be due to processing speed (as seen in the correlations with Quintile 1), much of this relation seems to be due to lapses of attention. Indeed, although Quintile 5 shared unique variance with WMC after controlling for Quintile 1, doing the opposite analysis suggested very little relation between WMC and Quintile 1 after controlling for Quintile 5 ($pr = .06$, $p = .03$, $N = 1{,}551$). These results are broadly consistent with a lapses of attention account and inconsistent with a basic speed of processing account.

Conclusions

In the current study we clarified the relation between WMC and sustained attention. We extended our prior locus coeruleus-norepinephrine account of WMC and attention control (Unsworth & Robison, 2017b) by proposing a cognitive-energetic model of attention control and used this model to account for the relation between WMC and sustained attention performance. Across four experiments it was found that WMC was consistently related to the slowest RTs in the psychomotor vigilance task in conditions where the ISI was varied or was fixed at a long interval. WMC was not related to performance when the ISI was fixed at a short interval. These results suggest that the individual differences in WMC and sustained attention are partially the result of normal variation in intrinsic alertness whereby low WMC individuals are less able to consistently control the intensity of attention than high WMC individuals. Other possible reasons for the relation between WMC and sustained attention such as differences in goal activation, speed of goal activation, goal maintenance during a trial, or sustaining goal maintenance across the duration of the task were associated with weaker and inconsistent evidence. Collectively we suggest that the current cognitive-energetic account (along with similar accounts suggesting that preparatory attention processes are important Braver, 2012; Kane & Engle, 2002, 2003), can be useful for elucidating the nature of the relation between WMC and sustained attention (and attention control more broadly).

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