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Individual Differences in Lapses of Sustained Attention: Oculometric Indicators of Intrinsic Alertness

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Two experiments examined individual differences in lapses of sustained attention. Participants performed variants of the psychomotor vigilance task while pupillary responses and fixations were recorded. Examining pupillary responses during the interstimulus interval in both experiments suggested that individuals particularly susceptible to lapses of attention (indexed by the slowest response times) demonstrated a decreased pupillary response during the interstimulus interval, whereas individuals less susceptible to lapses of attention demonstrated an increased pupillary response during the interstimulus interval. These results suggest that variation in lapses of attention are partially attributable to individual differences in the ability to voluntarily control the intensity of attention (intrinsic alertness) and fully engage preparatory processes on a moment-by-moment basis. Furthermore, across both experiments additional individual differences factors covaried with lapses of attention, including attention control, working memory capacity, susceptibility to off-task thinking, task-specific motivation, and fixation stability. These results provide evidence for the notion that individual differences in lapses of attention are multifaceted and that variation in intrinsic alertness and other factors are important contributors to this variation.

Public Significance Statement

Our ability to sustain attention is critical in a number of everyday tasks. In the current study we demonstrate that individual differences in lapses of sustained attention are related to individual differences in intrinsic alertness along with additional factors. Individuals who are susceptible to lapses of attention are less able to sustain their intensity of attention and engage preparatory processes than individuals who are less susceptible to lapses of attention. These results further our knowledge of who is likely to experience lapses of attention and why.

Keywords: individual differences, intrinsic alertness, lapses of attention, pupillary responses

Despite an efficient attentional system, we frequently experience fluctuations and lapses of attention. These attentional lapses reflect temporary shifts of attention away from the task at hand, which can result in failures to perform an intended action. Lapses of attention have been associated with a number of real-world outcomes such as accidents (Broadbent, Cooper, FitzGerald, & Parkes, 1982; Galéra et al., 2012; Reason & Mycielska, 1982) as well as professional (Reason, 1990) and educational difficulties (Brown, 1927; Lindquist & McLean, 2011; Unsworth, Brewer, & Spillers, 2012; Unsworth & McMillan, 2017). Given the importance of our attentional system in a diverse array of situations, it is necessary to understand under what conditions and for whom lapses of attention are most likely. A main goal of the current study was to examine variation in lapses of attention and what factors (ability, motivation, alertness, etc.) are associated with frequent lapses of attention.

Variation in Lapses of Attention

Broad sustained attention abilities are thought to be a core aspect of attention control (AC) abilities that are associated with the intensity of attention and are distinct from our ability to select and divide our attention (Posner & Petersen, 1990; Robertson & O'Connell, 2010; Sturm, 2003; Sturm & Willmes, 2001; van Zomeren & Brouwer, 1994). Additionally, we note that many of the current concepts (e.g., alertness, sustained attention, etc.) are difficult to uniquely define as they are not completely independent and will necessarily have some overlap. Sometimes attention is focused on the current task, leading to high levels of task engagement and subsequent performance, and other times the intensity of attention is lessened, leading to reduced levels of task engagement and poorer subsequent performance. As such, lapses in sustained attention can manifest in many different ways such as reflexive

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errors (Unsworth, Schrock, & Engle, 2004), performance failures (Adam, Mance, Fukuda, & Vogel, 2015; Peiris, Jones, Davidson, Carroll, & Bones, 2006; Robison & Unsworth, 2019), especially slow response times (RTs; Cheyne et al., 2009; Coyle, 2003, 2017; Kane & Engle, 2003; Larson & Alderton, 1990; Leth-Steensen, Elbaz, & Douglas, 2000; McVay & Kane, 2012b; Tse, Balota, Yap, Duchek, & McCabe, 2010; Unsworth, Redick, Lakey, & Young, 2010; Unsworth, Redick, et al., 2012; Weissman, Roberts, Visscher, & Woldorff, 2006), variability in performance (RTs and errors; Jackson, Balota, Duchek, & Head, 2012; Jensen, 1992; Unsworth, 2015; West, 2001), as well as self-reports of off-task thoughts (e.g., McVay & Kane, 2009; Smallwood & Schooler, 2015; Stawarczyk, Majerus, Maj, Van der Linden, & D'Argembeau, 2011; Unsworth & McMillan, 2014). Further, these different indicators of lapses may represent different states of disengagement (Cheyne et al., 2009).

A number of studies have suggested that there are robust individual differences in lapses of attention measured both behaviorally and with self-report thought-probe techniques (Cheyne et al., 2009; Kane et al., 2016; McVay & Kane, 2012a; Unsworth et al., 2010; Unsworth & McMillan, 2014). In our prior research we have found that lapses of sustained attention (measured as the longest RTs in the psychomotor vigilance task; Dinges & Powell, 1985) were strongly related to variation in working memory capacity (WMC), AC, and fluid intelligence. For example, Unsworth et al. (2010) found that the slowest RTs were related to WMC, AC, and fluid intelligence (consistent with the worst performance rule; Coyle, 2003; Larson & Alderton, 1990). In line with sleep deprivation research (Lim & Dinges, 2008), the results suggested that these slow trials were indicative of lapses of sustained attention (see also Bills, 1931, 1935) and that low ability individuals experienced more lapses of sustained attention than high ability individuals (Cheyne et al., 2009; McVay & Kane, 2012b; Robison & Unsworth, 2018; Unsworth et al., 2012; Unsworth, Spillers, & Brewer, 2009; Unsworth & McMillan, 2014, 2017; Unsworth & Robison, 2017a; Unsworth & Robison, 2020; Unsworth & Spillers, 2010). Prior research also suggests that variability in RTs are related to working memory, AC, and fluid intelligence (Jensen, 1992; Kane et al., 2016; Unsworth, 2015), indicating that low cognitive ability individuals tend to experience more fluctuations and lapses in attention than high cognitive ability individuals (see also Fortenbaugh et al., 2015; Seli, Cheyne, & Smilek, 2013; Seli et al., 2014).

In addition to relating to various cognitive abilities, behavioral indices of lapses of attention have been shown to be related to self-reports of off-task thinking (Kane et al., 2016; McVay & Kane, 2012b; Robison & Unsworth, 2018; Unsworth & McMillan, 2014; Unsworth & Robison, 2020), Attention-Deficit/Hyperactivity Disorder (Leth-Steensen et al., 2000; Tamm et al., 2012), autism spectrum disorders (Karalunas, Geurts, Konrad, Bender, & Nigg, 2014), and neuroticism (Klein & Robinson, 2019; Robinson & Tamir, 2005; Robison, Gath, & Unsworth, 2017). Recent research further suggests that lapses of attention are related to other factors such as task-specific motivation, task-specific interest, and alertness levels (Robison & Unsworth, 2018; Seli, Cheyne, Xu, Purdon, & Smilek, 2015; Stawarczyk & D'Argembeau, 2016; Unsworth & McMillan, 2013; Unsworth & Robison, 2020). Furthermore, behavioral indicators of lapses of attention are related to real world attention problems providing ecological validity for these measures (Steinborn, Langner, Flehmig, & Huestegge, 2016; Unsworth, McMillan, et al., 2012; Unsworth & McMillan, 2017). Collectively, prior research suggests there are robust individual differences in lapses of attention and lapses of attention tend to be related to various individual differences factors.

Intrinsic Alertness and Preparatory Processes

Although examining RT distributions and particularly slow RTs has been fruitful for examining lapses of attention and individual differences in lapses of attention, it is important to note that these RTs are an outcome variable and to fully understand lapses of attention it will be critical to examine what occurs prior to and during a lapse resulting in a particularly slow RT. For example, Weissman et al. (2006; see also Chee et al., 2008) examined fast and slow responses in a variant of a global-local task and found that the slowest RTs were associated with reduced activity in frontal-parietal areas prior to the onset of the stimulus suggesting that particularly slow RTs are associated with temporary reductions in AC processes that occur prior to stimulus onset. As such, it is critically important to measure and understand preparatory processes that occur prior to these slow RTs.

Broadly, lapses of attention (and slow RTs) are likely attributable, in part, to 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 research suggests that alertness can be divided 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 and maintenance of alertness over seconds to minutes in the absence of external cues: Langner et al., 2012; Sadaghiani & D'Esposito, 2015; Sturm & Willmes, 2001; Unsworth & Robison, 2020; van Zomeren & Brouwer, 1994). Thus, the amount (intensity) of attention that is allocated to a task is determined, in part, by the ability to control alertness levels (intrinsic alertness), which are important for determining the overall engagement of various preparatory processes.

One way of examining intrinsic alertness and lapses of attention is to use simple RT tasks like 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: 2–10 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. Intrinsic alertness and the intensity of attention fluctuate both within and between trials. This has an impact on goal management processes in which the participant needs 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 (Hockey, 2013; Unsworth & Robison, 2020). When intrinsic alertness is high, goal management 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, goal management processes are not fully engaged, leading to a weakened task goal activation and/or an inability to maintain the task goal over the interval. Thus, lowered intrinsic alertness should result in a higher frequency of lapses of attention and longer than normal RTs. Note, this does not mean that intrinsic alertness and goal management processes are identical. It is theoretically possible to be high in intrinsic alertness, but low in goal management (and vice versa). Thus, intrinsic alertness levels (within and between individuals) likely influence goal management processes, but they are also distinct.

In terms of individual differences we recently suggested that intrinsic alertness abilities were critical for the association between working memory and sustained attention (Unsworth & Robison, 2020). Specifically, we suggested that low working memory individuals are less able to voluntarily control and adapt their intensity of attention (intrinsic alertness) in a goal directed manner compared with high working memory individuals. Thus, we suggested that working memory was related to sustained attention partially due to differences in intrinsic alertness which results in differences in lapses of attention. Variation in goal management processes are also important for variation in working memory. In the current article we extend these ideas by specifically examining individual differences in lapses of attention and examining whether variation in intrinsic alertness are related to lapses of attention.

Of course, differences in intrinsic alertness can manifest in different ways. For example, it is possible that high-lapse individuals have an overall lower intensity of attention (intrinsic alertness) compared with low-lapse individuals (Figure 1a). This would result in overall weakened goal management processes, slower RTs, and a higher likelihood of being captured by irrelevant stimuli such as internal thoughts (mind-wandering) or external distraction. Another possibility is that high- and low-lapse individuals both ramp up their attention during the ISI (Figure 1b), but that low-lapse individuals ramp up their intensity of attention to a greater extent than high-lapse individuals resulting in strengthened goal management processes, faster RTs, and fewer lapses of attention and less off-task thinking. An additional possibility is that high- and low-lapse individuals may differ in their ability to sustain the intensity of attention during the ISI (Figure 1c). That is, perhaps low-lapse individuals are better able to maintain the same level of intensity during the ISI, but high-lapse individuals are unable to sustain this same level of attention during the ISI. This would result in weakened goal management processes, slower RTs, and more frequent lapses of attention and off-task thinking for the high-lapse individuals compared with the low-lapse individuals. A final possibility is that perhaps high- and low-lapse individuals differ in the consistency of the intensity of attention over trials. That is, perhaps most of the time high- and low-lapse individuals allocate the same amount of attention to the current task, but on some trials high-lapse individuals are unable to fully allocate attention to the task resulting in weakened goal management processes, a slower than normal RT, and more off-task thinking. Thus, this would suggest that differences arise due to variability in intrinsic alertness and the intensity of attention. Of course some combination of these different accounts is also possible.

Each possibility suggests differences in the intensity of attention (intrinsic alertness) during the ISI of a simple RT task. To examine these possible differences in the intensity of attention, one can exploit changes in pupillary responses. Prior research has suggested that phasic pupil dilation changes as a function of the cognitive demands of a task (see Beatty & Lucero-Wagoner, 2000 for a review). Kahneman (1973) and Beatty (1982) suggested that these phasic pupillary responses are reliable and valid psychophysiological markers of cognitive effort and the intensity of attention. Prior research has also suggested that pupillary responses can be informative for examining fluctuations and lapses of attention linked to changes in alertness and the intensity of attention associated with functioning of the locus coeruleus norepinephrine system (Konishi, Brown, Battaglini, & Smallwood, 2017; Kristjansson, Stern, Brown, & Rohrbaugh, 2009; Unsworth & Robison, 2015, 2016, 2017a, 2017b, 2018; Unsworth, Robison, & Miller, 2018; van den Brink, Murphy, & Nieuwenhuis, 2016).

As noted above, when intrinsic alertness is high, goal management processes should be more engaged resulting in faster overall responses. Indeed, prior pupillometry studies have found that during the ISI the pupil increases up to the expected occurrence of the stimulus and peaks shortly thereafter (phasic response to the onset of the stimulus), suggesting that intrinsic alertness increases throughout the foreperiod with near peak readiness at the expected onset of the stimulus (Bradshaw, 1968, 1969; Jennings, van der Molen, & Steinhauer, 1998; Richer, Silverman, & Beatty, 1983; Richer & Beatty, 1987; van der Molen, Boomsma, Jennings, & Nieuwboer, 1989). Similar results have been found in variants of the psychomotor vigilance task. For example, Unsworth et al. (2018) found that slow RTs were associated with small dilation responses during both the ISI and when the target stimulus appeared, suggesting that lapses were associated with a lowered intensity of attention. Similarly, Massar, Lim, Sasmita, and Chee (2019) found that pupil dilation during the ISI in was related to subsequent RTs, suggesting that greater intensity of attention resulted in faster responses. Furthermore, Hutchison et al. (2020) found that in the antisaccade task that when participants reported being on-task (via thought probes) that the pupil tended to remain constant prior to stimulus onset, but when participants reported being off-task the pupil tended to constrict. Additional research has suggested that the pupil tends to increase prior to stimulus onset in a number of AC tasks and this increase in pupil dilation is positively associated with performance (Chatham, Frank, & Munakata, 2009; Chiew & Braver, 2013; Irons, Jeon, & Leber, 2017; Wang, Brien, & Munoz, 2015). As such, prior research suggests that pupillary responses prior to stimulus onset can provide a means of tracking the intensity of attention to preparatory processes.

The Current Study

The main goal of the present study was to examine possible factors for variation in lapses of attention. In particular, we were interested in testing the notion that lapses of sustained attention are related to intrinsic alertness abilities. We were also interested in examining whether other factors that have been shown to be related to lapses of attention (WMC, AC, off-task thinking, task-specific motivation) would be related to intrinsic alertness and account for shared or unique variance in lapses of attention. To examine these notions participants performed a variant of the psychomotor vigilance task we continuously tracked eye movements and pupillary responses. Whereas prior research (Unsworth & Robison, 2017a) examined pupillary responses during the pretrial baseline and when the target stimulus occurred, here we focus on pupillary responses during the ISI to better examine variation in intrinsic alertness and preparatory processes. By examining pupillary responses during the ISI, we should be able to examine

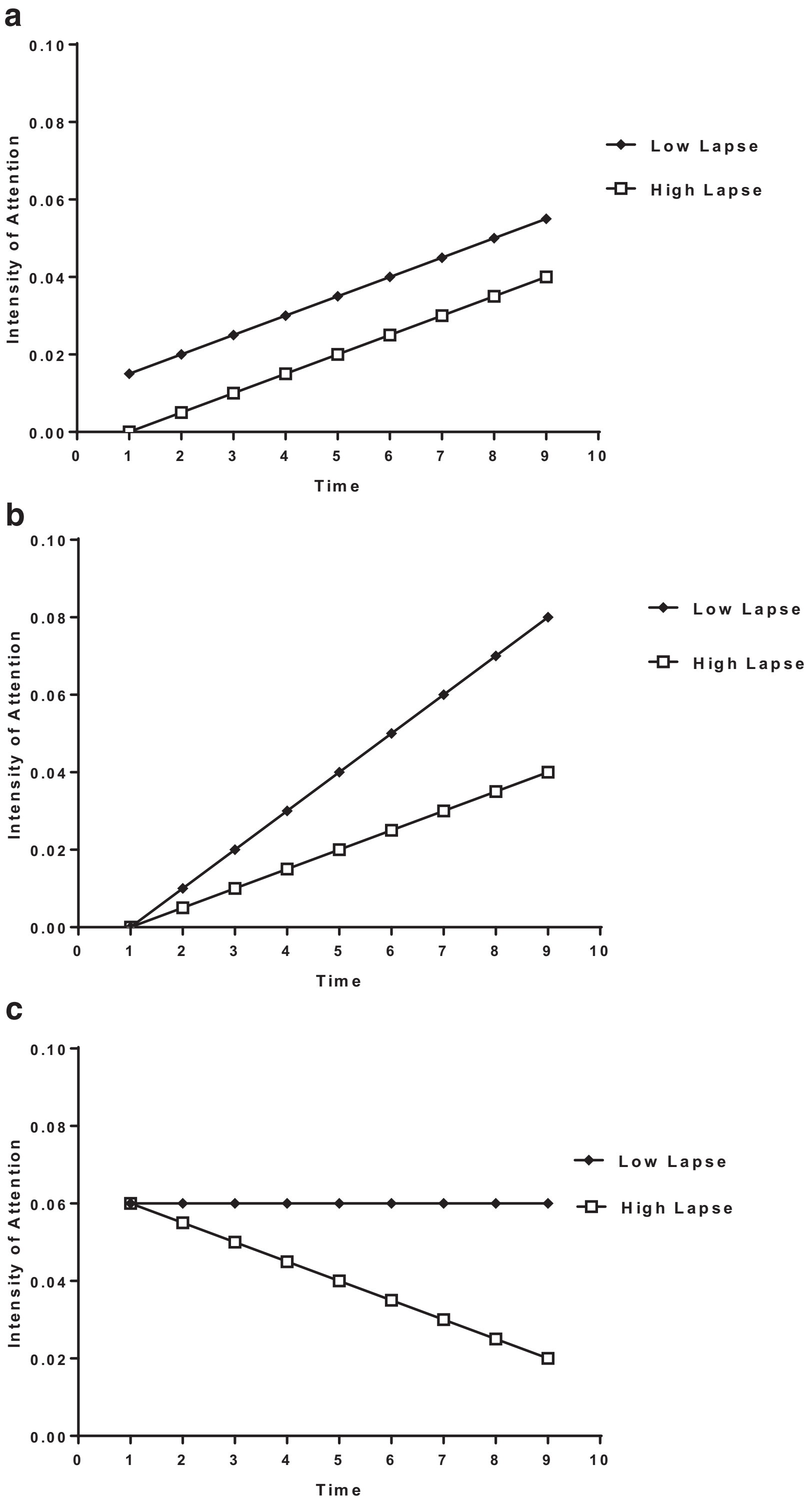

Figure 1. (a) Differences between high- and low-lapse individuals in terms of overall differences in the intensity of attention (arbitrary units) during the interstimulus interval. (b) Differences between high- and low-lapse individuals in terms of differences in the ability to ramp up the intensity of attention during the interstimulus interval. (c) Differences between high- and low-lapse individuals in terms of differences in the ability to sustain the intensity of attention during the interstimulus interval.

individual differences in intrinsic alertness levels and how these are potentially related to behavioral indicators of lapses of attention (such as slow RTs) based on the four possibilities outlined earlier (see Figure 1).

In addition to examining pupillary responses during the ISI we also were interested in examining individual differences in fixation stability during the ISI. Fixation stability refers to the ability to maintain fixation on a stimulus for a brief amount of time and various measures of dispersion (Holmqvist et al., 2011) including standard deviation of eye position are examined. For example, Di Russo, Pitzalis, and Spinelli (2003) had elite shooters and control participants stare at a fixation point for 1 min. Di Russo et al. found that elite shooters were better at maintaining their gaze on the fixation point and having better fixation stability than control participants. Examining periods of mind-wandering versus on-task focus, Grandchamp, Braboszcz, and Delorme (2014) found some evidence for poorer fixation stability during mind-wandering than when participants reported being on-task. Additional research has suggested that individuals with poor sustained attention abilities (Dankner et al., 2017), Schizophrenic patients (Benson et al., 2012; Barton, Pandita, Thakkar, Goff, & Manoach, 2008), individuals with Attention-Deficit/Hyperactivity Disorder (Fried et al., 2014; Munoz, Armstrong, Hampton, & Moore, 2003), and individuals with lower intelligence (Smyrnis et al., 2004) all demonstrated poorer fixation stability (more fixation instability). In a recent study Unsworth, Robison, and Miller (2019) found that AC (measured with the psychomotor vigilance and antisaccade tasks) was negatively related to fixation instability suggesting that individuals lower in AC demonstrated more fixation instability. As such, fixation stability seems essential for performance on various AC tasks where fixation must be kept on center to rapidly respond to the target stimulus. Thus, there are both practical (if not looking at the numbers in the psychomotor vigilance task then slower RT; Anderson, Wales, & Horne, 2010; Johns, Crowley, Chapman, Tucker, & Hocking, 2009) and theoretical (maintaining fixation is attention demanding) reasons for examining fixation stability as a potential factor in variation in lapses of attention.

Finally, we measured other factors thought to be related to variation in lapses of attention. Specifically, given prior research has shown that self-reports of off-task thinking are related to behavioral indicators of lapses of attention, during the psychomotor vigilance task participants were periodically presented with thought-probes asking them to report on their current attentional state. Additionally, given that prior research has consistently found that individual differences in both WMC and AC (measured by tasks like antisaccade, Stroop, and flankers) are related to lapses of attention (Unsworth et al., 2010; Unsworth & McMillan, 2014; Unsworth & Robison, 2020; Unsworth & Spillers, 2010), we also examined the extent to which these abilities were related to lapses of attention and the different eye measures.

Experiment 1

In Experiment 1 we examined individual differences in lapses of attention by having participants perform a variant of the psychomotor vigilance task while recording various eye measures (pupillary responses and fixation stability). Periodically during the psychomotor vigilance task participants were presented with thought probes asking them to classify their immediately preceding thoughts to assess variation in off-task thinking. Participants also performed multiple measures of AC and working memory to more fully examine how various factors are related to variation in lapses of sustained attention.

Method

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in our study.

Participants. A total of 175 participants were recruited from the subject-pool at the University of Oregon, a comprehensive state university. With list-wise deletion there was complete data on the psychomotor vigilance task (behavioral and eye tracking variables), WMC, and AC measures for 136 participants. With this sample size, power of .80, and alpha set at .05 (two-tailed) we had sufficient power to find a correlation of .25. Participants received course credit for their participation. Each participant was tested individually in a laboratory session lasting approximately two hours. We tested participants over two full academic quarters, using the end of the second quarter as our stopping rule for data collection. Note some of the data has been reported in Unsworth and Robison (2017a). The purpose of that study was to examine relations among WMC, AC, and pupillary responses at the latent level. None of the critical ISI pupillary response data were examined in that study and none of the specific hypotheses regarding individual differences in lapses of attention were tested.

Materials and procedure. After signing informed consent, all participants completed operation span, symmetry span, reading span, psychomotor vigilance task, antisaccade, Stroop, Ravens Advanced Progressive Matrices, letter sets, syllogisms, and a visual working memory filtering task. All tasks were administered in the order listed above. In the current study we used the three complex span tasks as our measures of working memory, the antisaccade and Stroop as our measures of AC, and the psychomotor vigilance task as our measure of sustained attention.

WMC tasks.

Operation span. Participants solved a series of math operations while trying to remember a set of unrelated letters (see Unsworth, Heitz, Schrock, & Engle, 2005). 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. At recall participants were asked to recall letters from the current set in the correct order by clicking on the appropriate letters. For all of the span measures, items were scored correct if the item was recalled correctly from the current list. Participants were given practice on the operations and letter recall tasks only, as well as two practice lists of the complex, combined task. List length varied randomly from three to seven items, and there were two lists of each list length for a maximum possible score of 50. The score was total number of correctly recalled items.

Symmetry span. Participants recalled sequences of red squares within a matrix while performing a symmetry-judgment task (see Unsworth, Redick, Heitz, Broadway, & Engle, 2009). 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 by clicking on the cells of an empty matrix. Participants were given practice on the symmetry-judgment and square recall task as well as two practice lists of the combined task. List length varied randomly from two to five items, and there were two lists of each list length for a maximum possible score of 28. We used the same scoring procedure as we used in the operation span task.

Reading span. While trying to remember an unrelated set of letters, participants were required to read a sentence and indicated whether or not it made sense (see Unsworth et al., 2009). Half of the sentences made sense, whereas the other half did not. Nonsense sentences were created by changing one word in an otherwise normal sentence. After participants gave their response, they were presented with a letter for 1 s. At recall, participants were asked to recall letters from the current set in the correct order by clicking on the appropriate letters. Participants were given practice on the sentence judgment task and the letter recall task, as well as two practice lists of the combined task. List length varied randomly from three to seven items, and there were two lists of each list length for a maximum possible score of 50. We used the same scoring procedure as we used in the operation span and symmetry span tasks.

AC tasks.

Stroop. Prior to each trial, there was a 2-s baseline period with "+++++" in the center of the screen to determine baseline pupil diameter (luminance = 208 lux). Following this, participants were presented with a color word (red, green, or blue) presented in one of three different font colors (red, green, or blue: average luminance = 214 lux). The participants' task was to indicate the font color via key press (red = 1, green = 2, blue = 3). Participants were told to press the corresponding key as quickly and accurately as possible. Participants received 15 trials of response mapping practice and 6 trials of practice with the real task. Participants then received 100 real trials. Of these Trials 67% were congruent such that the word and the font color matched (i.e., red printed in red) and the other 33% were incongruent (i.e., red printed in green). The dependent variable was the RT difference between incongruent and congruent trials. Twelve thought probes were randomly presented after incongruent trials.

Antisaccade. Prior to each trial, there was a 2 s baseline period with "+++++" in the center of the screen to determine baseline pupil diameter (luminance = 12 lux). Following this, participants were instructed to stare at a fixation point which was onscreen for a variable amount of time (200–2200 ms). A flashing white "=" was then flashed either to the left or right of fixation (11.33° of visual angle) for 100 ms (luminance = 10 lux). This was followed by the target stimulus (a B, P, or R) onscreen for 100 ms. This was followed by masking stimuli (an H for 50 ms followed by an 8 which remained onscreen until a response was given). The participants' task was to identify the target letter by pressing a key for B, P, or R (the keys 4, 5, or 6) as quickly and accurately as possible. In the prosaccade condition the flashing cue (=) and the target appeared in the same location. In the antisaccade condition the target appeared in the opposite location as the flashing cue. Participants received, in order, 10 practice trials to learn the response mapping, 15 trials of the prosaccade condition, and 50 trials of the antisaccade condition. The dependent variable was proportion correct on the antisaccade trials. Eleven thought probes were randomly presented after trials.

Psychomotor vigilance task. Prior to each trial, there was a 2-s baseline period with "+++++" in the center of the screen to determine baseline pupil diameter (luminance = 208 lux). Following this, participants were then presented with a row of zeros in the center of the screen (luminance = 212 lux) and after a variable wait time (equally distributed from 2–10 s in 500-ms increments) the zeros began to count up in 17-ms intervals from 0 ms. 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. Following feedback a 500-ms blank screen was presented and then either the next trial started or participants were presented with a thought-probe. The entire task lasted for 10 min for each individual (75 total trials). Fifteen thought probes were randomly presented after trials. Our primary behavioral dependent measure was the average RT for the slowest 20% of trials (Dinges & Powell, 1985). Specifically, each individual's RTs were ranked from fastest to slowest and placed into quintiles and the slowest quintile (Quintile 5) was our primary measure of interest. For completeness we also examined other putative behavioral indicators of lapses in this task including the RTs >500 ms (Dinges & Powell, 1985; Unsworth et al., 2010), standard deviation and coefficient of variation of RTs (Unsworth, 2015), as well as fitting an ex-Gaussian function to the entire RT distribution and examining estimates of the tau parameter (Unsworth et al., 2010).

Thought probes. During the psychomotor vigilance task (and the other AC tasks), participants were periodically presented with thought probes asking them to classify their immediately preceding thoughts. The thought probes asked participants to press one of five keys to indicate what they were thinking just prior to the appearance of the probe. Specifically, participants saw:

> 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/temperature or by physical sensations (hungry/thirsty).
>
> 4. I am daydreaming/my mind is wandering about things unrelated to the task.
>
> 5. I am not very alert/my mind is blank.

During the introduction to the task, participants were given specific instructions regarding the different categories. Response 1 was considered on-task. Response 2 measures task-related interference and was not included in the analyses. Responses 3–5 were considered as off-task thinking. Prior research has demonstrated that the different off-task probes are correlated at the individual differences level and that variance common to the various off-task probes is what is important for the relation between WMC and AC (Unsworth & McMillan, 2014). Thus, responses 3–5 were combined into a single off-task measure (proportion of off-task thoughts) for each AC task.

Eye tracking. For the psychomotor vigilance (as well as antisaccade and Stroop) task participants were tested individually in a dimly lit room. Pupil diameter and gaze were continuously recorded binocularly at 120 Hz using a Tobii T120 eyetracker. Participants were seated 60 cm from the monitor. Stimuli were presented on a 17-in monitor with a 1024 × 768 screen resolution. Data from each participant's left eye was used. Missing data points due to blinks, off-screen fixations, and/or eyetracker malfunction were removed. We did not exclude whole trials for missing data.

Pretrial baseline pupil was computed as the average pupil diameter during the fixation screen (2,000 ms). Pupillary responses during the ISI were corrected by subtracting out the pretrial baseline and locked to when the numbers appeared on-screen on a trial-by-trial basis for each participant. To examine the time course of pupillary responses during the ISI, the pupil data were averaged into a series of 200-ms time windows following the appearance of the numbers for each trial. We examined both the mean and standard deviation of pupillary responses for each 200 ms time window.

Consistent with prior research, fixation stability was computed as the standard deviation of the eye position for each sample averaged along both the horizontal and vertical dimensions (Di Russo et al., 2003; Unsworth et al., 2019) during the ISI. Missing data points owing to blinks, off-screen fixations, and/or eyetracker malfunction were removed and not included in the fixation stability averages.

Results

Pupillary responses during the interstimulus interval. First, we examined pupillary responses during the ISI. As noted previously, pupillary responses during the ISI were baseline corrected and averaged into a series of 200-ms time windows following the appearance of the numbers for each trial. All ISIs from 2–10 s were averaged together into a single pupillary response for each participant. Thus, there were naturally more trials entering into the shortest ISIs because all ISIs included at least 2 s. Overall similar results are obtained when only examining the 10 s ISI condition. Examining the pupillary response during the ISI suggested a significant effect of time, $F(49, 6615) = 2.15$, $MSE = .003$, $p < .001$, partial $\eta^2 = .02$, indicating that the pupillary response tended to decline slightly early in the ISI, but then increased during the end of the ISI (Figure 2a). Next, we tested our main question of interest to examine whether the pupillary response during the ISI differed as a function of individual differences in lapses of attention (as indicted by particularly slow RTs). For all the RT results reported, false alarms (i.e., hitting the spacebar before the numbers started counting) were excluded.[1] In addition, RTs that fell below 150 ms were excluded from all RT analyses. Our main dependent variable for the RT results was the slowest 20% of RTs (Quintile 5) in the psychomotor vigilance task (see the Appendix for correlations with other putative indicators of behavioral lapses and relations with all of the RT distributional measures). To examine potential individual differences in lapses of attention, we repeated the above analysis, but now entered in Quintile 5 as an indicator of lapses into an analysis of covariance as a covariate. The analysis suggested a main effect Quintile 5, $F(1, 134) = 7.79$, $MSE = .198$, $p = .006$, partial $\eta^2 = .06$, in which Quintile 5 was negatively related ($r = -.23$) with the average pupillary response during the ISI suggesting that participants who have frequent lapses of attention have a smaller pupillary response during the ISI. Critically, there was also an interaction between time and Quintile 5, $F(49, 6566) = 12.16$, $MSE = .003$, $p < .001$, partial $\eta^2 = .08$, suggesting that the pupillary response differed as a function of individual differences in lapses of attention. To illustrate the effects of interest, we present differences in Quintile 5 via a quartile split with low-lapse individuals (bottom 25%) and high-lapse individuals (top 25%). Note, however, that all analyses treated lapses (Quintile 5) as continuous, rather than as arbitrary, discrete groups. As shown in Figure 2b, for low-lapse individuals their pupillary response increased during the ISI, but for high-lapse individuals their pupillary response tended to decrease during the ISI. These results suggest that low-lapse individuals increased their intensity of attention during the ISI, but that high-lapse individuals were unable to increase or sustain their intensity of attention during the ISI, leading to large differences at the end of the ISI.

We also examined whether similar results would be found when examining within-subject effects. Specifically, we examined the ISI pupillary response for slow (Quintile 5) and fast (Quintile 1) trials within participants (e.g., Unsworth et al., 2018). For these analyses we used multilevel modeling to compare pupillary responses for lapse and nonlapse trials across the ISI because mean-based analytic techniques (e.g., repeated measures ANOVA) only use data from participants with complete data. That is, only those participants who had lapse and nonlapse trials on all ISIs would be included, thereby drastically reducing the sample size. Using multilevel modeling we were able to leverage observations from participants that would have been excluded. In the model, pupillary responses during the ISI were nested within trials and subjects. Our fixed effects included the linear effect of time bin, the quadratic effect of time bin, trial type (slow vs. fast), and the cross-level interaction between the linear effect of time bin and trial type. Critically, there was a significant quadratic interaction between time bin and trial type, suggesting differences in the pupillary responses during the ISI for slow and fast trials [$b = -.00003$, $SE = .000008$, $t(105636.07) = -3.40$, $p < .001$]. As demonstrated in Figure 3a, on fast trials the pupil tended to increase during the ISI, but on slow trials the pupil tended to decrease during the ISI. These within participant results were very similar to the between participant results, suggesting that fast (nonlapse) trials are associated with increased intensity of attention during the ISI, whereas slow (lapse) trials are associated with a decrease in the intensity of attention during the ISI. These results broadly replicate prior research (Unsworth et al., 2018).

Similar analyses were conducted for when a participant indicated they were on-task via thought probes compared with when a participant reported being off-task. As with the comparison of slow versus fast trials, there was a significant quadratic interaction between trial type (on- vs. off-task) and time bin [$b = -.00003$, $SE = .00001$, $t(36{,}875.30) = -3.99$, $p < .001$]. As seen in Figure 3b, when participants reported being on-task, the pupil increased during the ISI, but when participants reported being off-task the

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[1] Note that, in Experiment 1, there were on average 1.36 ($SD = 1.59$) false alarms. False alarms were only significantly related to AC ($r = -.23$, $p = .009$) and ISI PupilSD ($r = -.23$, $p = .009$). In Experiment 2 there were on average 2.36 ($SD = 1.86$) false alarms. False alarms were only significantly related to Quintile 5 ($r = .27$, $p = .002$) and ISI GazeSD ($r = .31$, $p < .001$).

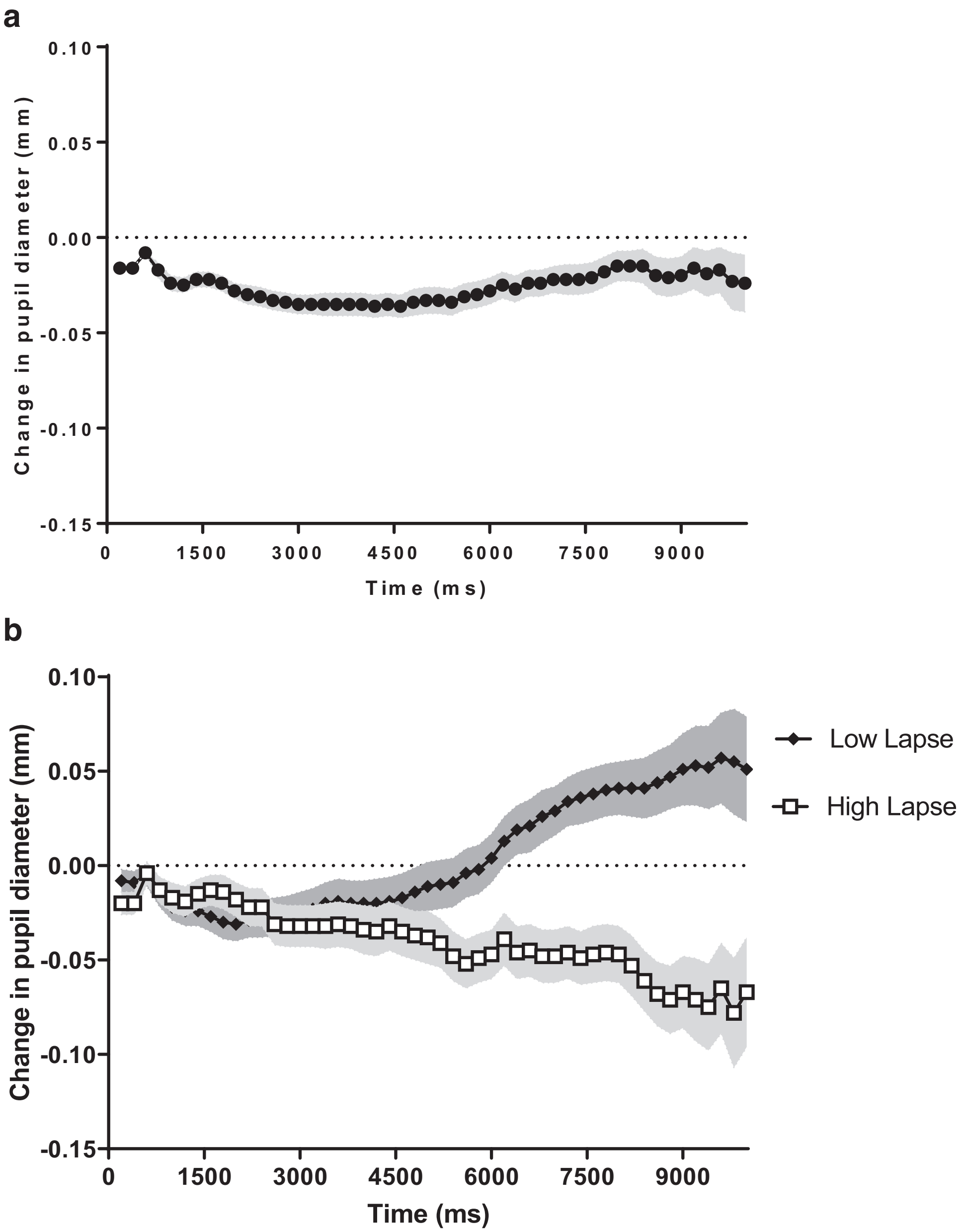

Figure 2. (a) Change in pupil diameter as a function of time during the ISI in Experiment 1. (b) Change in pupil diameter as a function of time during the ISI for high- and low-lapse individuals in Experiment 1. Shaded areas reflect one standard error of the mean.

pupil decreased during the ISI. These results are consistent with recent research by Hutchison et al. (2020) who found that on-task reports in the antisaccade were associated with larger pupillary responses during the preparatory interval than off-task reports.

Finally, we also examined whether there were within subject differences in slow versus fast and on-task versus off-task trials in fixation instability (standard deviation of gaze) during the ISI. The results suggested that slow trials (M = .035, SD = .032) were associated with more fixation instability than fast trials (M = .024, SD = .022) [b = 0.003, SE = .0004, t(129.15) = 6.63, $p < .001$]. Similarly, when participants reported being off-task (M = .037, SD = .030) there was greater fixation instability than when they reported being on-task (M = .021, SD = .019) [b = .003, SE = .0005, t(976.01) = 6.24, $p < .001$]. Collectively, these results suggest that lapses of attention (both behavioral and self-report) are associated with lower pupillary responses and greater fixation instability during the ISI, consistent with the notion that lapses are associated with a temporary reduction in intrinsic alertness.

Correlations among the measures. Next we examined relations between Quintile 5 and the other measures. We computed three different eye measures that occurred during the ISI. Specifically, we computed the average change in pupillary response

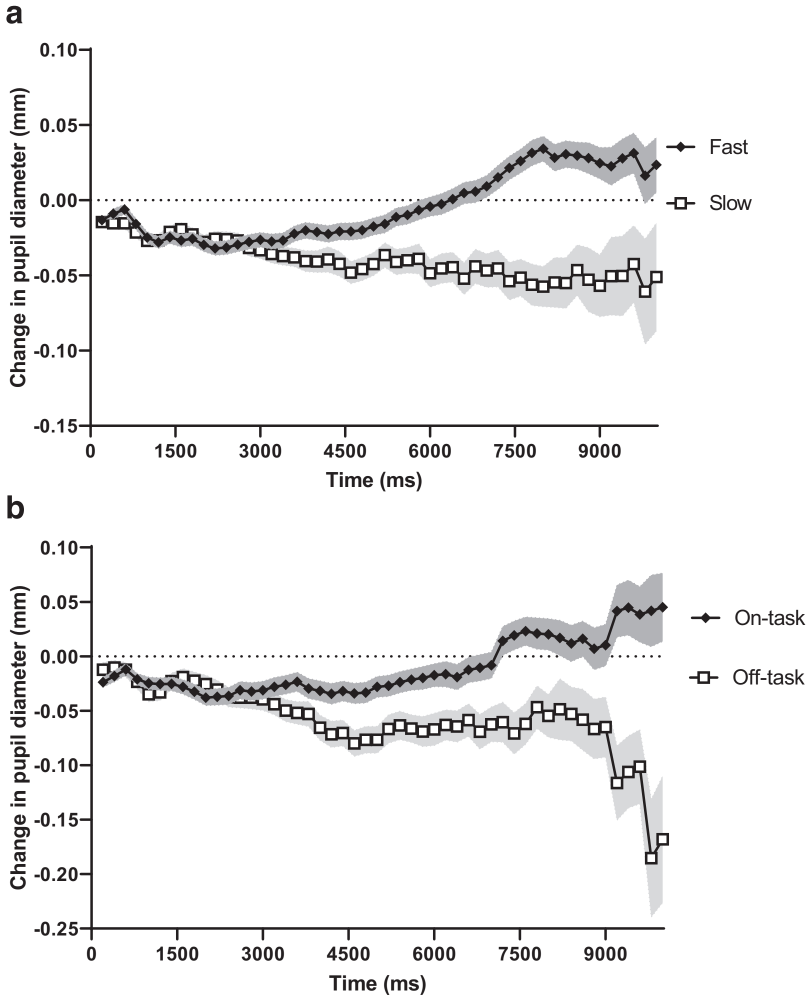

Figure 3. (a) Change in pupil diameter as a function of time during the ISI for lapse and nonlapse trials in Experiment 1. (b) Change in pupil diameter as a function of time during the ISI for on-task and off-task trials in Experiment 1. Shaded areas reflect one standard error of the mean.

during the last second of the 10-s ISI to represent differences in the intensity of attention. We selected the last second of the 10-s ISI given that is where the largest differences occurred (Figure 2b). This decision was partially post hoc because we did not know a priori where differences would emerge, but two of the three possibilities suggested that the largest differences would occur at the end of the ISI (see Figure 1). In Experiment 2 we used the same measure in an entirely new sample of participants. We also computed the trial-to-trial standard deviation of pupillary response during the ISI to examine possible differences in the consistency of the intensity of attention across trials. Finally, we computed the within-trial standard deviation of gaze during the ISI to examine fixation instability during the ISI. Shown in Table 1 are the descriptive statistics for all measures. As can be seen, most of the measures had generally acceptable values of internal consistency and most of the measures were approximately normally distributed with values of skewness and kurtosis under the generally accepted values.

Consistent with prior research we created a WMC composite given that the three working memory span measures were correlated (Operation Span–Symmetry Span $r = .39$; Operation Span–Reading Span $r = .55$; Symmetry Span–Reading Span $r = .31$). The composite WMC score was computed 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 .84, .47, and .66, respectively. Likewise, we computed a factor composite for AC (Antisaccade—Stroop $r = -.17$, factor loadings .41 and $-.41$).

Shown in Table 2 are the correlations between Quintile 5 and the other measures. As can be seen, Quintile 5 was significantly related to all of the measures. Consistent with prior research, Quintile 5 was related to WMC, AC, and off-task thinking during the task (e.g., Unsworth et al., 2010; Unsworth & McMillan, 2014; Unsworth & Robison, 2020). Consistent with the prior results (Figure 2b), Quintile 5 was negatively related to the pupillary response during the last second of the ISI. Additionally, variability in the pupillary response during the ISI was positively related to Quintile 5, suggesting that greater variability in pupillary responses during the ISI were related to particularly slow RTs. Likewise, greater variability in gaze was positively related to

Table 1
Descriptive Statistics and Reliability Estimates for All Measures in Experiment 1

Measure	*M*	*SD*	Skew	Kurtosis	Reliability
Quintile 5	451.19	82.62	0.96	1.32	.92
Ospan	36.70	8.57	−0.73	0.09	.77
Symspan	19.44	5.26	−0.52	−0.28	.73
Rspan	36.36	9.30	−0.98	1.56	.77
Anti	0.65	0.17	−0.62	−0.16	.86
Stroop	169.42	89.54	0.43	0.93	.52
PVToff	0.33	0.26	0.81	−0.03	.70
ISI Pupil	−0.02	0.12	−0.15	0.88	.99
ISI Pupil*SD*	0.15	0.05	1.43	3.49	.99
ISI Gaze*SD*	0.04	0.02	1.02	1.21	.99

Note. Quintile 5 = slowest 20% of trials in the psychomotor vigilance task; Ospan = operation span; Rspan = reading span; Symspan = symmetry span; Anti = antisaccade; PVToff = off-task thoughts psychomotor vigilance task; ISI Pupil = average pupillary response during the last second of the 10 s ISI; ISI Pupil*SD* = standard deviation of pupillary response during the ISI; ISI Gaze*SD* = standard deviation of gaze during the ISI.

Table 3
Simultaneous Regression Predicting Quintile 5 in Experiment 1

Variable	β	*t*	sr^2	R^2	*F*
WMC	−.08	−1.06	.00		
AC	−.27	−3.73**	.05		
PVToff	.36	5.20**	.11		
ISI Pupil	−.15	−2.15*	.02		
ISI Pupil*SD*	−.10	−1.39	.01		
ISI Gaze*SD*	.26	3.45**	.05	.50	21.22**

Note. WMC = working memory capacity; AC = attention control; PVToff = off-task thoughts psychomotor vigilance task; ISI Pupil = average pupillary response during the last second of the 10 s ISI; ISI Pupil*SD* = standard deviation of pupillary response during the ISI; ISI Gaze*SD* = standard deviation of gaze during the ISI.
$^{*}p < .05$. $^{**}p < .01$.

Quintile 5, suggesting that fixation instability during the ISI was a fairly strong predictor of the slowest RTs. These results suggest that pupillary responses and fixation instability during the ISI are providing important information on who is likely to experience frequent lapses of attention. Additional relations are worth noting. In particular, the AC composite and the measure of off-task thinking were related to the three different eye measures and to each other. Working memory was only related to gaze instability. Finally, all three eye measures were related to one another suggesting that they share some important variance.

To further examine the relations between the various measures and Quintile 5 we specified a simultaneous regression in which the different measures were all allowed to predict Quintile 5. Shown in Table 3 are the results. As can be seen, overall 50% of the variance in Quintile 5 was accounted for by the various measures. Furthermore, all of the measures except for WMC and the standard deviation of pupillary response during the ISI accounted for unique variance in Quintile 5. Specifically, AC accounted for roughly 5% unique variance, off-task thinking accounted for roughly 11% unique variance, the pupillary response during the last second of the ISI accounted for roughly 2% unique variance, and fixation instability during the ISI accounted for roughly 5% unique variance. Thus, the different measures accounted for roughly 23% unique variance and 27% shared variance in Quintile 5. These results suggest that there are a number of important factors that account for variation in lapses of attention.

Table 2
Correlations Among the Measures in Experiment 1

Measure	1	2	3	4	5	6	7
1. Quintile 5	—						
2. WMC	**−.28**	—					
3. AC	**−.47**	**.42**	—				
4. PVToff	**.54**	−.16	**−.22**	—			
5. ISI Pupil	**−.35**	−.08	**.22**	**−.28**	—		
6. ISI Pupil*SD*	**.23**	−.06	**−.20**	**.25**	**−.33**	—	
7. ISI Gaze*SD*	**.48**	**−.19**	**−.30**	**.35**	**−.28**	**.50**	—

Note. Bold correlations are significant. Quintile 5 = slowest 20% of trials in the psychomotor vigilance task; WMC = working memory capacity; AC = attention control; PVToff = off-task thoughts psychomotor vigilance task; ISI Pupil = average pupillary response during the last second of the 10 s ISI; ISI Pupil*SD* = standard deviation of pupillary response during the ISI; ISI Gaze*SD* = standard deviation of gaze during the ISI.

Discussion

The results from Experiment 1 suggested a number of interesting findings. Examining pupillary responses during the ISI and their relation to lapses of attention suggested that low-lapse individuals tended to ramp up their attention during the ISI resulting in an increase in the pupillary response, whereas high-lapse individuals could not sustain their attention during the ISI resulting in a decrease in the pupillary response. As such, the results suggest a combination of the ramp up and sustain hypotheses, with some individuals increasing their intensity of attention during the ISI and other individuals decreasing their intensity of attention during the ISI. Similar results were found when examining lapses within participants. Specifically, when a participant experienced a lapse of attention (based either on a slow RT or self-report response), the pupil tended to decrease during the ISI compared with when the participant was on-task, suggesting that lapses (and individual differences in lapses) are associated with reductions in the intensity of attention and preparatory control. There was also evidence for variation in the consistency of attention during the ISI with the standard deviation of the pupillary response during the ISI positively correlating with lapses of attention (although it did not account for unique variance in the regression). Thus, not only are high-lapse individuals unable to sustain their intensity of attention during the ISI, they are also less able to consistently allocate attention to the task during the ISI, and both of these factors result in lowered levels of intrinsic alertness and an increase likelihood of lapses of attention. A further indicator of variation in lapses of attention was the finding that high-lapse individuals tended to have greater fixation instability than low-lapse individuals and when a given individual was experiencing a lapse of attention (slow RT or self-report of off-task thinking) fixation instability was greater than when that individual was on-task. Examining cognitive control abilities (WMC and AC) and propensity for off-task thinking suggested that these variables were not only related to lapses of attention, but they also tended to be related to the various eye measures, suggesting that part of the reason these variables are related to lapses of attention is due to shared variance with intrinsic alertness abilities. At the same time, the regression analyses suggested that AC, off-task thinking, magnitude of the pupillary response during the ISI, and fixation instability all also accounted for unique variance in lapses of attention. These results suggest that there are a combination of factors that distinguish high- and low-lapse individuals.

Experiment 2

The results from Experiment 1 suggested a number of differences between high- and low-lapse individuals. Experiment 2 was conducted to replicate and extend these results. Specifically, our main goal in Experiment 2 was to examine how robust these effects were and to examine if variation in task-specific motivation is related to differences in intrinsic alertness and lapses of attention. Prior research has suggested that individual differences in task-specific motivation on the psychomotor vigilance task is related to behavioral lapses of attention and off-task thinking (Unsworth & Robison, 2020). Additionally, Massar, Lim, Sasmita, and Chee (2016) found that incentives increased overall pupil diameter and resulted in fewer lapses of attention compared with a condition in which there were no incentives for performance. As such, it is likely that task-specific motivation is an important factor in variation in lapses of attention and intensity of attention. Thus, to better test any potential role of motivation, following the psychomotor vigilance task participants were asked about their motivation to perform the task. Finally, in Experiment 1 we averaged across all 17 different ISIs when examining the time course of the pupillary response to ensure there were enough trials for analysis. However, this could have artificially distorted the results by making them appear more stable than they actually are (although note we found the same results when only examining the 10-s ISI condition). To examine each ISI separately, participants performed the same psychomotor vigilance task as Experiment 1, but only with ISIs of 2, 4, 6, 8, and 10 s. This has the benefit of increasing the number of trials per ISI, but the possible downside is that it makes the task more predictable and possibly less attention demanding (e.g., Langner & Eickhoff, 2013; Shaw, Finomore, Warm, & Matthews, 2012; Unsworth & Robison, 2020). To examine these issues a new sample of participants performed the psychomotor vigilance task while pupillary responses and gaze were recorded. Participants were presented with thought-probes during the task to assess off-task thinking and following the task participants indicated their motivation to perform the task. Participants also performed WMC and AC tasks consistent with Experiment 1.

Method

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in our study.

Participants. A total of 142 participants were recruited from the subject-pool at the University of Oregon, a comprehensive state university. Two participants were excluded for having excessive RTs on the psychomotor vigilance task. With this sample size, power of .80, and alpha set at .05 (two-tailed) we had sufficient power to find a correlation of .25. Participants received course credit for their participation. Each participant was tested individually in a laboratory session lasting approximately two hours. We tested participants over two full academic quarters, using the end of the second quarter as our stopping rule for data collection.

Materials and procedure. After signing informed consent, all participants completed operation span, symmetry span, reading span, antisaccade, Stroop, delayed free recall, picture source recognition, paired associates recall, and the psychomotor vigilance task. All tasks were administered in the order listed above. In the current study we only used the three complex span tasks as our measures of working memory, the antisaccade and Stroop as our measures of AC, and the psychomotor vigilance task as our measure of sustained attention. The long-term memory tasks were part of another research project and are not discussed further.

WMC tasks. These tasks were the same as Experiment 1.

AC tasks.

Stroop. The Stroop task was the same as Experiment 1 except there was no eye tracking and no 2-s baseline period.

Antisaccade. The antisaccade task was the same as Experiment 1 except there was no eye tracking, no 2-s baseline period, and there were 40 antisaccade trials.

Psychomotor vigilance task. The psychomotor vigilance task task was the same as Experiment 1 except that there were equal numbers of trials for ISIs of 2, 4, 6, 8, and 10 s.

Thought probes. The thought probes were the same as Experiment 1.

Motivation question. Following the psychomotor vigilance task, participants were asked how motivated they felt to perform well on the task (Robison & Unsworth, 2018). Specifically, participants were asked, "How motivated were you to perform well on the task?". Participants responded on a 1 to 6 scale.

Eye tracking. Same as Experiment 1.

Results

Pupillary responses during the interstimulus interval. As noted previously, pupillary responses during the ISI were baseline corrected and averaged into a series of 200-ms time windows following the appearance of the numbers for each trial. All ISIs from 2–10 s were averaged together into a single pupillary response for each participant. Unlike Experiment 1, examining the pupillary response during the ISI suggested there was not a significant effect of time, $F(49, 6811) = 1.08$, $MSE = .003$, $p = .334$, partial $\eta^2 = .01$ (Figure 4a). Next, we examined each ISI separately. There was a significant effect of time in the 2- and 4-s ISIs (both ps $< .001$, both partial η^2s $> .02$) indicating a slight decrease in pupil over time. The effect of time was not significant in any of the other ISIs (all ps $> .20$; all partial η^2s $< .01$).

Next, we tested our main question of interest to examine whether the pupillary response during the ISI differed as a function of individual differences in lapses of attention. To do so we repeated the above analysis with all ISIs averaged together, but now entered in Quintile 5 as an indicator of lapses into an analysis of covariance as a covariate. The analysis suggested a main effect of Quintile 5, $F(1, 138) = 6.64$, $MSE = .195$, $p = .011$, partial $\eta^2 = .05$, in which Quintile 5 was negatively related ($r = -.21$) with the average pupillary response during the ISI suggesting that participants who have frequent lapses of attention have a smaller

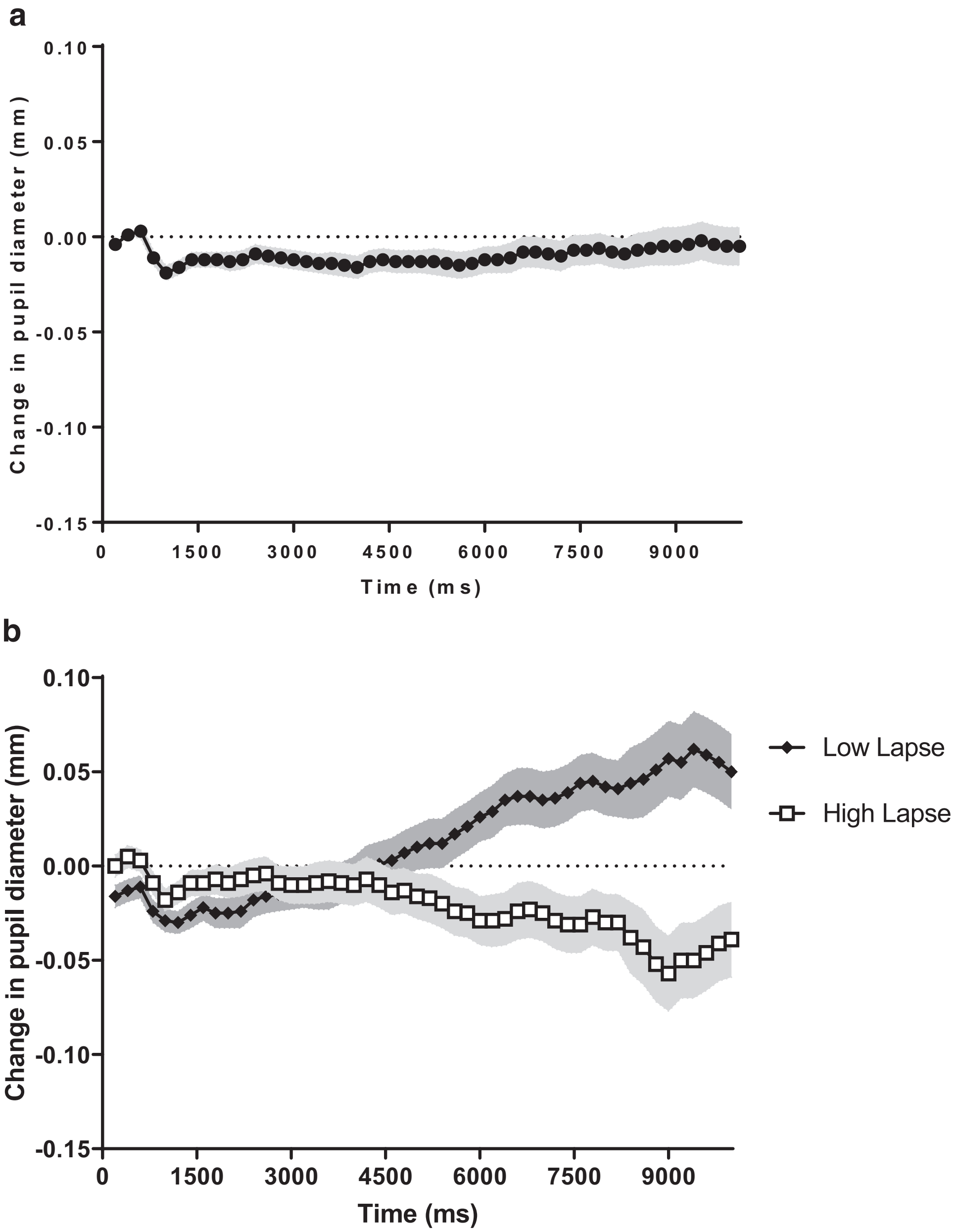

Figure 4. (a) Change in pupil diameter as a function of time during the ISI in Experiment 2. (b) Change in pupil diameter as a function of time during the ISI for high- and low-lapse individuals in Experiment 2. Shaded areas reflect one standard error of the mean.

pupillary response during the ISI. Consistent with Experiment 1, there was also an interaction between time and Quintile 5, $F(49, 6762) = 13.96$, $MSE = .002$, $p < .001$, partial $\eta^2 = .09$, suggesting that pupillary response differed as a function of individual differences in lapses of attention. As shown in Figure 4b, for low-lapse individuals their pupillary response increased during the ISI, but for high-lapse individuals their pupillary response tended to decrease during the ISI. Next, we examined each ISI separately. There was a significant interaction between Quintile 5 and time in each ISI (all ps $< .04$; all partial η^2s $> .01$) except for the 2-s ISI ($p = .38$, partial $\eta^2 = .008$). In fact, the results for the 10-s ISI were nearly identical to the overall results.

Similar to Experiment 1, we also examined the within subject effects. First, examining slow versus fast trials revealed a significant linear interaction between time bin and trial type, suggesting differences in the pupillary responses during the ISI for slow and fast trials [$b = -.001$, $SE = .0003$, $t(101524.62) = -3.51$, $p < .001$]. As shown in Figure 5a, and consistent with Experiment 1, fast trials were associated with an increase in the pupillary response during the ISI, but slow trials were associated with a

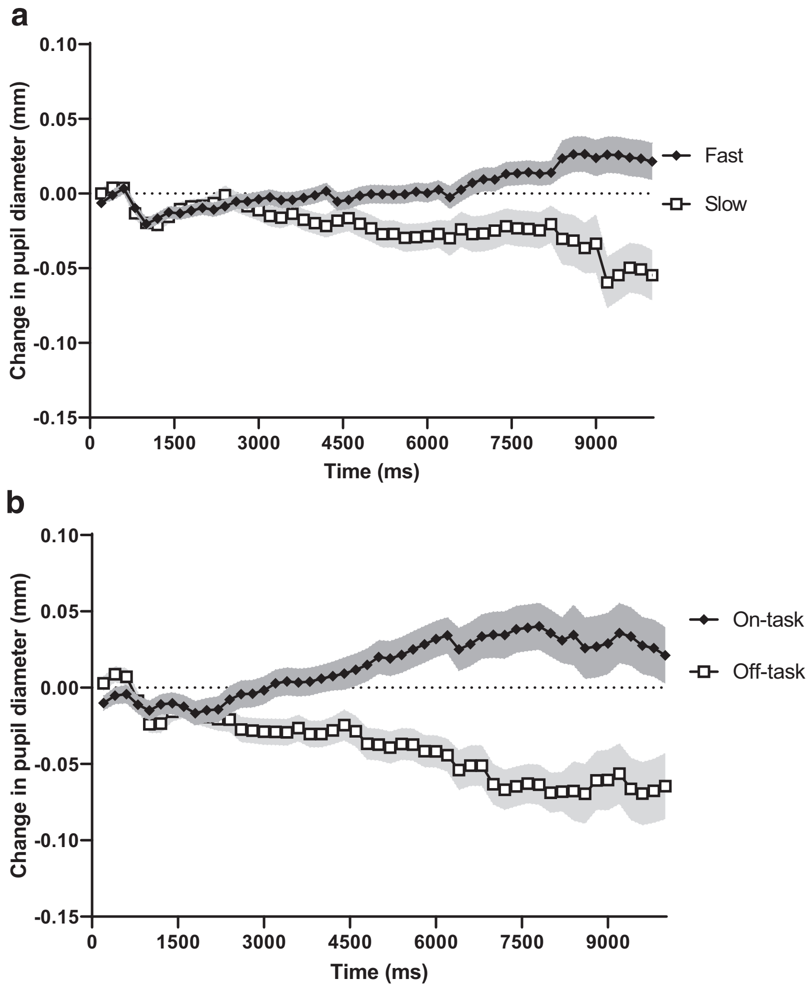

Figure 5. (a) Change in pupil diameter as a function of time during the ISI for lapse and nonlapse trials in Experiment 2. (b) Change in pupil diameter as a function of time during the ISI for on-task and off-task trials in Experiment 2. Shaded areas reflect one standard error of the mean.

decrease in the pupillary response during the ISI. Next, examining on-task versus off-task trials suggested similar results such that there was a significant linear interaction between trial type (on- vs. off-task) and time bin [$b = -0.003$, $SE = .0001$, $t(42{,}834.34) = -17.42$, $p < .001$]. As shown in Figure 5b, and consistent with Experiment 1, when participants reported being on-task, the pupil increased during the ISI, but when participants reported being off-task the pupil decreased during the ISI.

Finally, examining fixation instability during the ISI suggested overall similar results as Experiment 1. Specifically, the results suggested that slow trials ($M = .039$, $SD = .035$) were associated with more fixation instability than fast trials ($M = .024$, $SD = .023$) [$b = 0.003$, $SE = .0002$, $t(139.45) = 11.68$, $p < .001$]. Similarly, when participants reported being off-task ($M = .036$, $SD = .032$) there was greater fixation instability than when they reported being on-task ($M = .025$, $SD = .027$) [$b = .001$, $SE = .0004$, $t(1152.39) = 3.56$, $p < .001$].

Correlations among the measures. Next we examined relations between Quintile 5 and the other measures. The eye measures were the same as Experiment 1. Shown in Table 4 are the descriptive statistics for all measures. As can be seen, most of the measures had generally acceptable values of internal consistency and most of the measures were approximately normally distributed with values of skewness and kurtosis under the generally accepted values.

Similar to Experiment 1 we created a WMC composite given that the three working memory span measures were correlated (Operation Span–Symmetry Span $r = .26$; Operation Span–Reading Span $r = .56$; Symmetry Span–Reading Span $r = .31$). The composite WMC score was computed 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 .69, .38, and .81, respectively. Likewise, we computed a factor composite for AC (Antisaccade–Stroop $r = -.17$, factor loadings .42 and $-.42$).

Shown in Table 5 are the correlations between Quintile 5 and all of the measures. As can be seen, Quintile 5 was significantly related to most of the other measures. Specifically, Quintile 5 was related to AC, off-task thinking, as well as task-specific motivation on the psychomotor vigilance task consistent with prior research (Unsworth et al., 2010; Unsworth & McMillan, 2014; Unsworth & Robison, 2020). However, working memory was not related to Quintile 5, which is inconsistent with prior research.[2] Consistent with the prior results, Quintile 5 was negatively related to the pupillary response during the last second of the ISI. Likewise, greater variability in both pupillary responses and gaze were positively related to Quintile 5, consistent with Experiment 1. AC and off-task thinking demonstrated weaker relations with the eye measures compared with Experiment 1. Interestingly, task-specific motivation was not related to either WMC or AC, but was negatively related to off-task thinking. Furthermore, task-specific motivation was related to variability in pupillary responses during the ISI and gaze instability during the ISI, but was not quite significantly related to the pupillary response during the last second of the ISI. Finally, the three eye measures were related to one another, although the relations were a bit weaker than Experiment 1.

To further examine the relations between the various measures and Quintile 5 we specified a simultaneous regression in which the different measures were all allowed to predict Quintile 5. Shown in Table 6 are the results. As can be seen, overall 41% of the variance in Quintile 5 was accounted for by the various measures. Of this variance, AC accounted for roughly 3% unique variance, the pupillary response during the last second of the ISI accounted for roughly 3% unique variance, and fixation instability during the ISI accounted for roughly 13% unique variance. These results are largely consistent with Experiment 1. The one exception was that off-task thinking did not account for unique variance in Quintile 5. This is likely attributable to the fact off-task thinking and task-specific motivation were moderately negatively correlated, and thus were accounting for largely similar variance. Indeed, rerunning the analysis excluding motivation suggested that off-task thinking accounted for significant unique variance in Quintile 5 ($\beta = .16$, $p = .028$). Overall, the different measures accounted for roughly 19% unique variance and 21% shared variance in Quintile 5. Consistent with Experiment 1, the results suggest that there are a number of important factors that account for variation in lapses of attention.

Table 4
Descriptive Statistics and Reliability Estimates for All Measures in Experiment 2

Measure	*M*	*SD*	Skew	Kurtosis	Reliability
Quintile 5	526.33	132.71	1.60	3.71	.93
Ospan	39.67	7.75	−1.02	1.41	.63
Symspan	19.71	4.75	−0.62	0.24	.54
Rspan	39.07	8.16	−1.19	1.72	.69
Anti	0.61	0.17	−0.19	−0.54	.82
Stroop	153.41	96.12	0.46	−0.28	.55
PVToff	0.53	0.29	−0.19	−1.04	.62
PVTMot	3.74	1.17	−0.31	−0.31	—
ISI Pupil	−0.01	0.11	0.44	0.66	.99
ISI Pupil*SD*	0.15	0.05	1.07	1.52	.99
ISI Gaze*SD*	0.03	0.02	1.20	1.50	.99

Note. Quintile 5 = slowest 20% of trials in the psychomotor vigilance task; Ospan = operation span; Rspan = reading span; Symspan = symmetry span; Anti = antisaccade; PVToff = off-task thoughts psychomotor vigilance task; PVTMot = task-specific motivation on the psychomotor vigilance task; ISI Pupil = average pupillary response during the last second of the 10 s ISI; ISI Pupil*SD* = standard deviation of pupillary response during the ISI; ISI Gaze*SD* = standard deviation of gaze during the ISI.

Table 5
Correlations Among the Measures in Experiment 2

Measure	1	2	3	4	5	6	7	8
1. Quintile 5	—							
2. WMC	−.13	—						
3. AC	**−.32**	**.35**	—					
4. PVToff	**.32**	.01	**−.18**	—				
5. PVTMot	**−.30**	.11	.04	**−.42**	—			
6. ISI Pupil	**−.35**	.15	.15	**−.23**	.15	—		
7. ISI Pupil*SD*	**.26**	−.07	−.16	**.23**	**−.22**	**−.26**	—	
8. ISI Gaze*SD*	**.53**	−.16	**−.22**	**.19**	**−.24**	**−.23**	**.23**	—

Note. Bold correlations are significant. Quintile 5 = slowest 20% of trials in the psychomotor vigilance task; WMC = working memory capacity; AC = attention control; PVToff = off-task thoughts psychomotor vigilance task; PVTMot = task-specific motivation on the psychomotor vigilance task; ISI Pupil = average pupillary response during the last second of the 10 s ISI; ISI Pupil*SD* = standard deviation of pupillary response during the ISI; ISI Gaze*SD* = standard deviation of gaze during the ISI.

Discussion

The results from Experiment 2 broadly replicated the findings from Experiment 1. Similar to Experiment 1, low-lapse individuals tended to increase their pupillary response during the ISI, whereas high-lapse individuals could not sustain their pupillary response during the ISI. Fixation instability was also greater for high-lapse individuals compared with low-lapse individuals. Furthermore, examining within-participant effects suggested that when participants experienced a lapse of attention their pupillary response decreased and they had greater fixation instability during the ISI compared with when they were on-task. Examining WMC and AC suggested that they tended to be related to lapses of attention and demonstrated some weak relations with the eye measures. The somewhat weaker relations could be partially attributable to the fact that with fewer ISIs the task became somewhat more predictable and thus required less control for optimal performance. Off-task thinking and task-specific motivation were negatively related, demonstrated similar relations with the other variables, and generally accounted for the same variance in terms of predicting lapses of attention. Thus, task-specific motivation was related to lapses of attention and to intrinsic alertness, and most of this relation was shared with variation in off-task thinking. Finally, similar to Experiment 1, AC, magnitude of the pupillary response during the ISI, and fixation instability all accounted for unique variance in lapses of attention, suggesting that there are a number of factors that account for variation in lapses of attention.

Combined Analysis

Given the similarities in results across experiments, we further examined the data via a combined cross-experimental analysis.

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[2] Because there were some outliers in this relation, we examined the relation with Spearman's rho which is less sensitive to outliers. The resulting correlation was $\rho = -.19$ which is consistent with prior research.

This was done to better examine the relations among the constructs and how the different measures potentially account for variation in lapses of attention with a larger combined sample with more power. To examine the relations for the combined sample (N = 276) we specified a confirmatory factor analysis where the three working memory tasks loaded onto a WMC factor, the two AC tasks loaded onto a AC factor, and Quintile 5, off-task thinking, mean pupillary responses during the ISI, variability of the pupillary response during the ISI, and fixation stability were treated as manifest variables. All of the factors and measures were allowed to correlate. The overall fit of the model was acceptable, $\chi^2(19)$ = 22.75, p = .249, RMSEA = .03, NNFI = .98, CFI = .99, SRMR = .03.[3] All three working memory tasks loaded on the WMC factor (Operation Span = .73; Symmetry Span = .44; Reading Span = .77). Similarly, both AC measures loaded onto the AC factor (antisaccade = .57; Stroop = −.28). Shown in Table 7 are the resulting correlations. As can be seen, lapses of attention were related to all of the variables except WMC. AC was strongly related to lapses of attention and WMC, and demonstrated moderate relations with the other variables. All of the remaining variables were correlated similar to the results from each experiment separately.

Next, we wanted to better examine a potential path model in which some measures have direct relations with lapses of attention and other measures may have more indirect (or mediated) relations with lapses. Therefore, we specified a model in which the relation between WMC and lapses was primarily mediated through variation in AC. That is, the reason WMC is related to lapses of attention is because of variation in broad AC abilities. The influence of AC on lapses of attention likely manifests in different ways. For example, AC is likely related to lapses of attention partially via variation in off-task thinking in which those individuals with poorer AC abilities are more susceptible to mind-wandering and external distraction during the task, resulting in behavioral lapses of attention. AC is also likely related to the ability to increase the intensity of attention during the ISI (intrinsic alertness indexed by pupillary responses during the ISI) and the ability to consistently increase the intensity of attention during the ISI across trials (variability in pupillary responses during the ISI), both of which are related to behavioral lapses of attention. AC is also likely related to the ability to maintain fixation on the numbers during the ISI to prevent behavioral lapses of attention (fixation stability indexed by the standard deviation of gaze during the ISI). Finally, AC might have a direct effect on behavioral lapses due to variation in overall goal management abilities that are not being captured by the other measures in the study. To test these notions using the combined data, we specified a structural equation model in which WMC predicted AC. AC predicted off-task thinking, the mean pupillary responses during the ISI, variability (standard deviation) of the pupillary response during the ISI, fixation stability during the ISI, and had a direct path to lapses of attention. Off-task thinking, mean pupillary responses during the ISI, variability of the pupillary response during the ISI, and fixation stability during the ISI all had direct paths to lapses of attention. Note that we also allowed the error variances for off-task thinking, mean pupillary responses during the ISI, variability of the pupillary response during the ISI, and fixation stability during the ISI to correlate given that the prior results demonstrated that they were related to one another. The overall fit of the model was acceptable, $\chi^2(24)$ = 36.53, p = .049, RMSEA = .04, NNFI = .96, CFI = .98, SRMR = .05. Shown in Figure 6 is the resulting model. As can be seen, WMC predicted AC abilities, which in turn were related to off-task thinking, increases in the pupillary response during the ISI, variability in the pupillary response during the ISI, and fixation instability. Each of these factors had direct relations with lapses of attention. Furthermore, AC had a direct relation to lapses of attention even after accounting for the other factors. These results suggest that the relation between AC abilities and lapses of attention can manifest in many different ways. Additionally, these results suggest that the relation between WMC and lapses of attention was largely mediated by AC abilities and the different manifestations of control. Indeed, WMC had an indirect effect on lapses of attention (indirect effect = −.24, p < .001). WMC also tended to have indirect effects on each manifestation of

Table 6
Simultaneous Regression Predicting Quintile 5 in Experiment 2

Variable	β	*t*	*sr*^{2}	*R*^{2}	*F*
WMC	0.04	0.61	.00		
AC	−0.19	−2.55*	.03		
PVToff	0.11	1.44	.01		
PVTMot	−0.12	−1.62	.01		
ISI Pupil	−0.18	−2.50*	0.03		
ISI Pupil*SD*	0.04	0.59	.00		
ISI Gaze*SD*	0.39	5.38**	.13	.41	12.92**

Note. WMC = working memory capacity; AC = attention control; PVToff = off-task thoughts psychomotor vigilance task; PVTMot = task-specific motivation on the psychomotor vigilance task; ISI Pupil = average pupillary response during the last second of the 10 s ISI; ISI Pupil*SD* = standard deviation of pupillary response during the ISI; ISI Gaze*SD* = standard deviation of gaze during the ISI.
* p < .05. ** p < .01.

Table 7
Correlations Among the Measures From the Confirmatory Factor Analysis in the Combined Data

Measure	1	2	3	4	5	6	7
1. Quintile 5	—						
2. WMC	−.13	—					
3. AC	**−.70**	**.71**	—				
4. Off-task	**.45**	−.01	**−.35**	—			
5. Pupil	**−.30**	.04	**.27**	**−.22**	—		
6. Pupil*SD*	**.24**	−.07	**−.25**	**.24**	**−.3**	—	
7. Gaze*SD*	**.37**	**−.25**	**−.46**	**.17**	**−.2**	**.36**	—

Note. Bold correlations are significant. Quintile 5 = slowest 20% of trials in the psychomotor vigilance task; WMC = working memory capacity factor; AC = attention control factor; off-task thinking (Off-task), pupillary responses during the ISI (Pupil), variability in the pupillary response during the ISI (Pupil*SD*), and fixation instability (Gaze*SD*).

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[3] For the model testing (using Lisrel 8.80), we report several fit statistics. Non-significant chi-square tests indicate adequate model fit; with large samples like ours, however, they are nearly always significant. Comparative fit indices (CFI) and nonnormed fit index (NNFI) of ≥ .90 indicate adequate fit, whereas the root mean square error of approximation (RMSEA) and standardized root mean square residual (SRMR) values of ≤ .08 indicate adequate fit (e.g., Schermelleh-Engel, Moosbrugger, & Müller, 2003).

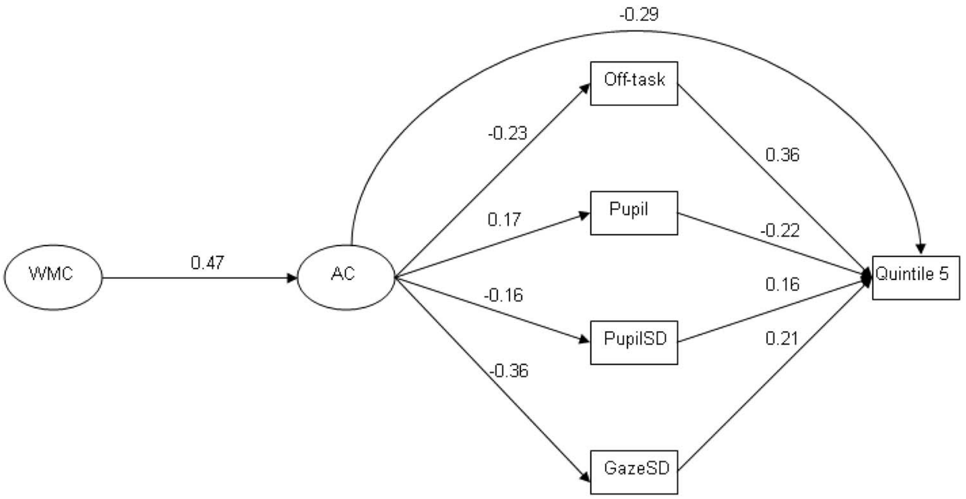

Figure 6. Structural equation model in which working memory capacity (WMC) predicts attention control (AC); AC predicts Quintile 5, off-task thinking (Off-task), pupillary responses during the ISI (Pupil), variability in the pupillary response during the ISI (Pupil*SD*), and fixation instability (Gaze*SD*); and each of these predict Quintile 5. Single-headed arrows connecting variables to each other represent standardized path coefficients, indicating the unique contribution of the variable. Solid lines are significant at the $p = .05$ level. ISI Pupil*SD* = standard deviation of pupillary response during the ISI; ISI Gaze*SD* = standard deviation of gaze during the ISI.

control (off-task thinking indirect effect = −.11, $p = .009$; ISI pupil indirect effect = .08, $p = .040$; fixation instability = −.17, $p < .001$) although the indirect effect on variability of the pupillary response during the ISI was not quite significant (indirect effect = −.07, $p = .054$). Overall, 49% of the variance in lapses of attention was accounted for by the measures with some measures primarily having direct relations and other measures having more indirect relations with lapses of attention.

We also tested a model to examine how speed of processing may influence the relations. As noted previously, Quintile 5 likely not only measures lapses of attention, but it also likely captures speed of processing as participants with overall slower speed of processing will tend to have their distributions shifted over resulting in slower RTs at each quintile. Thus, to examine the influence of speed of processing we reran the prior model, but now include Quintile 1 as a measure of speed of processing to see if it accounted for additional variance in Quintile 5. Error variances for Quintile 1 were allowed to correlate with error variances for off-task thinking, mean pupillary responses during the ISI, variability of the pupillary response during the ISI, and fixation stability during the ISI similar to the prior model. The overall fit of the model was acceptable, $\chi^2(28) = 37.62$, $p = .106$, RMSEA = .04, NNFI = .97, CFI = .99, SRMR = .05. Shown in Figure 7 is the resulting model. As can be seen, the overall model remained pretty much the same as the prior model, but now AC significantly predicted Quintile 1 and Quintile 1 significantly predicted Quintile 5. Thus, variation in processing speed did have an influence on Quintile 5, but the other factors remained significant predictors of Quintile 5 even when taking into account Quintile 1, suggesting that these relations were not simply due to speed of processing. The one exception to this was that AC no longer predicted Quintile 5, suggesting that the direct path from AC to Quintile 5 in the prior model was likely due to shared variance with speed of processing. Overall, in this Model 62% of the variance in Quintile 5 was accounted for by the measures with additional variance being accounted for by variation in speed of processing.

General Discussion

In two experiments we examined individual differences in intrinsic alertness and their relation with variation in lapses of attention. In both experiments participants performed a variant of the psychomotor vigilance task while their eyes were continuously tracked. A consistent pattern of results was obtained across both experiments. In particular, examining pupillary responses during the ISI suggested that low-lapse individuals (indexed by the slowest RTs) tended to demonstrate an increased pupillary response during the ISI, whereas high-lapse individuals tended to demonstrate a decreased pupillary response during the ISI. Similar results arose when examining within-subject effects such that fast RTs and trials where participants reported being on-task were associated with an increased pupillary response during the ISI, whereas slow RTs and trials where participants reported being off-task were associated with a decreased pupillary response during the ISI. These results are consistent with prior research (Hutchison et al., 2020; Unsworth et al., 2018). Nonlapse (fast RT, on-task reports) trials were also associated with less fixation instability compared with lapse (slow RT, off-task report) trials consistent with some prior research (Grandchamp et al., 2014). These results suggest that interindividual and intraindividual differences in lapses of attention are associated with distinct pupillary responses (and fixation instability) that occur as participants are waiting for the target stimulus to appear and are preparing the appropriate response.

Examining relations with other factors suggested that lapses of attention were related not only to the magnitude of the pupillary response during the ISI, but also to trial-to-trial variability in the pupillary response during the ISI with high-lapse individuals dem-

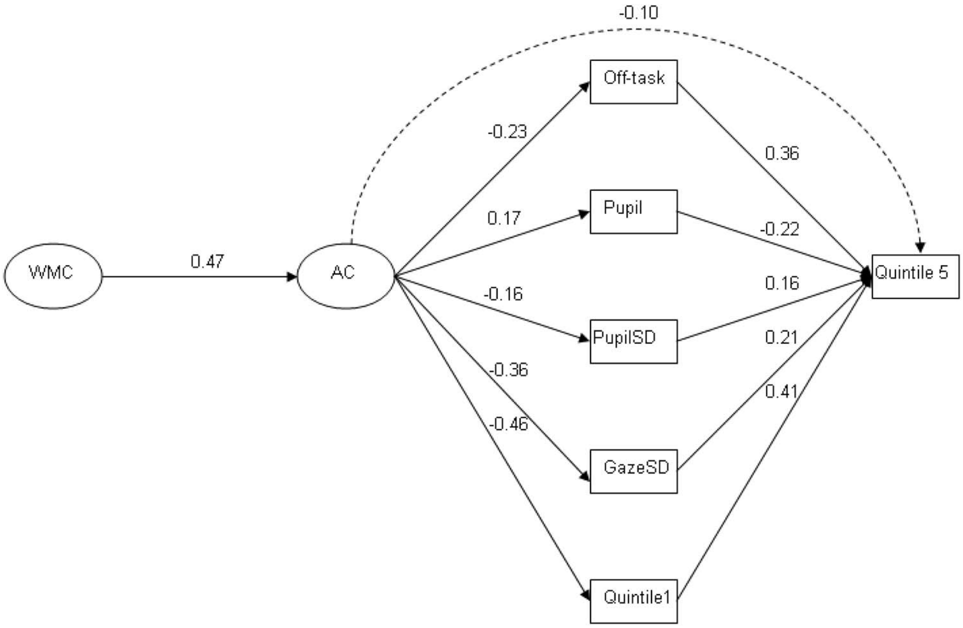

Figure 7. Structural equation model in which working memory capacity (WMC) predicts attention control (AC); AC predicts Quintile 5, off-task thinking (Off-task), pupillary responses during the ISI (Pupil), variability in the pupillary response during the ISI (Pupil*SD*), fixation instability (Gaze*SD*), and Quintile 1; and each of these predict Quintile 5. Single-headed arrows connecting variables to each other represent standardized path coefficients, indicating the unique contribution of the variable. Solid lines are significant at the $p = .05$ level, dashed lines are not significant. ISI Pupil*SD* = standard deviation of pupillary response during the ISI; ISI Gaze*SD* = standard deviation of gaze during the ISI.

onstrating more variability in the pupillary response across trials than low-lapse individuals. Similarly, fixation instability during the ISI was positively correlated with lapses, suggesting that high-lapse individuals were less able to maintain their fixation on the numbers during the ISI than low-lapse individuals. Self-reports of off-task thinking, WMC, and AC also tended to relate to lapses of attention and the various eye measures. Furthermore, when task-specific motivation was assessed in Experiment 2, it was found that task-specific motivation was related to lapses of attention and the eye measures and much of this relation was due to shared variance with self-reports of off-task thinking.

Examining relations in the combined sample of participants across experiments suggested that there were both direct and indirect relations in terms of predicting variation in lapses of attention. In particular, WMC demonstrated an indirect relation with lapses of attention (via AC, off-task thinking, pupillary responses during the ISI, and fixation instability). AC was similarly related to lapses via relations with the more proximal measures, and AC demonstrated a direct relation with lapses even after tasking the other measures into account. Overall, 49% of the variance in lapses of attention were accounted for by the various measures with roughly 33% of the variance being unique and 16% being shared among the measures. Including Quintile 1 in the model as a measure of speed of processing indicated that speed of processing accounted for additional variance in Quintile 5, suggesting that Quintile 5 is not necessarily just measuring lapses as noted previously. Furthermore, once Quintile 1 was included in the model, the direct relation between AC and Quintile 5 was no longer significant suggesting that the direct relation in the prior model was due to shared variance with speed of processing. Overall, in this model 62% of the variance in Quintile 5 was accounted for by the various measures with roughly 42% of the variance being unique and 20% being shared among the measures. These results suggest that there are a combination of factors that account for individual differences in lapses of attention and particularly slow RTs.

Intrinsic Alertness and Lapses of Attention

Previously it was suggested that intrinsic alertness was a likely reason for individual differences in lapses of attention. That is, variation in lapses of attention are partially due to individual differences in the ability to voluntarily control the intensity of attention on a moment-by-moment basis. When the intensity of attention is high, participants are fully engaged in the current experimental task leading to high levels of control in terms of goal management (e.g., proper goal selection, goal activation, and goal maintenance) and a resulting fast response. However, when current intensity of attention levels is low, participants are not fully engaged in the current task, leading to lowered levels of control and a higher incidence of lapses of attention. Furthermore, we suggested that there are a number of potential ways that individual differences in intrinsic alertness can manifest in terms of the intensity of attention during the preparatory interval.

Using pupillary responses during the ISI as an index of the intensity of attention suggested evidence consistent with several of the possibilities. Specifically, consistent with the ramp up hypothesis, low-lapse individuals tended to increase their pupillary response during the ISI, suggesting that they were increasing the intensity of attention while waiting for the numbers to begin counting. High-lapse individuals, however, tended to decrease their pupillary response during the ISI, suggesting that they were unable to sustain their intensity of attention while waiting for the numbers to begin counting. Thus, there was evidence for both the ramp up and sustain hypotheses. Furthermore, pupillary responses during the ISI tended to predict lapses of attention even when taking into account the other variables (in both the regressions and the structural equation model), suggesting that variation in the intensity of attention during the preparatory interval is a critical reason for variation in lapses of attention. There was also evidence consistent with the consistency hypothesis in that trial-to-trial variability in the pupillary response was positively related to lapses of attention, suggesting that high-lapse individuals were less able to consistently allocate attention to the task compared low-lapse individuals. Fluctuations in the pupillary response during the ISI tended not to account for unique variance in the regressions, but this measure did account for unique variance in the more powerful structural equation model, suggesting that fluctuations in intensity are also likely an important contributor to variation in lapses of attention.

Collectively, these results suggest that individual differences in intrinsic alertness are an important reason for lapses of sustained attention. Individuals who are less able to control their alertness levels are more likely to experience lapses of attention due to inabilities to sustain their intensity of attention during the preparatory interval and due to inabilities to consistently allocate attention (across trials) during the preparatory interval. Individuals who are better able to control their alertness levels are more likely to increase their intensity of attention during the preparatory interval and are better able to consistently allocate attention during the preparatory interval resulting on overall better task performance and fewer lapses of attention.

A Combination of Factors Contribute to Individual Differences in Lapses of Attention

In addition to variation in intrinsic alertness, the current results suggest that a number of factors were important for variation in lapses of attention. For example, prior research has suggested that individual differences in WMC are related to variation in lapses of attention (Unsworth et al., 2010; Unsworth & Robison, 2020). Furthermore, prior research has found that WMC is strongly related to AC (e.g., Unsworth & Spillers, 2010), and lapses of attention from the psychomotor vigilance task have been found to correlate strongly and load on the same factor as other AC tasks (e.g., Unsworth & Spillers, 2010). Thus, prior research has suggested that individual differences in AC should mediate the relation between WMC and lapses of attention (Unsworth & Robison, 2020). The current results were very much in line with this reasoning, suggesting that working memory had an indirect effect on lapses of attention via individual differences in AC. Thus, these results suggest that the relation between WMC and lapses of attention is more distal in nature, with variation in AC abilities mediating the relation.

Examining variation in AC suggested that AC abilities were related to lapses of attention and to the different eye measures. In particular, AC abilities predicted susceptibility to off-task thinking during the psychomotor vigilance task consistent with prior research (Robison & Unsworth, 2018; Unsworth & McMillan, 2014; Unsworth & Robison, 2017a). Individuals high in AC were better able to maintain focus on the task and prevent internal or external distractors from hijacking attention away from the task compared with low AC individuals. Furthermore, AC abilities predicted both the magnitude of the pupillary response during the ISI and trial-to-trial fluctuations in the pupillary response during the ISI, suggesting that AC abilities were related to intrinsic alertness. High AC individuals were more likely to ramp up their attention during the ISI than low AC individuals and high AC individuals were better able to consistently allocate attention to the task compared with low AC individuals. AC abilities were also related to fixation stability during the ISI in that high AC individuals were better able to maintain fixation on the numbers while waiting for the target stimulus to occur compared with low AC individuals. Collectively, these results suggest that AC abilities are related to lapses of attention, and this relation is manifested in a number of more proximal associations. That is, there are multiple reasons for the association between AC abilities and lapses of attention.

In the initial structural equation model, it was found that AC also had a more direct association with particularly slow RTs, suggesting that some additional variance was associated with processes not included in the model. However, once Quintile 1 was added into the model, the direct association between AC and Quintile 5 was no longer significant, suggesting that the prior direct relation was likely due to shared variance with speed of processing. This could be attributable to shared variance between speed of processing and the specific AC measures used in the current study such that better performance on these AC measures is partially attributable to better speed of processing. Additionally, this shared variance could be attributable to the need for AC processes on basic speed measures (Cepeda, Blackwell, & Munakata, 2013), such that more concentration and task-engagement (less off-task thinking) should result in faster overall RTs. As such, the current results are consistent with prior research suggesting that at least some of the relation between AC abilities and particularly slow RTs is likely attributable to shared variance with speed of processing (Coyle, 2017; Unsworth et al., 2010; Unsworth & Robison, 2020). At the same time, it is clear that speed of processing does not fully account for this relation as AC was related to the slowest RTs via other means (off-task thinking, intrinsic alertness, fixation stability) and this variance likely reflects variation in lapses of attention.

Self-reports of off-task thinking and task-specific motivation demonstrated consistent relations with lapses of attention, suggesting that those individuals who are more susceptible to off-task thoughts or are not motivated to perform the task tended to have more lapses of attention. As noted above, the relation between off-task thinking and lapses of attention seems at least partially attributable to shared variance with AC abilities whereby those individuals lower in AC are less able to stay engaged with the task and prevent mind-wandering distraction. The relation between off-task thinking and lapses could also be attributable to variation in personal concerns, such that those individuals who have more current personal concerns (i.e., stressed about an upcoming exam, ruminating about a fight with a significant other, higher in trait-level neuroticism) will likely have stronger off-task thoughts that are more difficult to suppress leading to more frequent lapses of attention (Klinger, 1999; McVay & Kane, 2010; Robison et al., 2017; Unsworth & Robison, 2020). Similarly, susceptibility to off-task thoughts during the task are also likely attributable to lowered levels of motivation (Robison & Unsworth, 2018). As seen in Experiment 2, off-task thinking and motivation were strongly related and tended to account for the same variance in lapses of attention. Thus, those individuals who are less motivated to perform the task will likely be less engaged with the task resulting in the entertainment of more off-task thoughts and a greater likelihood of lapses of attention.

The final factor that seemed to be an important determinant of variation in lapses of attention was fixation stability (or instability). In both experiments fixation instability (measured as the standard deviation of eye position during the ISI) was strongly related to lapses of attention and accounted for unique variance when predicting lapses of attention. Those individuals who were better able to maintain fixation on the numbers during the ISI were more likely to experience fewer lapses of attention. Note that these relations held even when we specified an area of interest that only included the numbers. That is, in the primary analyses we computed the standard deviation of eye position during the ISI across the entire computer screen. Rerunning the analyses examining fixation instability with an area of interest restricted to the numbers resulted in overall very similar results as those reported. Thus, much of the variation in fixation instability seemed to be attributable to more minor fixational eye movements such as microsaccades and drift (Martinez-Conde, Otero-Millan, & Macknik, 2013). Prior research has found that fixational eye movements are related to the cognitive load of a task with more fixational eye movements occurring under low load conditions than high load conditions (Dalmaso, Castelli, Scatturin, & Galfano, 2017; Gao, Yan, & Sun, 2015; Krejtz, Duchowski, Niedzielska, Biele, & Krejtz, 2018; Siegenthaler et al., 2014) and fixational eye movements are reduced during the preparatory interval of attention demanding tasks (Betta & Turatto, 2006; Dalmaso, Castelli, & Galfano, 2019a, 2019b; Watanabe, Matsuo, Zha, Munoz, & Kobayashi, 2013). In terms of individual differences, Fried et al. (2014) found that individuals with ADHD demonstrated more fixational eye movements during the preparatory interval of a sustained attention task, and suggested that this was due to an inability to maintain attention and optimal levels of arousal on the task. These results suggest that fixational eye movements might index the overall intensity of attention similar to pupillary responses. This could be partially attributable to reliance on similar neural structures such as the Superior Colliculus (Hafed, Goffart, & Krauzlis, 2009; Wang, Blohm, Huang, Boehnke, & Munoz, 2017). As such, fixational stability seems to be an important factor for variation in lapses of attention for both practical and theoretical reasons.

Conclusions

The current results suggest that variation in intrinsic alertness abilities is critical for understanding individual differences in lapses of attention. Individuals who experience frequent lapses of attention are less able to voluntarily control their alertness levels to sustain their intensity of attention (within trials) and to consistently allocate attention (across trials) during the preparatory interval compared with individual who are less susceptible to lapses of attention. Additional factors are also important for accounting for variation in lapses of attention including AC (and indirectly WMC), susceptibility to off-task thinking, task-specific motivation, and fixation stability. Collectively, the current results suggest that individual differences in lapses of sustained attention are multifaceted and that a number of factors (both direct and indirect) contribute to variation in lapses of attention.

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Appendix

Correlations Among Measures of Lapses in Each Experiment

We examined whether different putative indicators of lapses of attention were related to one another. As noted previously, our main dependent variable was the slowest 20% of RTs (Quintile 5) in the psychomotor vigilance task. However, other indicators of lapses in this task include the number of reaction times > 500 ms (Dinges & Powell, 1985; Unsworth et al., 2010), standard deviation and coefficient of variation of RTs (Unsworth, 2015), as well as fitting an ex-Gaussian function to the entire RT distribution and examining estimates of the tau parameter (Unsworth et al., 2010). Therefore, we computed all of these measures and examined the extent to which they were related and possibly measuring the same construct. Shown in Table A1 and Table A2 are the correlations. As can be seen, Quintile 5 was strongly related to all of the other putative indicators of lapses, suggesting that these indices all largely measure the same thing.[4] Note that we are not suggesting that these different measures are process pure indicators of lapses of attention. It is likely that these different RT measures are indexing other abilities such as differences in overall processing speed in addition to variation in lapses of attention. Correlations among RT distribution measures and the other measures are shown in Table A3 and Table A4.

Table A1
Correlations Among the Reaction Time Indicators of Lapses in Experiment 1

Measure	1	2	3	4	5
1. Quintile 5	—				
2. Lapse sum	**.89**	—			
3. RT *SD*	**.86**	**.75**	—		
4. RT CoV	**.65**	**.53**	**.94**	—	
5. τ	**.90**	**.80**	**.92**	**.77**	—

Note. Bold correlations are significant. Quintile 5 = slowest 20% of reaction times; Lapse Sum = number of reaction times > 500 ms; RT *SD* = standard deviation of reaction times; RT CoV = coefficient of variation of reaction times; τ = τ parameter after fitting the ex-Gaussian function to the entire reaction time distribution.

Table A2
Correlations Among the Reaction Time Indicators of Lapses in Experiment 2

Measure	1	2	3	4	5
1. Quintile 5	—				
2. Lapse sum	**0.83**	—			
3. RT *SD*	**0.91**	**0.63**	—		
4. RT CoV	**0.84**	**0.53**	**0.98**	—	
5. τ	**0.93**	**0.67**	**0.95**	**0.93**	—

Note. Bold correlations are significant. Quintile 5 = slowest 20% of reaction times; Lapse Sum = number of reaction times > 500 ms; RT *SD* = standard deviation of reaction times; RT CoV = coefficient of variation of reaction times; τ = τ parameter after fitting the ex-Gaussian function to the entire reaction time distribution.

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[4] We also examined Quintile 1 to ensure that it not simply the case that all of the RTs are strongly related. Specifically, in Experiment 1 although Quintile 1 was related to Quintile 5 (r = .68), Quintile 1 demonstrated much weaker relations with the other RT variables than Quintile 5 (lapses r = .61, RT *SD* r = .27, RT Cov r = −.03; Tau r = .40). Similar results were obtained in Experiment 2 with Quintile 1 and 5 being correlated (r = .50) and much weaker relations between Quintile 1 and the other RT measures (lapses r = .71, RT *SD* r = .22, RT Cov r = .09; Tau r = .23).

(*Appendix continues*)

Table A3

Correlations for the Reaction Time Measures From the Psychomotor Vigilance Task With the Cognitive and Oculometric Indicators in Experiment 1

Measure	WMC	AC	PVToff	ISI Pupil	ISI Pupil*SD*	ISI Gaze*SD*
Quintile 1	−.11	**−.32**	**.37**	**−.37**	.16	**.24**
Quintile 2	−.13	**−.42**	**.46**	**−.39**	**.20**	**.33**
Quintile 3	−.15	**−.45**	**.51**	**−.39**	**.21**	**.38**
Quintile 4	**−.18**	**−.47**	**.52**	**−.39**	**.23**	**.44**
Quintile 5	**−.28**	**−.47**	**.54**	**−.35**	**.23**	**.48**
Lapse sum	−.15	**−.37**	**.42**	**−.26**	**.19**	**.39**
μ	−.05	**−.37**	**.35**	**−.36**	**.14**	**.20**
σ	−.01	**−.41**	**.22**	−.15	.09	.16
τ	**−.30**	**−.36**	**.49**	**−.25**	**.22**	**.49**
RT *SD*	**−.32**	**−.38**	**.46**	**−.20**	**.19**	**.43**
RT CoV	**−.33**	**−.28**	**.35**	−.08	.13	**.35**

Note. Bold correlations are significant. Quintile = reaction time quintile in the psychomotor vigilance task; Lapse Sum = number of reaction times > 500 ms; μ = μ parameter after fitting the ex-Gaussian function to the entire reaction time distribution; σ = σ parameter after fitting the ex-Gaussian function to the entire reaction time distribution; τ = τ parameter after fitting the ex-Gaussian function to the entire reaction time distribution; RT *SD* = standard deviation of reaction times; RT CoV = coefficient of variation of reaction times; WMC = working memory capacity; AC = attention control; PVToff = off-task thoughts psychomotor vigilance task; ISI Pupil = average pupillary response during the last second of the 10 s ISI; ISI Pupil*SD* = standard deviation of pupillary response during the ISI; ISI Gaze*SD* = standard deviation of gaze during the ISI.

Table A4

Correlations for the Reaction Time Measures From the Psychomotor Vigilance Task With the Cognitive and Oculometric Indicators in Experiment 2

Measure	WMC	AC	PVToff	PVTMot	ISI pupil	ISI Pupil*SD*	ISI Gaze*SD*
Quintile 1	**−.25**	**−.32**	**.25**	**−.23**	**−.29**	.07	**.37**
Quintile 2	**−.22**	**−.34**	**.29**	**−.28**	**−.34**	.13	**.44**
Quintile 3	**−.21**	**−.34**	**.32**	**−.30**	**−.35**	**.18**	**.49**
Quintile 4	**−.18**	**−.34**	**.32**	**−.31**	**−.35**	**.22**	**.54**
Quintile 5	−.13	**−.32**	**.32**	**−.30**	**−.35**	**.26**	**.53**
Lapse sum	−.12	**−.30**	**.32**	**−.31**	**−.32**	**.17**	**.50**
μ	**−.24**	**−.24**	**.18**	**−.19**	**−.25**	.03	**.26**
σ	−.07	**−.17**	**.24**	**−.21**	−.07	.13	**.24**
τ	−.03	**−.26**	**.28**	**−.24**	**−.22**	**.25**	**.44**
RT *SD*	−.06	**−.27**	**.27**	**−.23**	**−.23**	**.24**	**.39**
RT CoV	−.04	**−.24**	**.24**	**−.22**	**−.18**	**.24**	**.34**

Note. Bold correlations are significant. Quintile = reaction time quintile in the psychomotor vigilance task; Lapse Sum = number of reaction times > 500 ms; μ = μ parameter after fitting the ex-Gaussian function to the entire reaction time distribution; σ = σ parameter after fitting the ex-Gaussian function to the entire reaction time distribution; τ = τ parameter after fitting the ex-Gaussian function to the entire reaction time distribution; RT *SD* = standard deviation of reaction times; RT CoV = coefficient of variation of reaction times; WMC = working memory capacity; AC = attention control; PVToff = off-task thoughts psychomotor vigilance task; PVTMot = task-specific motivation on the psychomotor vigilance task; ISI Pupil = average pupillary response during the last second of the 10 s ISI; ISI Pupil*SD* = standard deviation of pupillary response during the ISI; ISI Gaze*SD* = standard deviation of gaze during the ISI.

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